



Transparent and printed RF electronics: a comprehensive review of materials, and applications

Prabhakar Jepiti^a, Junghyeon Kim^b, Sumin Bark^b, Sungjoon Lim^{a,b,*}

^a School of Electrical and Electronics Engineering, Chung-Ang University, Seoul 06974, Republic of Korea

^b School of Intelligent Semiconductor Engineering, Chung-Ang University, Seoul 06974, Republic of Korea

ARTICLE INFO

Keywords:

Printed electronics
Transparent RF devices
Conductive inks
Transparent antennas
Transparent metamaterial absorbers
Transparent frequency-selective surfaces

ABSTRACT

The development of transparent radio-frequency (RF) electronics has enabled the creation of flexible, lightweight devices with novel applications. A key driver of this advancement is *printed electronic devices*, which offer scalable and environmentally friendly manufacturing methods. This study reviews recent progress in materials, fabrication techniques, and design strategies for transparent RF devices. The review examines *critical materials*, including conductive nanoparticle inks, conductive polymers, and emerging nanowire-based materials, and it assesses their electrical, mechanical, and optical properties. In addition, various *printing technologies*, such as inkjet, screen, electrohydrodynamic jet, offset, and roll-to-roll printing, are also evaluated for their ability to produce high-performance, miniaturised, and transparent RF devices. Current challenges, including the optimisation of conductivity, metallisation, transparency, and material durability, are also discussed. Finally, key application areas (such as antennas, metamaterial absorbers, and frequency-selective surfaces) are explored, with a focus on balancing transparency and functional performance. Finally, future challenges and opportunities are highlighted to encourage further research in this rapidly evolving field of transparent RF electronics.

1. Introduction

In recent years, transparent electronics have made rapid progress, fuelled by breakthroughs in materials science and manufacturing techniques [1–11]. This evolving field encompasses a broad range of devices and systems designed to maintain functionality while remaining optically transparent. The growing significance of transparent electronics stems from their transformative applications across multiple industries, including consumer electronics, military, aerospace, automotive, wearables, optoelectronic, and emerging energy technologies [1,12–17]. Among these advancements, transparent radio-frequency (RF) technology stands out as a particularly promising development. In this context, RF refers to the frequency range of 3 kHz to 300 GHz [18]. Specifically, flexible and transparent RF electronics have gained attention for their ability to integrate seamlessly into various surfaces and devices, which enables connectivity without compromising aesthetics or functionality. The rapidly evolving field of wireless communication continually drives innovation in antenna, metamaterial absorbers (MA), and frequency-selective surfaces (FSS) technologies. As the demand for ubiquitous connectivity grows, traditional approaches to designing and fabricating these components are being redefined. Antennas, which are crucial for

transmitting and receiving electromagnetic waves, have advanced to meet modern performance requirements. Among these advancements, transparent RF antennas stand out for their ability to integrate seamlessly into their surroundings. This offers significant advantages in applications where aesthetics, structural integration, and multifunctionality are key considerations. Similarly, flexible and transparent MA structures that can efficiently absorb electromagnetic waves at specific frequencies enable lightweight, adaptable solutions for many designs. FSS, which allows specific frequencies to pass while blocking others, further enhances these technologies by enabling precise control over electromagnetic wave propagation. Together, these innovations offer exciting possibilities for next-generation applications. The concept of transparency in antennas, MA, and FSS transcends aesthetics. It presents a practical innovation that addresses several key challenges in modern electronics. Transparent RF antennas, MA, and FSS are particularly valuable in applications such as wearable electronics, transparent displays, automotive systems, and Internet-of-Things (IoT) devices, where conventional opaque antennas would be impractical or undesirable. Integrating transparent antennas into these systems enhances functionality while maintaining (or even improving) the visual appeal and ergonomic comfort of the devices.

* Corresponding author.

E-mail address: sungjoon@cau.ac.kr (S. Lim).

<https://doi.org/10.1016/j.matdes.2025.114583>

Received 20 April 2025; Received in revised form 18 July 2025; Accepted 13 August 2025

Available online 14 August 2025

0264-1275/© 2025 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Fig. 1 illustrates how a variety of smart-city applications can utilise this novel type of transparent RF electronics without disrupting the operations of the existing structures by their implementation. For example, precisely engineered periodic structures, known as reconfigurable intelligent surfaces (RIS), can enhance 5G and next-generation communication by improving coverage, spectral efficiency, and energy utilisation [19]. Transparent RIS integrated into windows in buildings, automobiles, and trains can dynamically adjust signal reflection and transmission properties based on user positioning, utilising tunable and switchable devices [20]. Transparent antennas on vehicles can support multiple connectivity functions, including smartphones, GPS, radio, television, and other communication devices, while maintaining aesthetic appeal [21–23]. This technology could also become a standard feature in self-driving cars, where radar antennas integrated into the vehicle's body enhance sensing and navigation capabilities. A transparent FSS, which is a periodic structure that selectively blocks out undesirable frequency bands while permitting bands of interest to pass through, is another example [24–27]. Other examples of transparent radio frequency electronics are RF circuits [28], RF shielding [29–32], and EM absorbers [33–35].

Transparent substrates are crucial in the field of RF electronics. Commonly used materials include polyethylene terephthalate (PET), polyethylene naphthalate (PEN), polyethylene (PE), polytetrafluoroethylene (PTFE), polyimide (PI), polyamide (PA), polycarbonate (PC), and polydimethylsiloxane (PDMS). These materials are widely used due to their combination of flexibility, transparency, favourable dielectric properties, and low-loss tangent (minimal signal loss) [36–41]. Printed electronics are a leading technology for developing transparent and flexible RF electronics due to their strong benefits. They are more cost-effective to manufacture, offer large-area scalability, and require simpler equipment [42,43] and processes compared to conventional fabrication techniques such as etching, milling, and photolithography [23,28,34,44,45].

Moreover, emerging printing processes, such as inkjet printing, gravure offset, and electrohydrodynamic (EHD) jet printing, can achieve conductive line resolutions in the micrometre range for width and nanometre range for thickness. Printable transparent conductive inks present innovative opportunities for fabricating RF electronics. These inks, made from materials like silver nanowires (AgNWs) and copper nanowires [46–50], carbon-based nanomaterials [51–53], and conductive polymers [54–56], enable the creation of electronic components on a range of substrates using printing techniques like inkjet or screen printing. Their unique combination of electrical conductivity and optical transparency makes them particularly useful for modern RF devices such

as antennas, sensors, and electromagnetic shielding. In addition, the ability to print directly onto flexible or unconventional surfaces reduces manufacturing costs and enhances design flexibility. Current research aims to enhance conductivity, stability, and adhesion to expand their applications in advanced RF technologies.

The foundation of transparent RF electronics lies in the development of suitable materials and fabrication techniques to enable the dual objective of high transparency and excellent RF performance. This review focuses on the comprehensive landscape of these advancements and highlights advancements in materials science and engineering that make these devices a reality. Transparent conductive materials, such as conductive polymers, nanomaterials like graphene and carbon nanotubes, and metallic nanowires, are at the forefront of this paradigm change. Each material brings its own set of properties and challenges, which can affect the overall performance of the RF electronic devices. For example, conductive polymers offer a combination of flexibility, transparency, and conductivity that makes them suitable for a wide range of applications. Graphene, with its exceptional electrical properties and transparency, has been heralded as a revolutionary material in the field. Similarly, metallic nanowires provide a compelling solution with their delicate balance of conductivity and transparency. In this context, this paper also provides a brief overview of the conventional methods for achieving transparent radio frequency electronics and presents a wide range of printing technologies, including roll-to-roll, screen, inkjet, and EHD. This review explores these materials in detail by comparing their properties and suitability for transparent RF-electronic-device applications. In addition, the fabrication techniques used to create flexible and transparent RF electronics devices are equally important as the materials.

2. Materials and methods

2.1. Transparent substrates

Transparent substrates contribute significantly to the advancement of RF electronics technology. Flexible and transparent substrates such as PEN, PE, PI, PET, PTFE, PA, PC, KP, and PDMS provide mechanical conformability and enable RF devices to be both bendable and stretchable [36–41]. These materials can be integrated into curved surfaces and withstand mechanical stress, while their transparency is essential for seamless aesthetic integration.

Moreover, these substrates have low dielectric constants and loss tangents—both properties are crucial to maintaining RF signal integrity. These properties help reduce signal attenuation, especially at the higher



Fig. 1. Illustration of examples integrating future RF electronics to establish next-generation infrastructure.

frequencies utilised in 5G and 6G communication technologies, but also in high-frequency RF circuits and antennas for wireless communication systems. In addition, the substrates ensure efficient energy transfer and consistent RF performance by minimising signal loss. Flexible and transparent substrates have enabled significant advancements in several RF applications, including wearable RF devices, transparent antennas, smart packaging, MA, FSS, and RIS.

2.2. Printed electronics

Printed electronics are a groundbreaking technology with significant advantages over conventionally fabricated devices. Conventional techniques, such as photolithography, employ a subtractive approach, where material is selectively removed through processes like etching, cutting, drilling, and grinding to create the desired patterns [57,58]. This production process involves multiple steps, including photoresist coating, patterning, development, chemical etching, and cleaning [37] – see Fig. 2. These multi-step procedures are not only time-consuming but also expensive, partly because many require a cleanroom environment. In contrast, printing simplifies fabrication into only two steps: printing the pattern, followed by annealing [38,41,59–70] – see Fig. 2. This innovative approach also enables the production of electronic devices on a variety of substrates, which unlocks a wide range of new applications and benefits.

2.2.1. Advantages of conventional fabrication process

Conventional fabrication technologies have significant advantages over printed circuits. They offer superior electrical performance and long-term stability, making them ideal for dependable electronic products. These technologies may produce extremely fine and precise features, which are required for sophisticated and compact components. A variety of high-quality materials can be employed, enabling more sophisticated and efficient gadget designs. These procedures are well-established in industry, so they benefit from mature infrastructure, standardized tools, and great production efficiency. They are also entirely compatible with silicon-based technology, which simplifies

integration with current systems. Furthermore, devices built using traditional methods can survive high temperatures and mechanical stress, which is vital for use in difficult situations. Finally, because they are carried out in controlled surroundings, the likelihood of defects is reduced, resulting in superior quality and yields.

2.2.2. Advantages of printed electronics

- I. **Cost efficiency:** Printed electronics often require fewer materials and less energy, which typically results in substantial cost savings. The *additive* nature of the process involves depositing materials only where necessary, i.e., it minimises waste and maximises resource efficiency. One of the key advantages of digital, drop-on-demand printing techniques (e.g., inkjet and direct writing) is that material is deposited only where required, significantly reducing material wastage. However, this benefit does not extend to all printing methods; for instance, screen printing may involve higher material consumption due to the use of stencils and excess ink.
- II. **Flexibility and lightweight:** Unlike conventional rigid electronics, printed electronics can be created on flexible substrates like plastic, paper, and fabric. This flexibility is essential for developing wearable devices, flexible displays, and smart-packaging solutions, where the ability to bend and be lightweight is crucial.
- III. **Streamlined manufacturing:** The production process for printed electronics can be further simplified using efficient roll-to-roll techniques for mass production. This method allows for continuous production, which improves efficiency and scalability compared to the batch processing used in conventional electronics manufacturing.
- IV. **Customisation and rapid prototyping:** Printed electronics make it easy to customise designs and perform (quick) changes without the need for complex tooling. This feature is particularly valuable for rapid prototyping and small-scale production. It enables faster innovation cycles and more efficient product development.
- V. **Environmentally sustainable:** The reduced use of materials and energy, along with the potential for using biodegradable or recyclable substrates, enhances the environmental sustainability of printed electronics. This aspect is increasingly important as industries strive to reduce their ecological footprint.

2.2.3. Applications of printed electronics

The rapidly growing field of printed electronics offers a promising approach to manufacturing innovative functional electronic devices. As illustrated in Fig. 3, printed electronics are widely used, e.g., for conductive lines and transparent electrodes, energy conversion and storage devices (e.g., solar cells and batteries), flexible displays, healthcare devices (biosensors), wearable electronics (smart watches, health patches), Internet of Things (RFID tags, environmental sensors) and smart/interactive packaging. Today, printed electronics span a range of applications (from micro and nanoscale electronic devices to large-area electronics) encompassing numerous products. Substantial advances in printing technology have enabled the cost-effective and high-volume production of electronic devices on flexible substrates like soft plastics, paper, and textiles. This versatility enables the integration of printed and flexible electronics into everyday objects and surroundings, transforming visionary concepts into reality.

Several printed technologies play a crucial role in developing flexible and transparent RF electronic applications, and each offers unique benefits. *Screen printing* is a cost-effective and straightforward method where conductive inks are pushed through a patterned stencil onto a flexible substrate. Hence, this method is suitable for large-area designs but with limited resolution. *Inkjet printing* enables high precision by accurately placing tiny ink droplets on the substrate. This makes it ideal

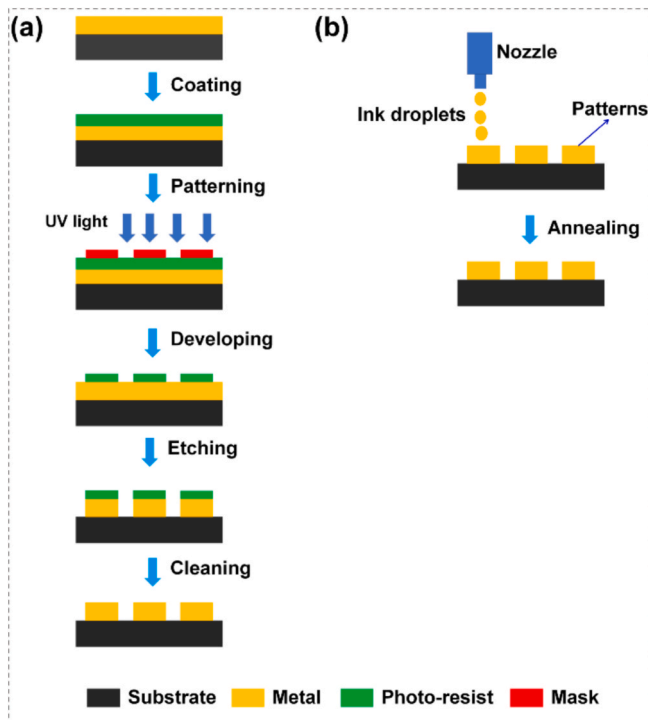


Fig. 2. Schematic comparing (a) conventional manufacturing (photolithography) with (b) printing (inkjet printing) for antenna production.

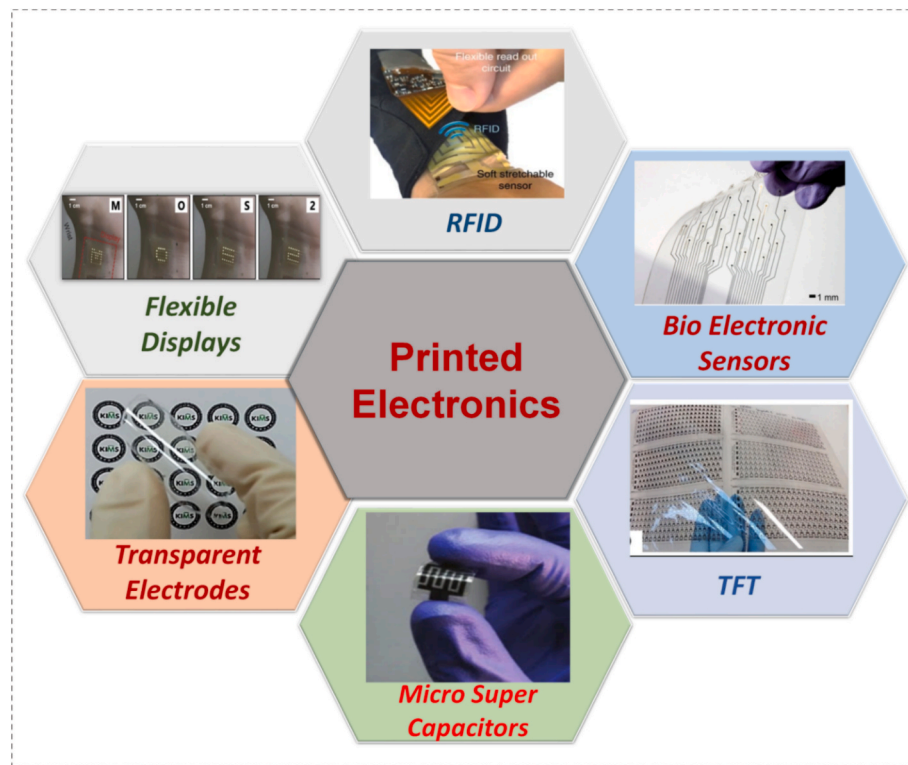


Fig. 3. Applications of printed electronics various fields. Reprinted with permission from [71–76](Copyright 2018, Science Advances), (Copyright 2019, Nature electronics), (Copyright 2016, Scientific Reports), (Copyright 2019, Advanced Functional Materials), (Copyright 2014, Scientific Reports), (Copyright 2016, Advanced Functional Materials).

for intricate and detailed patterns while minimising material waste. *Gravure printing* uses an engraved roller to transfer inks efficiently. It allows for high resolution and good scalability for large-scale production, but it has significant setup costs. *Flexographic printing*, on the other hand, relies on flexible relief plates to deposit ink rapidly [77]. Therefore, it is suitable for roll-to-roll processing, although the achievable resolution is moderate.

More advanced techniques, such as *aerosol jet printing*, utilise a fine mist of conductive material to achieve precise patterning (even on curved or complex surfaces). *EHD jet printing* employs electric fields to generate ultra-fine ink droplets, which enables exceptionally high-resolution patterns, which are particularly useful for nanoscale designs. Similarly, *microcontact printing* uses a soft elastomeric stamp to transfer conductive materials onto substrates to ensure consistent and delicate patterns across flexible surfaces. *Offset printing* involves

transferring patterns via an intermediate medium. This method offers high-speed production of large volumes. *Laser-induced forward transfer* (LIFT) uses a laser to deposit materials with exceptional precision, which minimises material usage. Finally, *transfer printing* involves placing pre-patterned films or circuits (such as those that use advanced materials like graphene or metallic nanowires) onto flexible substrates. The essential factors (ink viscosity, line width, printing layer thickness, and printing speed) of these printing methods are summarised in Table 1. These factors play a critical role in determining the performance, resolution, and efficiency of each technique. Overall, all of these printing methods provide scalable, cost-efficient, and versatile solutions and meet the demands of flexible and transparent RF electronics for modern applications.

Table 1

Key factors of major printing methods.

Printing method	Ink viscosity (cP)	Linewidth (μm)	Printing layer Thickness (μm)	Throughput	Cost efficiency	Scalability (R2R)	Printing speed (m min ⁻¹)	Substrate interaction	References
EHD inkjet	1–10 ⁴	0.1–0.7	0.001–0.1	Very low	Low	Limited	Slow	Non-contact	[78–80]
Inkjet (CJC, DOD)	2–100	30–50	0.1–20	Low	Moderate	Limited	0.02–5	Non-contact	[81,82]
Screen printing	500–5000	30–100	3–30	High	High	Good	0.6–100	Contact	[83,84]
Aerosol jet printing	0.7–2500	10–10 ³	0.01–6	Low-Moderate	Low	Limited	6	Non-contact	[85–87]
Dispenser/Extruder printing	10–10 ⁶	50–10 ³	10–200	Low	Moderate	Limited	0.6	Non-contact	[88–90]
Flexo printing	10–500	30–80	0.17–8	Very high	High	Excellent	5–180	Contact	[77,81]
Gravure offset	500–50000	5–20	0.8–8	High	Moderate	Good	1–10	Contact	[91]
Gravure printing	100–1100	50–200	0.02–12	Very high	High	Excellent	0.5–18	Contact	[81,92,93]
LIFT	—	0.3–10	0.1–1	Very low	Low	—	Slow	Non-contact	[94–96]
Nanoimprint	—	0.005–0.1	0.1–1	Very low	Low	—	≤15	Contact	[97,98]
Offset printing	30000–110000	20–90	0.6–2	High	High	Moderate	Fast	Contact	[99]
Reverse offset	0.5–40	1–10	0.05–1	High	Moderate	Good	0.01–3	Contact	[100–103]

2.2.4. Scalability, Efficiency, and manufacturing considerations of printing techniques

To enable the practical integration of printed electronics into large-scale device manufacturing, it is important to assess not only the resolution and compatibility of printing techniques, but also their efficiency, cost-effectiveness, and scalability. Each printing method offers trade-offs between performance and production viability. For instance, ink-jet printing provides high design flexibility and minimal material waste but suffers from slower throughput and frequent nozzle clogging, limiting its scalability. In contrast, screen and gravure printing are better suited for high-speed and large-area production, though they require higher ink volumes and offer lower resolution. Roll-to-roll (R2R) processing, often integrated with screen or gravure methods, significantly improves production speed and cost-efficiency, making it promising for commercial applications. However, challenges such as maintaining pattern precision at high speeds, controlling ink spreading, and ensuring uniform layer thickness remain. Additionally, process-specific factors like substrate compatibility, drying or sintering temperature, and ink rheology must be optimized to maintain both device performance and structural integrity. A comparative summary of these aspects has been included in Table 1 on selecting the most suitable printing method based on application needs, material properties, and production goals.

2.3. Transparent conducting materials for printing technologies

Transparent conductive materials are crucial for printed technologies in flexible and transparent RF electronic applications. These materials offer both electrical conductivity and optical transparency, which makes them ideal for devices like antennas, sensors, and circuits. Indium Tin Oxide (ITO) is widely used because of its excellent conductivity and transparency; however, its brittleness and high cost, driven by the limited supply of indium, make it less suitable for flexible or large-area applications. In contrast, AgNWs offer low sheet resistance, high transparency, and flexibility, which makes them an excellent choice for applications requiring bending or stretching. However, challenges such as junction resistance and susceptibility to oxidation necessitate the use of protective coatings to enhance their durability and stability. Other notable materials include carbon nanotubes (CNTs) and graphene, both of which are lightweight and highly flexible. CNTs provide moderate levels of conductivity and transparency, which makes them suitable for stretchable electronics. However, ensuring uniform performance over large areas can be challenging. Graphene, with its exceptional transparency and mechanical strength, shows great promise for RF applications but faces limitations due to high sheet resistance and complexity when it comes to large-scale manufacturing.

Hybrid materials that combine graphene with other components, such as AgNWs or CNTs, help address these problems and improve overall performance. Metal meshes (consisting of ultra-thin metallic grids) offer an excellent balance between low electrical resistance and high optical transparency. Their exceptional conductivity renders them suitable for applications demanding low-loss RF performance. However, producing uniform, fine metal grids at a nanoscale level for transparent and flexible electronics requires advanced fabrication techniques, which can increase production costs considerably.

Certain emerging materials, such as conductive polymers, MXenes, and hybrid systems, also offer unique benefits. Conductive polymers like PEDOT: PSS are lightweight, printable, and flexible although their lower conductivity makes them more suitable for low-cost and low-frequency applications. However, a major limitation of conductive polymers lies in their long-term operational stability, as they are highly sensitive to environmental factors such as humidity, UV radiation, and thermal fluctuations. Their intrinsic electrical conductivity is typically lower than that of metallic counterparts, often necessitating doping or post-treatment steps, which add complexity and cost to the fabrication process. While these materials are compatible with scalable solution-based printing methods, maintaining consistent film uniformity over large

areas especially on substrates with diverse surface properties remains a significant challenge [54]. MXenes, a family of two-dimensional materials, exhibit outstanding conductivity and adjustable transparency, which makes them a promising candidate for advanced RF applications. However, their long-term stability under different environmental conditions is still unclear. Hybrid materials, such as AgNWs, graphene and CNTs, and graphene composites, combine the benefits of several materials to improve conductivity, flexibility, and stability. However, the key performance factors, such as sheet resistance and transparency, are critical in determining the suitability of these materials for flexible and transparent conductive films and are summarised in Table 2. Understanding the strengths and limitations of these materials enables researchers to develop effective, innovative solutions for high-performance RF applications.

2.4. Figure of merit for transparent conductive electrodes

Transparent conductive electrodes (TCEs) are crucial components in many optoelectronic and radio frequency (RF) systems that require both excellent optical transparency and low electrical resistance. The figure of merit (FoM) is a typical measure for evaluating TCE's overall performance. The basic definition of FoM is the ratio of DC electrical conductivity (σ_{DC}) to optical conductivity (σ_{opt}).

$$FOM = \frac{\sigma_{DC}}{\sigma_{opt}} \quad (1)$$

This equation states that a high-performance TCE should have strong electrical conductivity while reducing visible light absorption or reflection. Because these conductivity values are not often directly measured, researchers frequently depend on simplified FoM formulas incorporating sheet resistance (R_s) and transmittance (T) at a certain wavelength, usually 550 nm. A widely used practical formulation is Haacke's figure of merit, [113,114], which is given by

$$\Phi_{TC} = \frac{T^{10}}{R_s} \quad (2)$$

where, Φ_{TC} is the FOM, T is the transmittance of the film (measured at the center of the visible spectrum, i.e. 550 nm), and R_s is the sheet resistance of the film. The transmittance is raised to the tenth power to account for the fact that an acceptable TCE material should transmit at least 90 % of the light that passes through it. Alexandra Madeira et al. [115] demonstrated silver nanowire-based transparent electrodes achieving a low sheet resistance of 5 Ω /sq at 94 % optical transmittance, representing one of the highest figures of merit reported to date for scalable nanowire electrodes. As illustrated in Fig. 4, the performance of these electrodes is compared with other AgNWs electrodes produced using scalable deposition methods, along with ITO-coated glass substrates. To facilitate comparison, iso-lines of Haacke's figure of merit (T^{10}/R_s) are also included. These results underscore the exceptional performance potential of AgNWs networks fabricated through scalable techniques.

2.5. Metallisation techniques

Following the printing process, sintering is an essential step to convert the printed conductive inks or pastes into the final design. In this way, it is possible to achieve the desired electrical properties, mechanical integrity, and surface quality. This technique is particularly critical for metal nanoparticle inks or pastes because it eliminates organic contaminants, facilitates the fusion of metal nanoparticles, and enhances conductivity. For example, silver nanoparticle inks typically require post-deposition sintering to achieve high conductivity. While conventional thermal sintering often occurs at temperatures above 150 °C, recent formulations have enabled lower temperature sintering (80–120 °C), making them compatible with flexible substrates [116].

Table 2

Transparent and electrical properties of several transparent conducting films reported in prior studies, featuring materials fabricated using various printing methods.

Transparent conducting film material	Printing technique	Sheet resistance [$\Omega \text{ sq}^{-1}$]	Transmittance [%]	Cost	Application Priority	Reference
Metal NPs (Metal Grids)	Inkjet printing	12 (PEDOT: PSS/Ag grid)	89 (550 nm)	Moderate	Flexible, transparent devices	[104]
	Screen printing	0.015 (Ag grid)	64	Moderate	Flexible RF devices	[105]
CNTs	Inkjet printing	156	81 (600)	Moderate-High	Transparent conductive films	[106]
Graphene	Screen printing	$1.86 \times 10^4 \text{ S m}^{-1}$ (conductivity)	—	High	—	[83]
Metal NWs	Inkjet printing	13 k	22 (550 nm)	High	Transparent conductive films	[107]
	Screen printing	≈ 0.823	—	Moderate	Wearable Thin Film Transistors	[108]
	Gravure printing	10.9 (IZO/Ag NWs)	90 (550 nm)	Moderate	Transparent conductors	[109]
	Inkjet printing	8	≈ 50 (550 nm)	Moderate	—	[110]
	Roll-to-Roll (R2R)	8 (graphene/Ag NWs)	94 (550 nm)	Moderate	Transparent electrodes	[111]
PEDOT:PSS	Inkjet printing	—	89 (525 nm)	Low	Solar cell	[112]

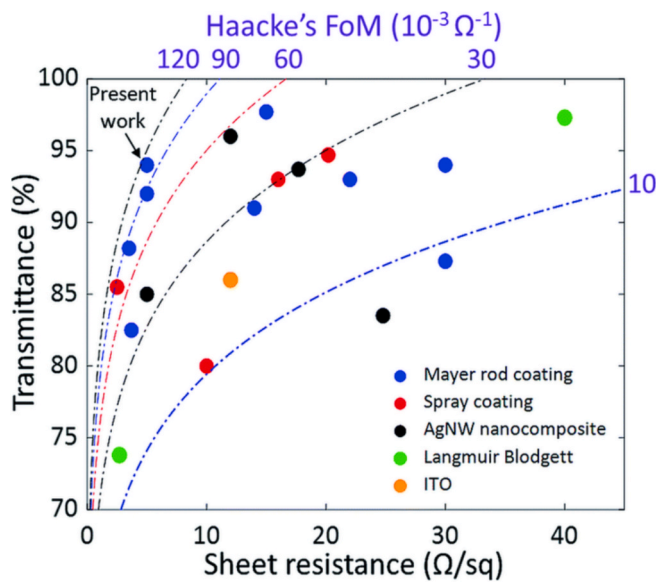


Fig. 4. Comparison of sheet resistance and optical transmittance for silver nanowire-based transparent conductors fabricated via scalable deposition methods.[115](Copyright 2020, Royal Society of Chemistry).

The sintering standard of metal-nanoparticle inks is affected by components like the type of protective agents, the size and structure of the nanoparticles, and the surface properties of the substrate. For metal-particle-free inks, sintering decomposes or reduces the metal precursors and eliminates organic materials, forming the metal and providing the required conductivity. The final conductivity is determined by the properties of the precursors, sintering conditions, and residual organics.

Thermal sintering is the most common method. It is typically done on a hotplate or in an oven at temperatures ranging from 90 to 200 °C for five to 60 min. This method is mainly suited for silver-based inks [38,117]. In contrast, copper-based inks need additional precautions, such as a protective environment (vacuum or inert gas) or advanced sintering methods, to avoid oxidation. Alternative sintering methods have been developed for heat-sensitive flexible substrates like polymer films or paper. These include photonic sintering, electrical sintering, plasma sintering, and microwave sintering. *Photonic sintering* uses light sources like flash lamps or lasers, where the light's emission spectrum matches the material's absorption spectrum to produce heat for sintering without damaging the substrate [118]. *Plasma sintering* uses ionised

gas to treat the material, and if hydrogen is included, it acts as a reducing agent [119,120]. *Microwave sintering* involves microwaves to heat the material, evaporate organic components, and complete the sintering process [121]. Additional details are available in previous reports [122,123]. Each sintering technique offers unique benefits and limitations, as outlined in Table 3. Since these methods use different equipment and mechanisms, selecting the most suitable approach depends on the specific requirements. However, sintering is critical to ensure good electrical performance of the conductive patterns, such as those in RF electronics. Therefore, employing an efficient and cost-effective sintering method is crucial for large-scale industrial production.

The selection of materials for printed transparent RF electronics such as transparent substrates, transparent conductive inks, printing techniques and metallization (after printing surface treatments) plays a critical role in determining the appropriate manufacturing techniques and, ultimately, the performance of the final devices. For instance, materials with high conductivity and low-temperature sintering capability are better suited for fine-resolution printing methods like inkjet or aerosol jet, enabling the fabrication of compact, high-frequency antennas. Similarly, the mechanical flexibility and optical transparency of substrates influence not only the device design but also the choice of fabrication process and post-processing steps. Understanding these interdependencies is essential for bridging the gap between material properties and real-world RF applications. In the following sections, we explore how these materials and processes are applied in the development of transparent antennas, metamaterial absorbers, and frequency-selective surfaces.

3. Transparent RF electronics using advanced manufacturing techniques

In the previous sections, we discussed the materials and fabrication

Table 3

Strengths and weaknesses of different sintering methods.

Sintering Method	Strength	Weakness
Thermal	Low-cost and high-throughput	Requires much time and damages the substrates
Photonic	Selective sintering	High cost
Electrical	Short sintering time, Reduced damage to the substrate	Requires contact with the printed patterns
Plasma	Low temperature	Low throughput surface effect
Microwave	Fast volumetric heating	Limited penetration depth, local overheating

methods for transparent RF electronics. Transparent RF electronics manufactured using printing technology can be used in a variety of applications, such as consumer electronics, smart environments, and wearables, due to their simplicity and low cost. Thanks to these benefits, numerous studies on transparent RF electronics utilising printed fabrication technology have emerged, and this trend is expected to grow in the coming years. In this section, we present the latest research and developments in transparent RF devices, including antennas, FSSs, and MAs fabricated using printing technology. Next, the limitations of current transparent RF devices and future challenges will be discussed.

3.1. Transparent antennas

Antennas are RF components that can transmit and receive electromagnetic waves. They are essential for a variety of wireless communications, including mobile communications, Bluetooth, and near-field communication (NFC). In recent years, the importance of antennas has grown as the demand for wireless devices such as smartphones and wireless earphones continues to increase, as well as the Internet of Things (IoT) and wearable devices. Among these, transparent antennas have garnered significant attention due to their versatility and potential for a wide range of applications, a trend that is expected to continue growing [124]. Transparent antennas are mainly made of transparent conductive materials such as ITO, Ag NWs, polymer-based transparent materials such as PEDOT:PSS, and metal-mesh structures implemented on the micro-metre scale. The specific design parameters of transparent antennas are resistance, optical transmittance, dielectric loss, and skin effect. Resistance and optical transmittance are closely related: for conductive films such as ITO and Ag NWs, thinner conductors yield higher optical transparency but also higher resistance [44,56,125]. Conversely, in metal-mesh structures, reducing the mesh-line width increases transparency at the expense of resistance [126–128]. Therefore, when designing transparent antennas, it is essential to understand the trade-off between optical transmittance and sheet resistance, since lower resistance directly improves radiation efficiency. Dielectric loss is an inherent property of the substrate material and varies with frequency; selecting a dielectric with low loss tangent at the design frequency likewise enhances radiation efficiency. The skin effect where high-frequency currents concentrate near a conductor's surface introduces additional losses whenever the conductor thickness is less than the skin depth. The skin depth δ is given by:

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}}, \quad (3)$$

where, ρ is resistivity, f is frequency, and μ is permeability. This factor must be accounted for during design, especially when using ultrathin transparent conductors. Once the parameters above are defined, we move on to antenna performance optimization. Performance metrics fall into three categories: resonance frequency, impedance matching, and radiation gain. The resonance frequency is given by:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}, \quad (4)$$

where, L is the inductance and C is the capacitance of the antenna. As the pattern's effective L or C increases, the resonance frequency f_0 decreases, so f_0 is adjusted by changing the antenna's electrical length. Impedance matching essential for maximizing the conversion of input power into radiated power is typically achieved in patch antennas by varying the width or length of the radiating patch [129]. Radiation gain measures the relative power radiated in a given direction, and transparent antennas generally exhibit lower gain than copper-based designs due to higher sheet resistance and consequently greater ohmic loss. To realize a practical transparent antenna, these trade-offs are balanced via systematic parameter sweeps and multi-objective optimization workflows so that resonance frequency, impedance matching, and radiation

gain targets are all met.

Among the transparent antennas studied so far, several designs leveraging straightforward fabrication processes and cost-effective printing techniques have been successfully demonstrated. Goliya et al. fabricated a transparent antenna by screen-printing Ag NW paste onto a PET substrate [130]. Fig. 5 (a) shows the fabricated transparent bow-tie antenna. Fig. 5 (b) illustrates the changes in reflection coefficient and radiation efficiency based on the transparency of the fabricated antenna. The antenna reached a radiation efficiency of 51.7 % with an optical transmittance of 85.29 %, and the reflection coefficient was measured to be below -20 dB at 2.4 GHz. When the same structure was fabricated using Ag flakes and copper, the radiation efficiencies were 80.8 % and 79 %, respectively. When comparing the fabricated transparent antenna with one made from silver flakes, a 28.9 % difference in radiation efficiency is observed, which is primarily due to conductive losses by the high sheet resistance of 8.45 O/sq. Fig. 5(c) shows the reflection coefficient results of the antenna based on the number of screen-printing cycles. As the number of screen-printing cycles increased, the reflection coefficient decreased. This is because the resistance decreases with an increasing number of screen-printing cycles. Fig. 5(d) illustrates a comparison of the reflection coefficient for the fabricated antenna in both bent and unbent states. The proposed transparent antenna is stable enough such that its resonant frequency does not change when bent. The authors tuned the sheet resistance and optical transmittance by repeating several screen-printing cycles to achieve optimal antenna performance. Although the transparent antenna proposed by the authors exhibited low radiation efficiency, it can be used for transparent RFID tags in vehicle and aircraft windows. Another study explored the integration of coating and printing techniques for the development of transparent antennas. Li et al. developed an Ag NW-based transparent electrode by integrating spin coating and ink-jet printing [131]. Fig. 5(e) presents a schematic that summarises the patterning process. The group first coated Ag NWs evenly using a spin-coating method and inkjet-printed a polymer material onto the areas to be patterned. Subsequently, the Ag NWs outside the polymer region were removed, and the polymer material was eliminated to complete the patterning process. The transparent electrode they developed exhibited a sheet resistance ranging from 7.1 to 36 O/sq and an optical transmittance of 84.2 % to 95.6 %. Fig. 5(f) shows a photograph of the fabricated transparent monopole antenna and its optical transmittance results. The fabricated antenna reached an optical transmittance of at least 70 % across the visible spectrum (400–800 nm) and 86.8 % at 550 nm. Fig. 5(g) displays the reflection-coefficient-measurement results of the transparent monopole antenna, which showed a reflection coefficient below -10 dB for the frequency range of 17.9–40 GHz. Fig. 5(h) shows the stability-test results of the fabricated transparent monopole antenna. The authors confirmed that the reflection coefficient remained unchanged when the antenna was bent to radii of 20 mm and 5 mm, and even after 1,000 bending cycles, its properties were maintained. While direct inkjet printing of Ag NWs encountered problems such as nozzle clogging and inconsistent patterning, the authors addressed these challenges by implementing a coat-and-print method. Another study utilised screen printing and photonic sintering for transparent antenna research. Li et al. developed high optical transparency and low-sheet-resistance electrodes by screen-printing Ag NWs to form patterns, which was followed by photonic sintering [50]. The fabricated transparent electrode exhibited a sheet resistance ranging from 1.1 to 9.2 O/sq and an optical transmittance of 75.2 % to 92.6 %. As shown in Fig. 5(i), the authors used the developed transparent electrode to fabricate an Ag-NW-based transparent fractal antenna. Fig. 5(j) shows the reflection-coefficient-measurement results of the fabricated antenna, which exhibited a reflection coefficient below -10 dB in the 1.5–4.8 GHz range, showing a dual-resonance characteristic. Fig. 5(k) shows the peak-gain measurement results of the fabricated antenna. The trend of the measured antenna gain was consistent with the simulation results. It reached a gain of over 1 dBi in the 2.3–4.1 GHz band. In addition, as shown in Fig. 5(l),

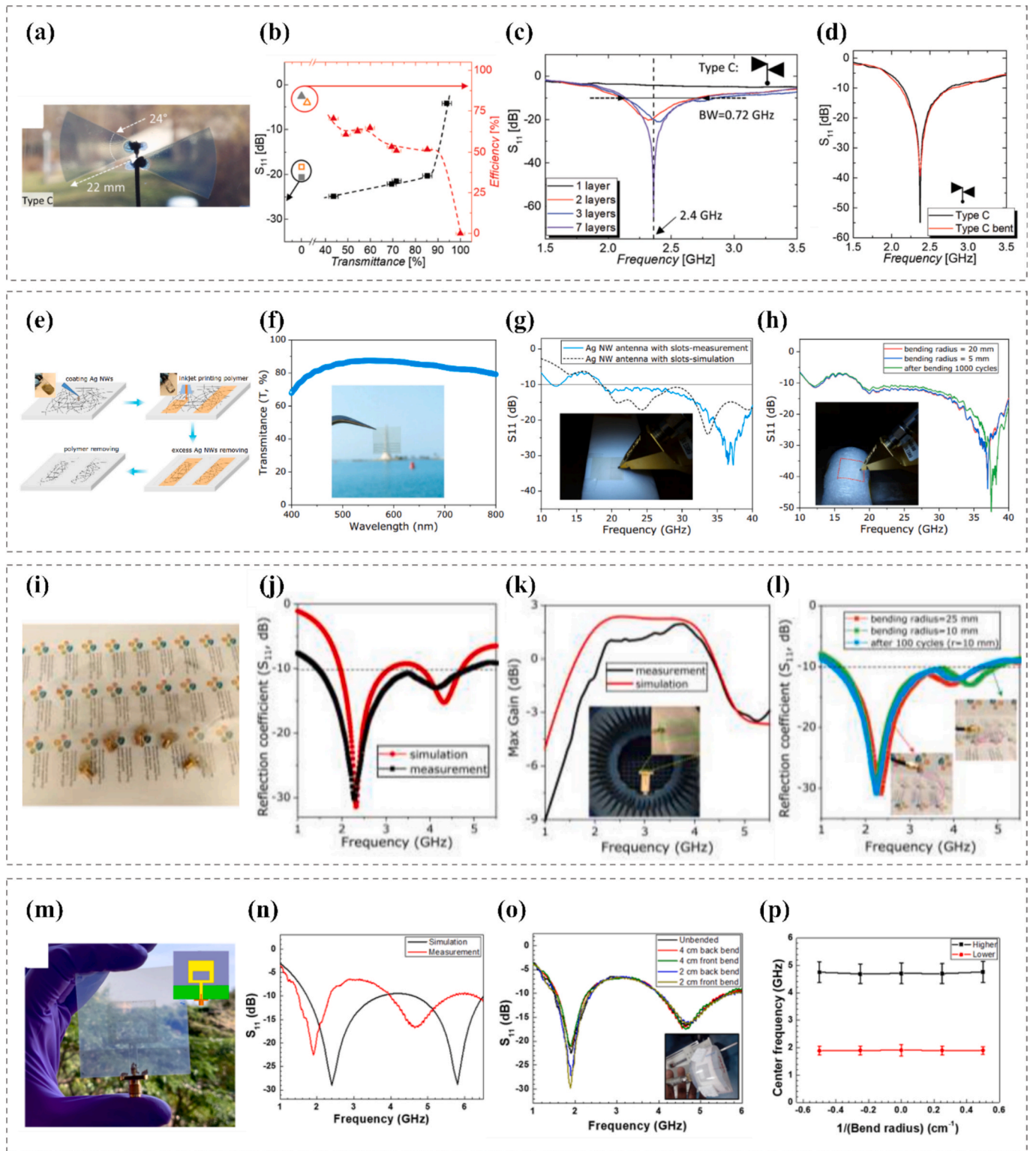


Fig. 5. (a) Fabricated transparent bow-tie antenna, (b) measured reflection coefficient, radiation efficiency, (c) measured reflection coefficient for different screen-printing cycles, (d) measured reflection coefficient measured in bent and unbent state. Reproduced with permission from [130] (Copyright 2019, Wiley-VCH GmbH). (e) Schematic illustrating the coat-and-print procedures, (f) measured reflection coefficient of the transparent monopole antenna, (g) measured reflection coefficient of the antenna under bending test with different bending radii and bending cycles, (h) measured optical transmittance result. Reproduced with permission from [131] (Copyright 2019, Springer Nature). (i) Fabricated transparent fractal antenna, (j) measured reflection coefficient, (k) measured peak gain, (l) measured reflection coefficient of the antenna during the bending test with different bending radii and bending cycles. Reproduced with permission from [50] (Copyright 2020, IOP Publishing Ltd). (m) Fabricated transparent monopole antenna, (n) measured reflection coefficient, (o) measured reflection coefficient of the antenna during the bending test with different bending radii, and (p) variation of the centre frequencies as a function of the bending radii. Reproduced with permission from [132] (Copyright 2020, American Chemical Society).

the authors evaluated the flexibility and reliability of the antenna. The reflection coefficient bandwidth remained consistent when the antenna was bent to radii of 25 mm and 10 mm, and its properties were preserved even after 100 cycles of bending and unbending. Nitheesh M et al. developed a composite transparent ink combining Ag NWs and PEDOT: PSS [132]. The films made with the developed composite transparent ink showed better thermal stability than Ag NW films. The film printed once using the direct-writing method had a sheet resistance of 23 Ω/sq and an optical transmittance of 86.4 %, while the film printed twice had a sheet of 6.6 Ω/sq and an optical transmittance of 77.2 %. As shown in Fig. 5(m), the authors fabricated a transparent monopole antenna using the developed composite transparent ink. Fig. 5(n) presents the reflection-coefficient-measurement results of the fabricated antenna, which reveals reflection coefficients below -17 dB at 2 GHz and 4.75 GHz. In addition, as shown in Fig. 5(o), the frequency stability of the

reflection coefficient was preserved when the antenna was bent inward and outward using radii of 4 cm and 2 cm. Fig. 5(p) illustrates the change in the centre frequency when the antenna was bent using different radii. The results demonstrate that the centre frequency remained stable despite the different bending conditions. Hence, this antenna is well-suited for applications that require flexibility, such as wearable devices.

Furthermore, a study that combined Ag NW-based transparent ink with photonic sintering yielded higher conductivity as well as high optical transmittance. Vaseem et al. developed an Ag NW-based transparent electrode using screen-printing, with a conductivity of 6.25×10^6 S/m and 83 % optical transmittance [133]. This result represents the highest conductivity among reported Ag NW transparent electrodes with high optical transmittance. The authors used the developed transparent electrode to fabricate a transparent monopole antenna. Fig. 6(a) depicts

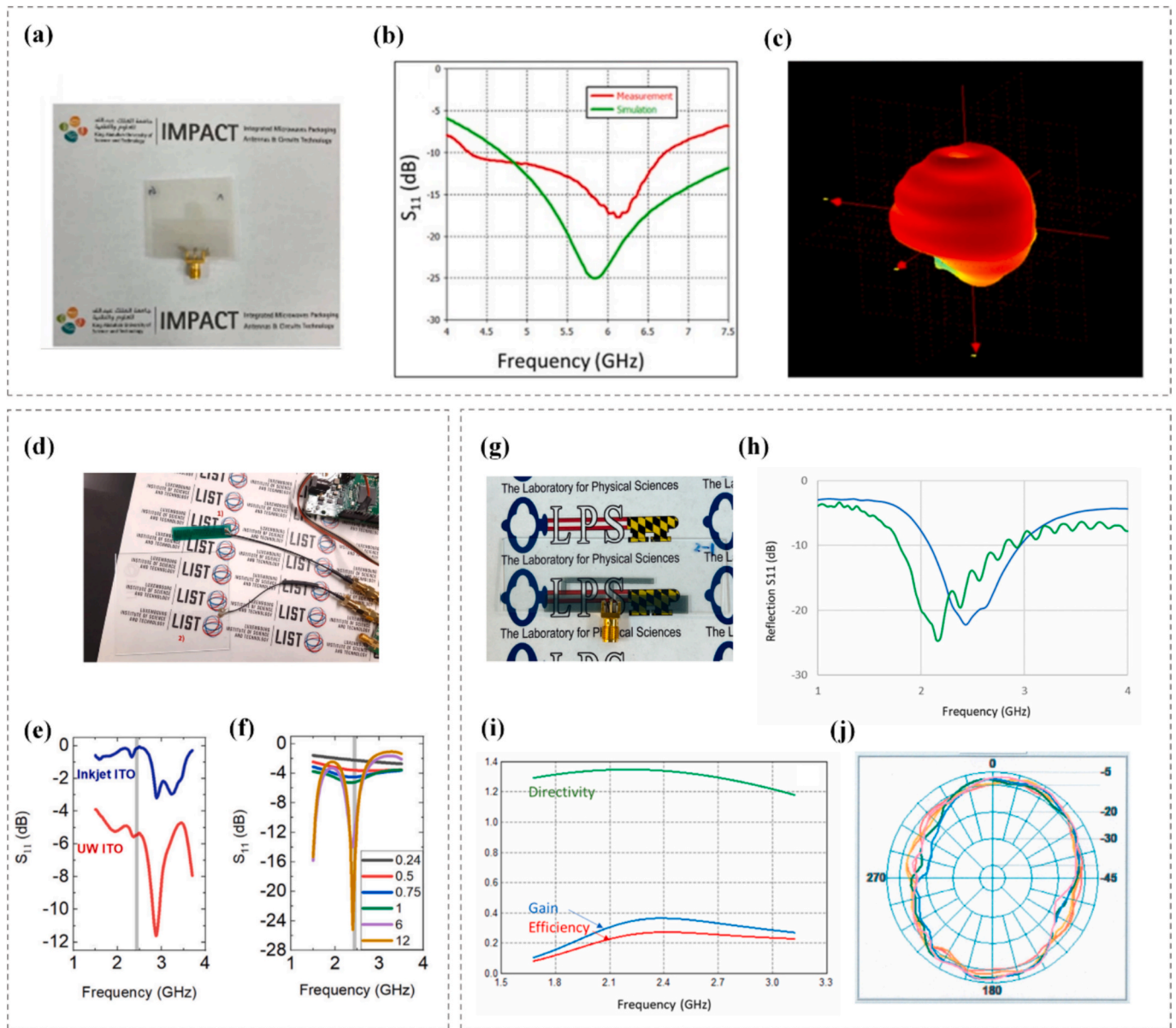


Fig. 6. (a) Fabricated Ag NW-based transparent monopole antenna, (b) measured reflection coefficient, (c) simulated 3D radiation pattern of the transparent monopole antenna. Reproduced with permission from [133] (Copyright 2022, IOP Publishing Ltd). (d) Fabricated ultra-wide ITO-based transparent patch antenna, (e) measured reflection coefficient of the fabricated antenna, (f) simulated reflection coefficient for different thickness of ITO. Reprinted with permission from [134] (Copyright 2023, Elsevier B. V.). (g) Fabricated transparent inverted-F antenna using aerosol-jet printing, (h) measured reflection coefficient, (i) simulated directivity, gain, and efficiency, and (j) measured radiation pattern of the fabricated antenna. Reproduced with permission from [135] (Copyright 2024 by the authors. Licensee MDPI, Basel, Switzerland).

the fabricated transparent monopole antenna. Fig. 6(b) compares the reflection-coefficient-simulation result with the measured outcomes. The measurements indicate a reflection coefficient below -10 dB within the frequency range of approximately 4.2 GHz to 6.7 GHz. Fig. 6(c) shows the simulated radiation pattern of the proposed antenna—it exhibits omnidirectional characteristics. Another study reported on highly transparent patch antennas that combined ITO ink with inkjet printing. Glinsek et al. successfully developed an inkjet-printable ITO ink [134]. The group's inkjet-printed ITO film exhibited a conductivity of 1,280 S/cm and an optical transmittance of 87 %. As shown in Fig. 6(e), the authors fabricated a meander-shaped patch antenna using the developed transparent electrode. Fig. 6(d) shows the reflection-coefficient-measurement results of the fabricated antenna. The antenna fabricated with the developed ink demonstrated a reflection coefficient of approximately -1 dB at 2.4 GHz, whereas the antenna fabricated with commercial ITO produced a reflection coefficient of -5 dB. Fig. 6(f) shows the simulation results of the reflection coefficient based on the thickness of the ITO layer. It can be observed that as the ITO thickness increased, the reflection coefficient increased. The authors discovered that the thin ITO layer caused the high reflection coefficient of the transparent antenna. The fabricated antenna was used in a low-power communication module based on the Bluetooth Low-Energy (BLE) protocol. This successfully demonstrated the transmission of energy level, light, and temperature data. Their results created new possibilities for applying transparent antennas to IoT systems. Another study used a different printing technology to obtain transparent antennas. Li et al. proposed a transparent planar inverted-F antenna (PIFA) by combining PEDOT:PSS-based Ag NW ink with aerosol-jet printing [135]. Fig. 6(g) shows the fabricated transparent planar inverted-F antenna. Fig. 6(h) shows the reflection coefficient measurement results of the fabricated antenna, where the green graph represents the antenna on a glass substrate, and the blue graph signifies the antenna on a Delrin substrate. The measurements show fractional bandwidths (FBW) of 27 % and 30 % centred at 2.2 GHz and 2.4 GHz, respectively. Fig. 6(i) displays the simulation results for the directivity, gain, and efficiency of the antenna that was fabricated on a Delrin substrate. The antenna's directivity was found to be 1.9 dBi, the gain was -3.6 dBi, and the radiation efficiency was 10 %. The authors attributed these results to the increased skin depth caused by low conductivity (approximately 10^5 S/m), which led to higher antenna losses. Fig. 6(j) shows the measured radiation pattern of the antenna, which indicates omnidirectional radiation. Although the gain and radiation efficiency of the fabricated antenna was very low, the aerosol-jet printing method they used allowed excellent fabrication resolution, which makes it potentially suitable for mm-wave applications.

Table 4 compares the performance of transparent antennas fabricated using printing technology. Recent studies on transparent antennas have predominantly utilised Ag NWs due to their excellent conductivity, high optical transmittance, and superior flexibility. The majority of transparent antenna studies using Ag NWs emphasise their flexible properties [50,130–133]. The antenna types that were predominantly

studied are dipole and monopole antennas, which feature omnidirectional radiation characteristics. Most operating frequencies have remained in the microwave range, i.e., the 2.4 GHz or 5 GHz bands. However, more recently, printing-based transparent antennas operating in the millimetre-wave range have also been reported. Printing offers significant benefits, such as reduced cost and simplified fabrication. We anticipate that research on transparent antennas that utilise printing technology will continue to grow in the future.

3.2. Transparent frequency-selective surfaces (FSS)

A FSS is an electromagnetic filter that can either block or allow signals of a specific frequency to pass through. In recent years, the need for shielding from unwanted electromagnetic waves has increased as wireless communication occurs in a wide range of frequencies [136–138]. FSS can meet this need by providing electromagnetic shielding. Typically, an FSS consists of a metal pattern and a dielectric, but recently, transparent FSSs, where both the metal pattern and dielectric are composed of a transparent material, have been reported [26,139,140]. The reason for the renewed interest is that making FSSs transparent can benefit a variety of applications. For example, a transparent FSS can be used at home or in car windows and even in incubators of newborns [38]. FSS designed to block electromagnetic waves require high insertion loss, whereas those intended to pass waves require low insertion loss. In general, FSS based on transparent conductive materials are better suited to blocking applications than to transmission, because when incident waves traverse the FSS, losses occur both from the high resistance of the transparent conductor and from the dielectric loss of the substrate. Therefore, just as with transparent antennas, the design of transparent FSS must take into account the material's resistance, optical transmittance, dielectric loss, and skin effect. From a performance to optimization perspective, both the resonance frequency and the insertion loss must be optimized, and the transparent conductor's intrinsic properties particularly its resistance and optical transparency are key design drivers.

Moreover, research on transparent FSS based on printing technology has also been reported. Yang et al. fabricated a transparent FSS by screen-printing custom Ag NW ink [27]. The group used a previously studied method of photonic sintering on screen-printed Ag NW patterns to obtain a sheet resistance of 4 Ω/sq [47,50]. Fig. 7(a) shows a photograph of the fabricated transparent FSS. Fig. 7(b) presents the optical transmittance results, which indicate over 80 % transmittance across most of the visible region and 81.6 % at 550 nm. Fig. 7(c) displays the measured transmission coefficient of the fabricated transparent FSS. The measured results exhibit shielding characteristics below -10 dB at 0.92 GHz and 1.9 GHz. However, the amplitude was 7 dB lower than the simulation results. The authors analysed the conductor thickness and surface roughness of the fabricated samples and verified the discrepancies through a post-simulation process that included these factors. Fig. 7(d) shows the measured transmission coefficient results after the fabricated transparent FSS was bent or rolled. The FSS demonstrated

Table 4
Antenna performance comparison of optically transparent antennas made using different printing technologies.

Ref.	Material	Sheet resistance (ohm/sq)	Optical transmittance (%)	Printing method	Antenna type	Centre frequency (GHz)	Gain (dB)	Radiation efficiency (%)
[130]	Ag NW	8.45	85.29	Screen-printing	Bow-tie antenna	2.45	N/A	51.7
[131]	Ag NW	7.1	86.8	Ink-jet printing	Monopole antenna	31	-1.7 -1.2	N/A
[50]	Ag NW	1.1	75.2	Screen-printing	Fractal antenna	3.15	1	N/A
[132]	Ag NW, PEDOT:PSS	6.6	77.2	Direct writing	Monopole antenna	2.02, 4.75	N/A	N/A
[133]	Ag NW	1.7	78	Screen-printing	Monopole antenna	5.45	N/A	N/A
[134]	ITO	6.2	85	Ink-jet printing	Meander patch antenna	2.4	-5.26	18
[135]	Ag NW, PEDOT:PSS	4	50	Aerosol-jet printing	Planar inverted-F antenna	2.4	-3.6	10

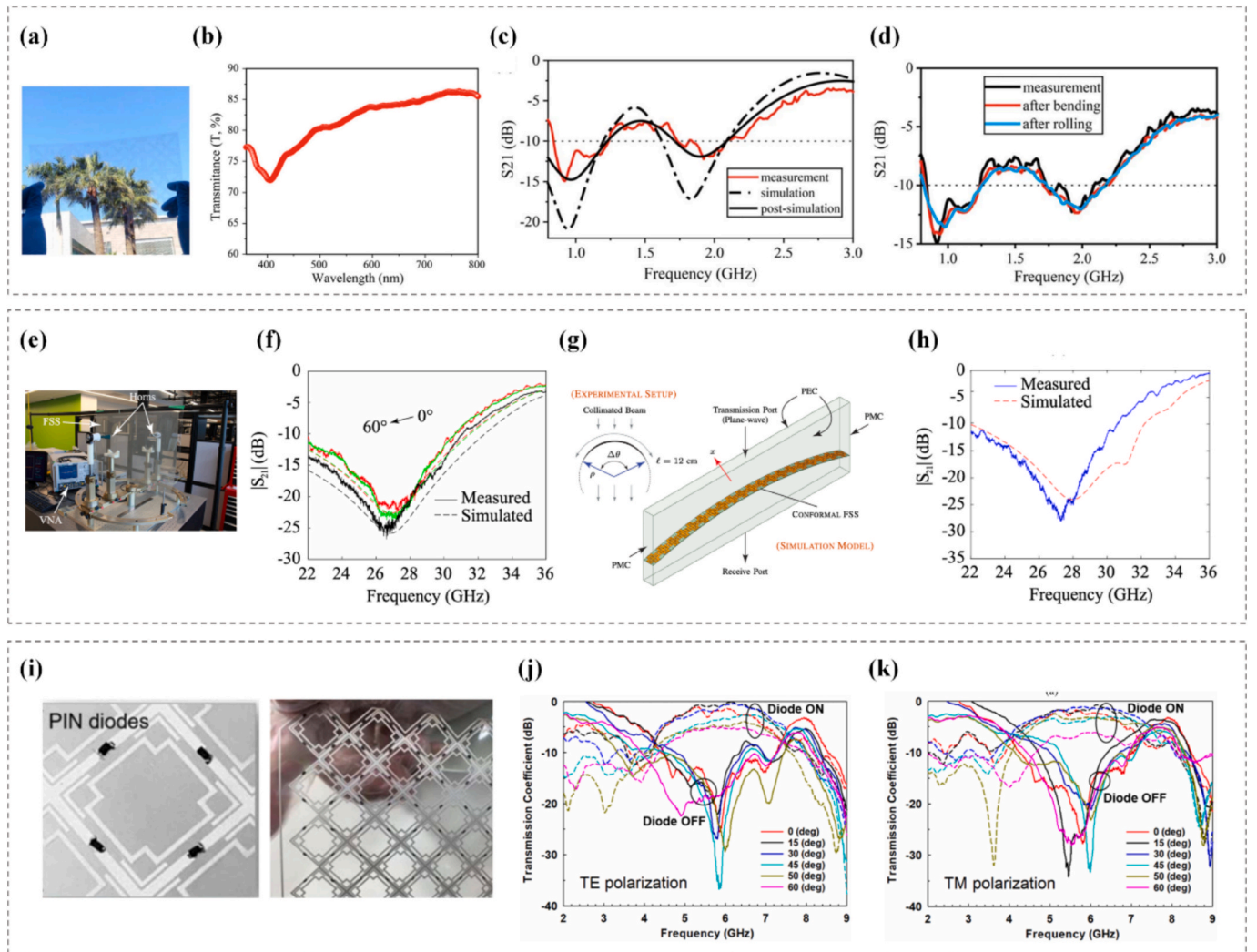


Fig. 7. (a) Fabricated Ag NW-based transparent FSS, (b) measured optical transmittance, (c) measured and simulated transmission coefficient, (d) measured transmission coefficient of the transparent FSS after bending and rolling. Reprinted with permission from [27] (Copyright 2021, IEEE). (e) Screen-printed transparent FSS and measurement setup, (f) measured transmission coefficient as a function of angle of incidence, (g) conformal FSS structure designed in the simulation. (h) Measured transmission coefficient for a conformal FSS structure Reprinted with permission from [141] (Copyright 2023, IEEE). (i) Proposed active FSS unit structure and fabricated prototype, (j) measured transmission coefficient for TE polarisation at various states and angles of incidence, and (k) measured transmission coefficient for TM polarisation at various states and angles of incidence. Reprinted with permission from [142] (Copyright 2024, IEEE).

good stability, as the measurement results remained unchanged after bending and rolling. Consequently, the proposed transparent FSS is well-suited for applications that require shielding in the global system for mobile communications (GSM) frequency band.

Furthermore, a study investigated transparent FSS using fine patterning of silver to enhance optical transmittance. King et al. proposed a transparent FSS that was fabricated using screen-printed silver-flake ink in a mesh pattern. The group demonstrated electromagnetic shielding properties at 26.7 GHz [141]. The unit cell design underwent a four-step miniaturisation process, which led to the final mesh structure. Fig. 7(e) illustrates the fabricated transparent FSS. Fig. 7(f) presents the measured transmission coefficient of the fabricated FSS. It features resonance at 26.7 GHz and stable shielding performance across incidence angles ranging from 0° to 60°. The authors also developed a conformal FSS structure, as shown in Fig. 7(g), and conducted both simulations and measurements. Fig. 7(h) displays the transmission coefficient results for the conformal FSS. It demonstrates resonance at 26.8 GHz, with a negligible deviation in resonant frequency compared to the flat structure. The fabricated transparent FSS reached 65 % optical transmittance. The proposed screen-printed transparent FSS can be used

for applications that require millimetre-wave shielding. In addition to this research, there has also been work on transparent active FSS (AFSS) that were fabricated via screen printing. Lai et al. proposed a transparent AFSS that could be fabricated using screen printing [142]. Fig. 7(i) shows the unit cell structure of the proposed AFSS and the actual fabricated AFSS. The group utilised screen printing to print silver ink on a PET substrate and mounted PIN diodes using conductive silver paste. Fig. 7(j, k) shows the TE and TM transmission coefficient measurements of the fabricated AFSS. The fabricated AFSS allows electromagnetic waves to pass in the ON state and provides shielding in the OFF state. The bandwidth of the TE mode ranged from 5.43 to 6.26 GHz, while the TM mode ranged from 5.28 to 6.78 GHz. The bandwidth remained stable with variations in the angle of incidence. The optical transmittance was calculated to be 72 %, which corresponds to the area without a pattern.

3.3. Transparent metamaterial absorbers (MA)

An electromagnetic wave absorber is a material that converts the incident electromagnetic wave into microscopic heat energy using the material's own dielectric losses and resistive losses and dissipates it.

Absorber types include pyramidal absorbers and MAs. MAs, first introduced by Landy in 2006 [143], are characterised by the ability to change the absorption frequency by changing the permittivity and permeability. Their strengths are low manufacturing cost, lightweight, and other functions such as transparency, flexibility, and stretchability. The specific design parameters of MA are resistance, optical transmittance, dielectric loss, and skin effect, which are the same as those of antennas and FSS, but different. Transparent antennas and transparent FSS required low resistance to minimize ohmic loss generated in transparent conductive materials, but MA, on the contrary, requires high resistance to achieve electromagnetic wave absorption performance, as ohmic loss contributes to absorption performance [144,145]. These characteristics enable the achievement of both high absorption performance and high optical transmittance. High dielectric loss also contributes to electromagnetic wave absorption performance, providing greater flexibility in dielectric material selection. Losses caused by the skin effect also contribute to electromagnetic wave absorption performance, making it advantageous to utilize thin-film transparent conductive materials such as ITO or AgNW. From a performance optimization perspective, it is necessary to form resonance characteristics in the target frequency band and optimize for low reflection loss. Based on these characteristics, active research is being conducted on transparent MA for various applications, such as optical windows [146–148], ultra-high-frequency radio frequency-identification systems [149], and broadband microwave invisibility of solar panels [150,151].

A number of transparent MA studies that utilise printing have also been reported. Wu et al. proposed a transparent MA that can be applied to terahertz devices through EHD printing [152]. As shown in Fig. 8(a), the group proposed a multilayer absorber structure with a fishnet-grid top pattern and ITO in the middle layer for impedance matching. Fig. 8(b) shows the prototype of the absorber fabricated via EHD printing. The optical transmittance of the fabricated absorber ranged from 65 % to 78 %. Fig. 8(c) shows the simulation results of the absorption rate for different line widths of the proposed absorber top pattern. The simulation results show that the absorption bandwidth variation with line width was not significant, which suggests that the proposed structure is tolerance insensitive. Fig. 8(d) shows the measured absorption results. The simulated and measured results of the proposed transparent MA appear very similar. The proposed terahertz transparent MA presented a new method for the design and fabrication of terahertz absorbers. Another research project involved transparent absorbers made via screen printing. Li et al. utilised a screen-printable Ag NW ink and laser treatment to develop a transparent electrode with a very low sheet resistance of 1.9 Ω/sq and an optical transmittance of 73 % [47]. The authors used the developed transparent electrode for the design of the absorber. Fig. 8(e) shows the fabricated transparent absorber. Fig. 8(f) shows the measured results. The researchers fabricated and measured a narrowband transparent absorber as well as a broadband transparent absorber. The broadband transparent absorber had an optical transmittance of 45 % at 550 nm. Fig. 8(g) shows the absorption results of the fabricated broadband absorber for different bending radii and the absorption results for different bending cycles (1 to 1000 bending cycles). The measurement reveals that the absorption rate drops sharply when the bending radius becomes 23 mm, which is due to the cracks in the Ag NW pattern, which increases resistance. The authors also performed repeatability tests on the fabricated absorber for up to 1000 cycles. It can be seen that the absorption characteristics were effectively maintained even after 1000 repetitions. Fig. 8(h) shows the strain-test measurement results of the fabricated absorber. The absorption properties were measured to be retained at 5–20 % strain, while the absorption properties were retained in repeatability tests (ranging from 1 to 1000). These absorbers can be utilised in applications that require flexible, stretchable properties.

In addition to EHD printing and screen printing, research on transparent MAs utilising ink-jet printing has also been performed. Jeong et al. proposed a transparent MA obtained via ink-jet printing [153].

Fig. 8(i) shows the structure of their transparent MA. The optical transparency was achieved by designing a thin square loop pattern with a width of 0.2 mm. Fig. 8(j) shows the fabricated transparent MA. It appears transparent because the printed silver ink area was small. The authors calculated the transparency by considering the opaque areas and found that the optical transparency exceeded 90 %. Fig. 8(k) shows the measurement results of the fabricated MA. The fabricated absorber exceeded 90 % absorption from 26.8 to 28.2 GHz. The group confirmed that the transparent MAs can be realised via inkjet printing. In addition, there have been studies of transparent absorbers that operate in the W-band and utilise EHD printing. Wu et al. proposed a flexible yet transparent absorber based on EHD printing [154]. Fig. 8(l) shows the transparent absorber they fabricated. The fabricated absorber is flexible and transparent enough to see the text behind it. The optical transmittance of the fabricated absorber was measured to be 58.1 %. Fig. 8(m) shows the reflection coefficient of the fabricated absorber, which was found to exceed 90 % absorption between 73.5 and 110 GHz. Fig. 8(n) shows the simulation results for the absorption at different angles of incidence. The proposed transparent absorber was reported to feature more than 80 % absorption for angles of incidence ranging from 0 to 45°. Such an absorber can be utilised in applications that require absorption in the W-band.

Another study combined Ag NWs with screen printing. Bark et al. proposed a transparent MA featuring a second-order cross-fractal pattern designed to achieve absorption in both the C-band and K-band [38]. Fig. 9(a) shows a photograph of the fabricated transparent MA. An air gap was created between the two PET films, which not only reduced the weight but also enhanced the optical transparency. Fig. 9(b) shows the measured optical transmittance. The optical transmittance of the fabricated transparent absorber was measured to be about 90 % at 550 nm, while the optical transmittance of the PET film without the pattern was measured to be about 63 % at 550 nm. Fig. 9(c) shows the measured absorption of the fabricated MA. The measured absorption of both the C-band and the K-band was similar to the simulation results. The proposed transparent MA, featuring a fractal structure, can be integrated into the windows of stealth aircraft. In addition, studies have explored transparent MAs that incorporate a combination of screen printing and metal mesh. Choi et al. proposed a transparent MA with absorption properties within the X-band by utilising screen-printed metal mesh [117]. The authors designed the top pattern as a second-order fractal structure to reduce the size of the unit cell compared to conventional metamaterial patterns, such as square patterns. Fig. 9(d) shows the fabricated transparent MA, while Fig. 9(e) displays the measured optical transmittance. The substrate with unpatterned PET and a bonding film was measured to be 84.12 %, while the fabricated absorber was 46.7 %. Fig. 9(f) shows the obtained absorption of the fabricated absorber. The measured absorption is 92 % at 8.85 GHz. The difference in absorption between simulation and measurement is because the ITO film used in the actual fabrication has a higher sheet resistance than the simulation. Fig. 9(g) shows the repeatability-test results of the fabricated absorber. After bending the absorber to a radius of 35 mm and repeating the recovery process up to 6000 cycles, we can see that the absorption rate remained above 90 %. Another study effectively utilised the benefits of Ag NWs and screen-printing. Kim et al. applied the high and low sheet resistance obtained by controlling the number of screen print cycles to the design of transparent MAs [41]. As illustrated in Fig. 9(h), the group assigned high sheet resistance to the square pattern and low sheet resistance to the cross pattern. As a result, the square pattern has a smooth patterned absorption trend and the cross pattern has a sharp patterned absorption trend. The combination of the two patterns with different trends results in a wider absorption bandwidth. Fig. 9(i) shows the fabricated transparent MA. Fig. 9(j) displays the absorption-measurement results of the fabricated transparent MA, revealing more than 90 % absorption between 8.68 and 11.48 GHz. Fig. 9(k) shows the measured optical transmittance. The substrate, composed of PET and optical clear adhesive (OCA), exhibited a transparency of 86.2 % at 550 nm. In contrast,

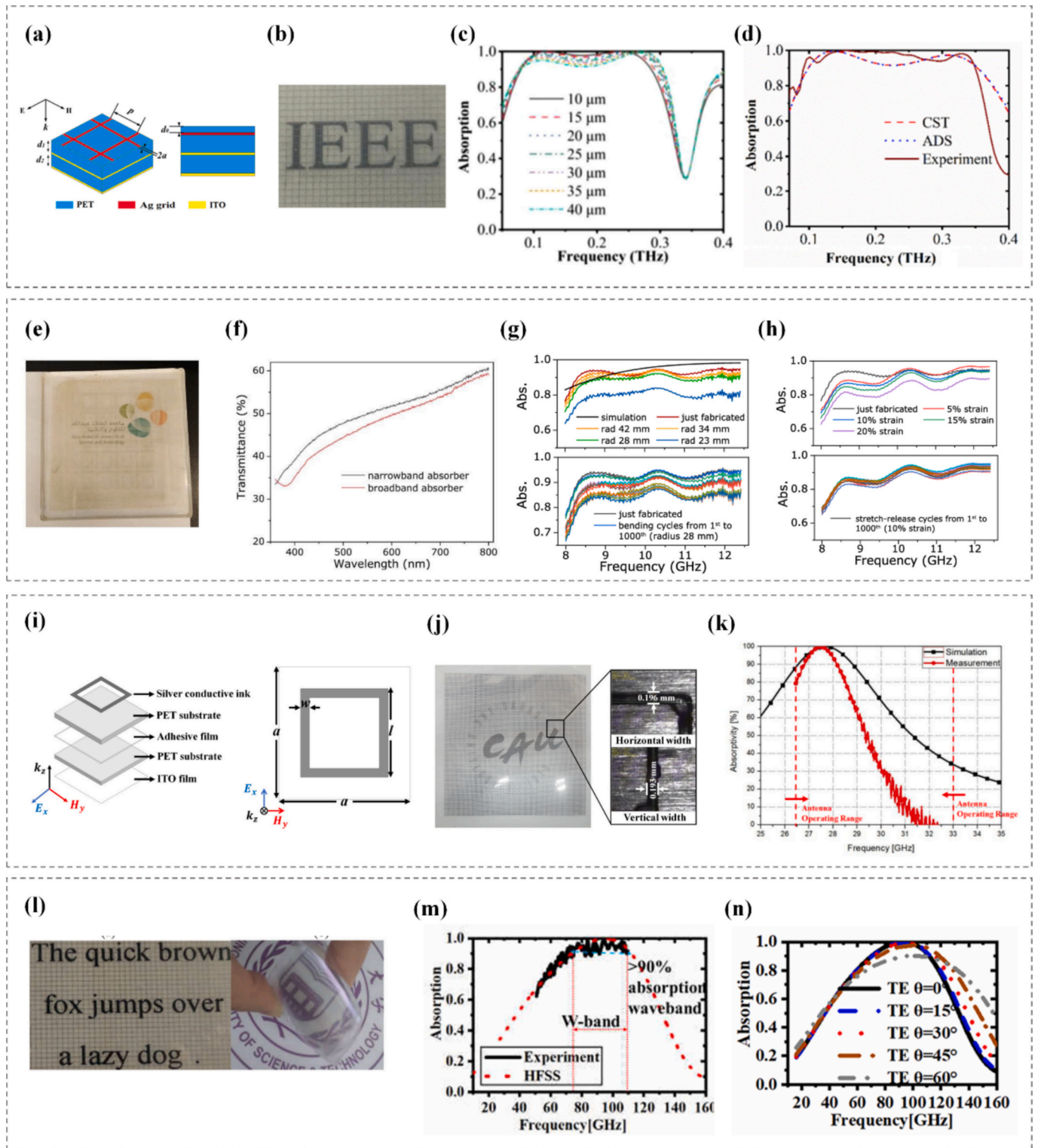


Fig. 8. (a) Proposed transparent MA for terahertz absorption using EHD printing, (b) fabricated prototype, (c) simulated absorption for different line widths, (d) measured absorption. Reprinted with permission from [152] (Copyright 2019, IEEE). (e) Fabricated transparent MA, (f) measured optical transmittance, (g) measured absorptivity for different bending radii (top), and bending cycles from 1 to 1000 with a radius of 28 mm (bottom), (h) measured absorptivity results for different tensile strains (top), and stretching cycles for 10 % strain (bottom). Reproduced with permission from [47] (Copyright 2019, Springer Nature). (i) Proposed transparent MA structure using ink-jet printing, (j) fabricated prototype, (k) measured absorptivity. Reproduced with permission from [153] (Copyright 2019 by the authors. Licensee MDPI, Basel, Switzerland). (l) Fabricated transparent MA using EHD printing, (m) measured absorption, and (n) simulated absorption for different angles of incidence. Reprinted with permission from [154] (Copyright 2020, IEEE).

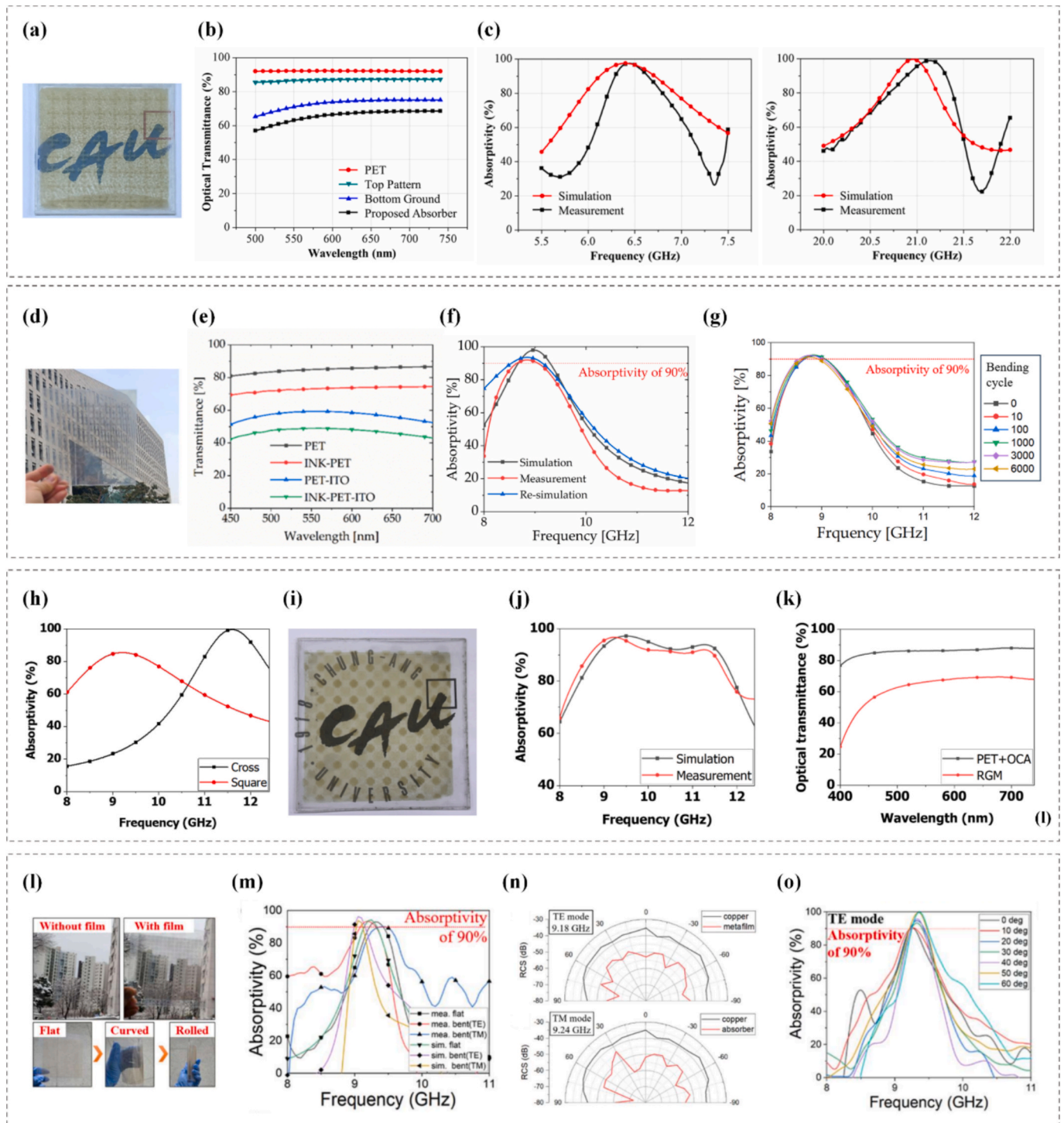


Fig. 9. (a) Fabricated transparent MA using Ag NW, (b) measured optical transmittance, (c) measured absorptivity C-band (left), K-band (right). Reproduced with permission from [38] (Copyright 2024 by the authors. Licensee MDPI, Basel, Switzerland). (d) Screen-printed metal mesh-based transparent MA, (e) measured optical transmittance, (f) measured absorptivity, (g) measured absorptivity for different bending cycles. Reproduced with permission from [117] (Copyright 2024 by the authors. Licensee MDPI, Basel, Switzerland). (h) Simulated absorptivity for each pattern in the unit cell, (i) fabricated transparent MA using resistance-gradient concept, (j) measured absorptivity, (k) measured optical transmittance. Reprinted with permission from [41] (Copyright 2024, Elsevier B. V.). All rights reserved. (l) Fabricated transparent metamaterial for electromagnetic absorption, (m) measured absorptivity, (n) measured radar cross-section of a metafilm sample for the TE-mode (up), TM-mode (down), and (o) measured absorptivity for different angles of incidence. Reprinted with permission from [155] (Copyright 2024, IEEE).

the proposed absorber demonstrated a transparency of 66.3 % at the same wavelength. In addition, screen-printed metafilms have been reported. Lim et al. proposed a rollable metafilm absorber based on a screen-printed metal mesh [155]. The authors constructed both the top pattern and the ground pattern with metal mesh to achieve optical

transparency. As shown in Fig. 9(l), the fabricated metafilm is both transparent and “rollable”. Fig. 9(m) displays the measured absorption, which indicates that the absorption at 9.32 GHz is 93 %. Fig. 9(n) presents the radar cross-section results measured at 9.18 GHz and 9.24 GHz. When comparing the reflected wave measurements of the fabricated

absorber with those of copper, the absorber demonstrated a significant reduction in reflection: 94.7 % in TE mode and 94.5 % in TM mode. Fig. 9(o) shows the absorption of the fabricated absorber as the angle of incidence changes. The absorption of the fabricated absorber exceeded 90 % for all angles of incidence (from 0 to 60°).

The key properties of transparent MA studies using different printing methods are summarised in Table 5. A range of materials, including Ag NWs, Ag nanoparticles, and ITO, were used in the design of the transparent MAs because low-sheet resistance and high-sheet-resistance materials can also be used in the design of the absorbers. In fact, the used sheet resistance varied from 0.015 O/sq to 200 O/sq. The optical transmittance ranged from 45 to 78 %, and the patterning method primarily was screen printing. Typically, transparent MAs require fabrication over large areas to facilitate straightforward measurement. Screen printing is particularly well-suited for this purpose because of its large-area printing. Unlike transparent antennas, which require very low sheet resistance, transparent metamaterial absorbers can be designed with high sheet resistance. This design flexibility is expected to drive further exploration and innovation in the field.

4. Applications and case studies

Transparent RF electronics, such as antennas, frequency selective surfaces (FSS), and metasurfaces with diverse functionalities, hold significant potential across a wide range of applications, including communication, military applications, and consumer electronics, as shown in Table 6. Transparent RF electronics, in particular, have gained significant attention from researchers due to their unique ability to maintain aesthetic integrity when integrated with the surrounding environment or other devices while still demonstrating RF performance comparable to traditional opaque and bulky RF electronics. This potential for effective utilisation across a wide range of applications has driven a surge in research interest in the field. Consequently, numerous studies have explored transparent RF electronics employing not only printing techniques but also a variety of other manufacturing processes. These studies highlight the versatility of transparent RF electronics, showcasing their potential in diverse applications such as communications, consumer electronics, and wearable technologies.

Unlike the previous sections, this section does not focus on case studies of RF electronics that were fabricated specifically via printing. This approach stems from the understanding that transparent RF electronics (whether produced via screen printing, ITO film, or other fabrication methods) can offer the same application potential as long as they achieve both good transparency and excellent RF performance. Moreover, to comprehensively highlight the broad application potential of transparent RF electronics, this chapter explores their use cases across

Table 6

Reported applications of transparent RF electronics.

Type of transparent electronics	Applications	Ref.
Antennas	Communication	5G (millimetre wave and sub-6 GHz) communication
	Smart city	[23]
	Indoor mobile communication	[161,162]
	Vehicular communication	[163]
	THz communication	[164,165]
	Automobile windows or rear glass	[166,169]
	Integration with solar cells for CubeSats	[170–173]
	Display of IoT devices	[167,174,175]
	Consumer electronics	Laptop computers [176]
		Smartwatches [177]
		Smartphones [178]
		Smart glasses [168]
	Wearable devices	[179–181]
	Intelligent health care system	[182–184]
	RFID technology	[185–190]
FSS	Wireless energy harvesting	[191]
	Sensors	[192]
	Communication	Communication-performance enhancement [139,193]
		Communication security [139,194,195]
	RF shielding	[27,194,196]
	Flexible electronics	[27,197]
	RCS reductions	[198]
	THz imaging	[199]
	Communication	Satellite-to-vehicle [200]
		O2I communication [201]
Refractive metasurface		
Transmissive metasurface		5G indoor communication [202]
Intelligent surface		I2O millimetre-wave communication [203]
EM skin		O2I millimetre-wave communication [203]
Metasurface absorber	Radar stealth	[38,117,204]
	EMI shielding	

a broad spectrum of fields without being limited to specific fabrication techniques. This inclusive perspective seeks to highlight the wide range of applications made possible by transparent RF electronics, irrespective of the manufacturing process used.

In order to comprehensively explore various types of applications and examine numerous research cases for each type of RF electronics (such as antennas and FSS), the following content is organised into three

Table 5

Key-property comparison of optically transparent MAs fabricated using various printing methods.

Ref.	Material	Sheet resistance (ohm/sq)	Optical transmittance (%)	Printing method	Absorption band (GHz)	FBW ^a (%)	Electrical thickness (λ_0)	Flexible
[152]	Ag grid, ITO	50 (Ag grid), 200, 8 (ITO)	65–78	EHD printing	98–353	113.1	0.13	No
[47]	Ag NW	51 ± 2.4 (Top), 7.5 (GND)	45	Screen-printing	8–12.4	43.1	0.093	Yes
[153]	Ag nanoparticle, ITO	N/A (Top), 5 (GND)	N/A	Ink-jet printing	26.8–28.2	5	0.05	No
[154]	Ag mesh, ITO	13.4 (Top), 8 (GND)	58.1	EHD printing	73.5–110	39.8	0.13	Yes
[38]	Ag NW	5.85 (Top), 8.3 (GND)	63	Screen-printing	6.45, 21.14 (Peak)	N/A	0.084	No
[117]	Ag nanoparticle, ITO	0.4 (Top), 45 (GND)	46.7	Screen-printing	9.02–9.56	5.8	0.043	Yes
[41]	Ag NW	8, 30 (Top), 15 (GND)	66.3	Screen-printing	8.68–11.48	27.8	0.045	No
[155]	Ag nanoparticle	0.015	51	Screen-printing	9.2–9.4	2.1	0.028	Yes

^a FBW (fractional bandwidth) is defined as $FBW = 2(f_H - f_L)/(f_H + f_L)$, where f_H and f_L denote the maximum and minimum frequency of the absorption band, respectively.

subsections. Subsections 4.1, 4.2, and 4.3 are dedicated to the wide range of the possible applications of transparent antennas, transparent FSS, and other transparent RF electronics, respectively.

4.1. Applications of transparent antennas

Among the diverse range of transparent RF electronics, transparent antennas stand out for their potential to be effectively integrated into a wide array of applications. Their unique ability to seamlessly blend into the surrounding environment while maintaining wireless communication capabilities makes them particularly promising. However, achieving both high transparency and good antenna performance simultaneously remains a significant challenge. Nevertheless, research that has successfully balanced both high transparency and strong antenna performance has demonstrated the broad applicability of transparent antennas. These antennas are now being effectively utilised in diverse fields, including 5G and 6G communications, terahertz communication, vehicle antennas, solar cell integration in small satellites, consumer electronics, the Internet of Things (IoT), RFID, RF energy harvesting, and intelligent health care. Furthermore, when transparent antennas are designed with flexible conductors and substrates, they can be seamlessly integrated into wearable technologies, such as smart glasses, and further expand their applications.

Several transparent antennas that achieved good performance suitable for 5G (millimetre wave and sub-6 GHz) communication systems have been reported [37,156–160]. For millimetre-wave 5G applications, in [156], an optically transparent antenna fabricated using AgHT-8, which covers a wide frequency range (23.92–43.8 GHz), has been proposed as an excellent candidate for 5G communication systems as well as for wideband code division multiple-access applications. In [157], a transparent antenna with 85 % transparency and a dual-band operating frequency range of 24.10 – 27.18 GHz and 33 – 44.13 GHz is proposed for use as a MIMO antenna in 5G communication systems. The antenna demonstrates acceptable MIMO/diversity performance and achieves a diversity gain over 9, an envelope correlation coefficient below 0.1, a total active reflection coefficient of less than –15 dB, and a mean effective gain ratio within the standard limit of ± 3 dB. In [37], a flexible MIMO antenna that reached a superior transparency of 93 % based on an embedded selective electrodeposited Ni dense mesh showed a maximum gain of 9.6 dBi and a scanning angle of approximately $\pm 75^\circ$. In [158], transparent antenna arrays with over 90 % transparency, fabricated using Gallium-doped Zinc Oxides, are presented. These arrays exhibit excellent gain and scanning characteristics. Research on optically transparent and flexible antennas has further suggested that transparent antennas could play a key role in realising the smart city concept. By enabling simultaneous monitoring and management of the communication network status and usage, transparent antennas offer a promising solution to address network capacity challenges in smart city environments. Since these antennas can be seamlessly integrated into urban environments, such as windows, building facades, and even displays, without obstructing the view, a greater number of antennas can be deployed to enhance the communication environment without being perceptible to the user. The concept of a smart city and the effective utilisation of optically transparent antennas have been explored in a thorough review [23]. In addition, optically transparent antennas that target sub-6 GHz 5G applications and WLAN bands have also been reported [159,160]. Furthermore, researchers have suggested that transparent antennas are especially suitable for indoor mobile applications thanks to their easy conformability and concealment (through high transparency) [161,162]. For example, these transparent antennas can be used with indoor security systems or future transparent communication devices, such as femtocells [162]. Moreover, transparent antennas designed explicitly for vehicular communication have also been proposed previously [163]. In addition, transparent antennas for THz communication have also been investigated in previous studies. In [164], a transparent U-shaped patch antenna operating at 0.7 THz was

fabricated using ITO and FTO materials, while in [165], a transparent patch antenna operating at 0.7 THz was developed based on Ta₄C₃ MXene.

In the case studies mentioned above, we reviewed transparent antennas that achieved both high transparency and excellent performance, which showcased their potential for seamless integration into their surroundings and excellent suitability for 5G communication systems. Moving forward, the discussion focuses on specific locations where transparent antennas can be installed and effectively utilised. A notable example is the integration of transparent antennas into automobile windows or rear glass. This approach has the potential to significantly reduce the space traditionally occupied by bulky, opaque antennas and offers a streamlined and aesthetically pleasing alternative [166,169]. In [166], a dual-band transparent inverted-F antenna based on a micro-metal mesh film was implemented on the rear glass of a real automobile (Hyundai K5), as shown in Fig. 10(a). By utilising the much larger surface area of the rear glass compared to the constrained available space on the roof, transparent antennas offer an effective solution to deal with the inherent space limitations of conventional roof-mounted shark-fin antennas. In addition, for both bands, the radiation pattern showed a sufficiently directive pattern outward from the car. In [169], a wideband transparent armor-embedded antenna was explored, which was specifically designed for terrestrial communication in military vehicles and operation in the UHF and VHF frequency bands. This design offers multiple benefits (not only reduced vehicle signature and air drag) as well as additional antenna protection and improved antenna gain.

One of the promising applications of transparent antennas is their integration on top of solar cells for CubeSats or small satellites [170–173]. The key benefits of integrating optically transparent antennas with solar cells are more effective space usage and a reduction in weight and volume. Small satellites have limited available surface area, and the majority is occupied by solar cells. Therefore, to efficiently accommodate all essential components—such as power systems, transceivers, and sensor circuits—within a limited space, maximising the use of the satellite's surface area is critical for small satellites. Transparent antennas save precious space within the satellite chassis through seamless integration with these solar panels. In addition, reducing the volume and weight of satellites is crucial to lowering launch and operation costs. Integrating antennas with solar panels also helps minimise the need for additional components, which contributes to overall weight and volume reduction. In [170], the proposed antenna utilised the cover glass of a solar cell directly as its substrate. For successful integration with the solar cell, the antenna must maintain sufficient transmittance to ensure the solar cell operates effectively. Measurements confirmed that the antenna achieves a high transmittance of 93 %, which meets this requirement. Later, transparent antennas based on water-dense dielectric patches [171] and fluorine-doped tin oxide [172,173] were proposed and successfully integrated with solar cells.

Another promising application of transparent antennas is their seamless integration into IoT device displays. Consumer electronics and IoT devices require high-speed, stable, wireless communication, which necessitates efficient and intelligent antennas. However, conventional antennas integrated within wireless devices suffer from low radiation efficiencies as they need to be small due to a lack of available space. By using transparent antennas, the entire display panel can serve as a radiating surface, which helps overcome the radiation performance limitations of miniaturised opaque antennas [167,174,175]. In [174], an optically invisible transverse magnetic-resonant-mode antenna fabricated based on using transparent conductive polymers, was integrated into organic light-emitting diode (OLED) touch displays. The antenna demonstrated efficient radiation performance at 2.4 GHz, which suggests its suitability for integrating effective antenna functionality into monolithic active display panels. In [167], a co-integration of a transparent antenna with an OLED light source was reported and experimentally tested. The experimental test showed that the three-layer antenna reduced the OLED luminance by 25 %. However, as shown in

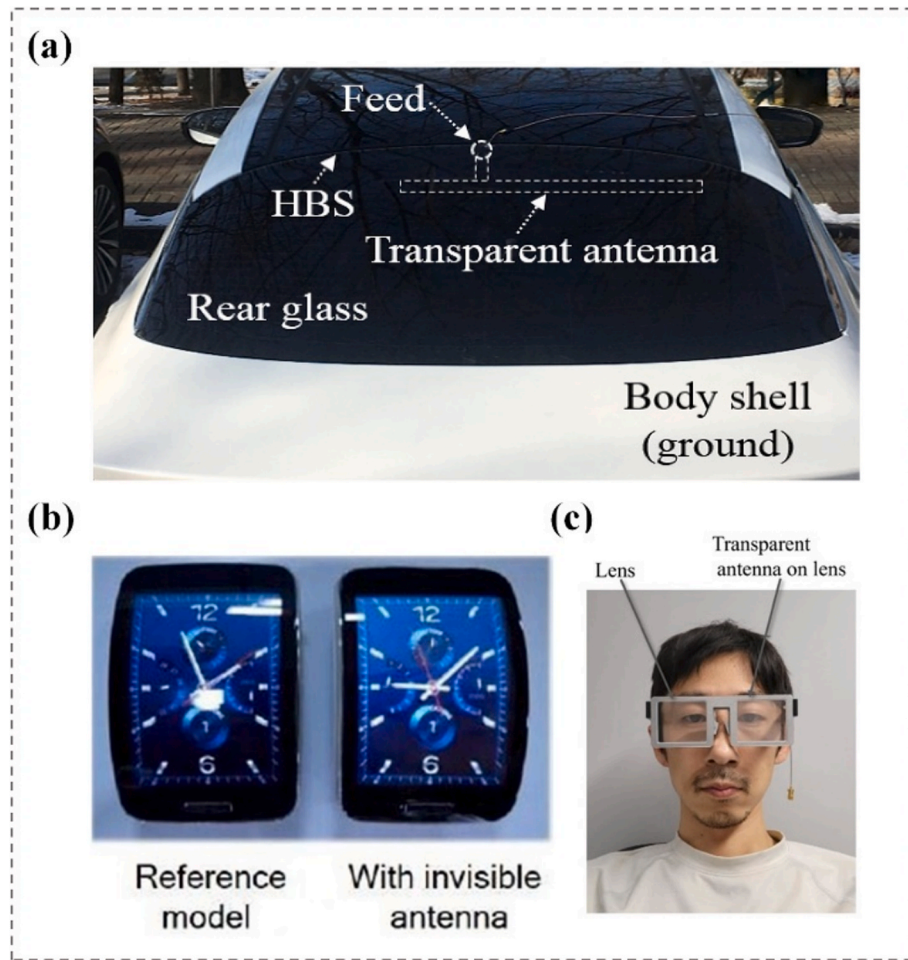


Fig. 10. Photographs of actual transparent antennas integrated into various electronic devices: (a) A transparent antenna installed on the rear glass of an automobile. Reprinted with permission from [166] (Copyright 2019, John Wiley and Sons); (b) An OLED display. Reprinted with permission from [167] (Copyright 2017, IEEE); (c) Smart glasses. Reproduced with permission from [168] (Copyright 2023, IEEE).

Fig. 10(b), the antenna remained nearly invisible when integrated with the OLED display. For future work, the authors proposed to enhance co-integration by moving beyond merely stacking transparent antennas on the OLED surface and instead utilising specific OLED layers as radiating elements of the antenna. This approach reduces the number of interfaces, simplifies the fabrication process, minimises transmission losses (to improve antenna efficiency), and maximises optical efficiency. All these factors help mitigate the associated luminance reduction of the OLED.

Previous studies on the successful integration with displays suggest that transparent antennas can be effectively incorporated into many consumer electronic devices. The transparent antenna can be effectively used in various types of consumer electronics, such as laptop computers [176], smart watches [177], smartphones [155], and smart glasses [156], as it enables wireless connections without obstructing the visual appeal of the devices. In [176], a flexible and transparent antenna made using a polyamide substrate and multilayer film (Indium-Zinc-Tin Oxide (IZTO)/Ag/IZTO) was combined with a computer laptop. The researchers studied how the electromagnetic radiation changed depending on the position of the antenna and the angles of the laptop display, which enabled them to demonstrate its practical applicability. In [178], a transparent antenna array was reported, dual-polarised meshed capacitive-fed patch antennas, with the feed section located on the mobile phone PCB and the radiating patch integrated into the rear glass of the phone. In [168], the transparent antenna is proposed as a promising solution to address volume constraints in smart glasses and

augmented reality glasses, as shown in Fig. 10(c). Furthermore, to mitigate performance limitations caused by coexistence with optical features, the edge slot antenna concept has been introduced. This design effectively reduces the RF loss from lossy optical features.

If the antenna features flexibility in addition to transparency, it can easily be attached to various curved surfaces, and its application range can be extended to wearable devices [179–181]. For an antenna to be effectively integrated into wearable technology, it must have minimal impact on the human body while transmitting and receiving electromagnetic waves through devices that are typically closely attached to the body. In addition, the antenna's performance should remain stable even when integrated into curved or flexible structures, such as wearable applications on the head, arms, or joints. In [179], a transparent and flexible monopole antenna made of multilayer film (IZTO/Ag/IZTO) for wearable glasses was proposed. Because glasses are typically worn close to the human head, the researchers analyzed three different monopole antenna designs, each with a distinct radiation pattern, to explore ways to reduce electromagnetic field absorption of the human head. [180] presented a flexible and transparent CP antenna that demonstrated robustness under bending conditions through experimental testing on a forearm phantom. The authors emphasised that in wearable applications, where antenna positioning varies due to user movement, CP is particularly effective in maintaining optimal communication performance by minimising polarisation mismatch losses. Transparent and flexible antennas are essential not only for wearable devices but also for the implementation of intelligent healthcare systems

that enable real-time wireless monitoring of physiological signals. [182,183] proposed wearable smart contact lenses equipped with highly transparent and stretchable sensors capable of continuously and wirelessly monitoring glucose and intraocular pressure—key risk indicators of diabetes and glaucoma, respectively. Both lenses incorporate transparent and flexible antennas: the transparent antenna in [182] was realized using a graphene–silver nanowire (AgNW) hybrid structure, while that in [183] was fabricated using one-dimensional, ultralong silver nanofibers (AgNFs). Furthermore, [184] proposed a transparent antenna based on silver nanofibers (AgNFs), which is suitable for applications in artificial electronic skins and human healthcare monitoring.

With the rapid growth of radio-frequency identification (RFID) technology, there is an increasing demand for tag antennas that are unobtrusive to their surroundings and adaptable to various curved surfaces. Transparent and flexible antennas, which are thin and lightweight, have been shown to be useful for RFID applications [185–190]. In [186], researchers suggested a specific use scenario for an RFID system utilising transparent antennas. A transparent antenna array was seamlessly integrated into the mirror surface of fitting rooms in apparel stores while preserving the mirror's shallow depth and ensuring low cost. This mirror-integrated antenna array reads RFID tags attached to clothing when customers try on garments, which provides interactive information about the selected items. [189] and [190] introduced transparent antennas with thinner and lighter structures than conventional non-transparent antenna designs, which enhances their suitability for integration into RFID systems. In [190], the proposed transparent and flexible antenna is completely encapsulated within the transparent polymer, which protects the antenna from dust, water, heat, and mechanical stress and thereby enhancing practical applicability.

In addition to the previously mentioned applications, transparent antennas have also been reported in the context of wireless energy harvesting [191] and sensors [192]. [191] proposed a transparent metasurface antenna based on Indium Tin Oxide (ITO) for wireless energy harvesting. The wireless energy-harvesting system reached a maximum RF-to-DC efficiency of 65 % and maintained a stable DC output voltage of 3.4 V. The overall RF energy-harvesting efficiency was 14.5 % at an input power level of 0 dBm. In [192], a dodecahedron-shaped, cost-effective wireless sensor node utilising transparent mesh antennas that can provide high-resolution air quality data was reported. Moreover, the smart, transparent antenna, with 87 % optical transparency and mounted on top of solar panels, focuses the emitted radiation toward the communication direction, which reduces electromagnetic pollution. In addition, the antenna creates a self-powered node that is 80 % smaller than a comparable planar antenna array.

4.2. Applications of transparent FSS

Like the transparent antennas described earlier, a transparent FSS can be seamlessly integrated into windows of buildings or vehicles, electronic devices, and other surfaces without compromising aesthetics. By selectively allowing or blocking specific radio frequencies at certain locations in space, it performs spatial filtering, controlling electromagnetic wave propagation based on frequency and direction. Possible applications of the proposed transparent FSS include improving communication environments [139,193], enhancing communication security [139,194,195], RF shielding [27,194,196], integrating flexible electronics [27,197], and reducing radar cross-section (RCS) [198]. In [27,139,193–196], it was proposed that a transparent FSS, when attached to window glass, can perform a signal filtering function that allows only specific frequencies to pass through without reducing the transparency of the glass. This approach can effectively prevent electromagnetic pollution from entering the building from the outside while enhancing information security by blocking indoor communication signals from leaking outside. In [27], a transparent and flexible single-

layer, dual-band FSS reflector, which is insensitive to polarisation and a wide range of angles of incidence, demonstrated its ability to shield global systems for improved mobile communication (GSM) signals. These FSSs in [27,197] can also be applied to the curved surfaces of flexible electronic devices and provide shielding to prevent malfunctions caused by electromagnetic interference. [198] introduced a compact, polarisation-insensitive, transparent tri-band tetraskelion-shaped FSS, which can be used to reduce the Radar Cross Section (RCS). The proposed design exhibited better RCS performance than simple planar structures. [26] suggested that transparent FSS structures at millimetre-wave frequencies have potential applications beyond building windows, including future intelligent vehicles, on-chip RF shielding components, and windshield sensor devices. In addition, the transparent fss has also been applied to terahertz (THz) technologies in previous studies. In [199], an FSS-based transparent window was proposed for broadband spectroscopic and imaging measurements in the THz frequency range. The transparent FSS in [199], fabricated by depositing 200 nm-thick gold on a quartz substrate using photolithography, was demonstrated to effectively suppress out-of-band signals in a customized measurement environment.

4.3. Applications of other RF electronic devices

Transparent RF electronics extend beyond transparent antennas and FSS to include transparent metasurfaces [200,201], intelligent surfaces [202], electromagnetic skins [203], and metamaterial absorbers [38,117,204]. These structures, which combine artificial electromagnetic properties capable of controlling reflection, refraction, and transmission of electromagnetic waves with optical transparency, can be effectively utilised in many different applications. Examples include enhancing communication environments and EMI shielding without obstructing the surrounding environment. In [200], a transparent refractive metasurface was reported, which was designed to refract incident waves toward a desired direction with minimal loss. This straightforward structure, which consists of only two metallic layers, offers significant potential to enhance satellite-to-vehicle and outdoor-to-indoor (O2I) communication. In [201], a transparent transmissive metasurface with wide-angle incidence stability and polarisation insensitivity was introduced. This innovative metasurface can be mounted on vehicles or building windows, effectively improving indoor 5G signal coverage at the 3.5 GHz band over a wide range of incident angles. [202] reported a transparent amplifying intelligent surface that was designed to refract and amplify incident waves. This architecture was designed to enhance uplink spectral efficiency in indoor-to-outdoor (I2O) millimetre-wave communication scenarios. In [203], transparent opportunistic electromagnetic skins were introduced to facilitate outdoor-to-indoor (O2I) millimetre-wave wireless communication through existing windows or glass panels. These EM skins improve O2I transmission efficiency by enabling refraction along non-Snell directions. In [38,117,204], transparent metamaterial absorbers were introduced, which were designed to absorb incident waves within specific frequency bands. These structures are promising candidates for applications such as radar stealth and EMI shielding when integrated into windows or glass panels.

4.4. Emerging application for transparent RF electronic devices

This subchapter introduces emerging application areas where transparent RF electronics have not yet been implemented but hold strong potential for effective integration in the future. While THz technology, operating in the 0.1 to 10 THz frequency range, has been applied to transparent antennas and frequency selective surfaces (FSSs) to a limited extent, other types of transparent RF devices—such as various metasurfaces and metasurface absorbers for EMI shielding—have not yet been explored in this domain. However, through the diverse fabrication methods presented in this paper, a broader range of transparent

RF devices could be extended to THz communication and THz imaging applications, offering significant utility. In addition, only transparent antennas have been applied so far to intelligent health sensing systems that detect and communicate biosignals and biomarkers in real time. However, in the case of non-transparent RF devices, electronic skin with EMI shielding [205], NFC technology [72,206], and metamaterials [207,208] have been successfully integrated into intelligent health sensing systems. Wearable intelligent health sensing networks can benefit greatly from transparency, as it allows devices to be unobtrusively attached to any part of the human body without compromising aesthetics. Therefore, transparent RF electronics beyond antennas—such as transparent FSSs and transparent metamaterials—are also expected to be effectively utilized in intelligent healthcare applications, even though they have not yet been explored in this domain.

Transparent RF electronics are also expected to find applications not only in THz technologies and intelligent healthcare systems, but also in emerging quantum communication and quantum computing technologies, which are rapidly advancing. Qubits—the fundamental units of quantum technologies—can be implemented using various platforms such as superconducting circuits, ion traps, semiconductor quantum dots, photons, and Rydberg atoms. Among these, superconducting qubits have emerged as one of the most promising candidates, as they support the implementation of fast and high-fidelity single- and two-qubit logic gates. Controlling and measuring superconducting qubits typically requires RF signals with high resolution and low noise, operating in the 4–8 GHz frequency range with bandwidths of several hundred MHz. Accordingly, RF synthesis devices, RF mixing modules, and related RF electronics are essential for the implementation of quantum computing systems [209,210]. In the field of quantum communication, however, photons are considered the most suitable carriers due to their low propagation loss at room temperature. Recent studies have aimed to establish microwave-to-optical transduction interfaces that connect superconducting qubits with photonic qubits [209], which could pave the way for quantum repeater architectures—one of the key goals in long-distance quantum communication. This suggests that RF electronics are not only critical for quantum computing, but also for enabling scalable quantum communication. While conventional RF systems for quantum applications have been extensively studied, little attention has been given to their transparency. By utilizing transparent RF components, it would be possible to enhance spatial integration without compromising aesthetics, thereby contributing to the miniaturization of complex quantum information processors. Despite the lack of current applications, quantum computing and communication platforms may serve as a compelling application area for transparent RF electronics.

5. Summary, limitations, challenges

This review emphasizes the key advantages of printed electronics compared to traditional fabrication methods, particularly in terms of cost efficiency, design flexibility, scalability, and compatibility with flexible and transparent substrates factors that are accelerating their use in transparent RF device development. Advances in functional materials such as metal nanowires, metal nanoparticles, CNTs, graphene, and conductive polymers, along with scalable printing techniques like inkjet, screen, and roll-to-roll printing, enabling the fabrication of compact, high-performance RF components with enhanced electrical and optical characteristics. The review also traces the field's progression from basic research to more practical and integrable solutions, including transparent antennas, transparent frequency-selective surfaces for smart environments, and transparent metamaterials. Despite this progress, challenges such as achieving the right balance between conductivity and transparency, ensuring material and device stability, and adapting novel materials for industrial-scale printing remain critical, offering valuable opportunities for future research. This study also reviews printed electronics adoption has been limited by a variety of problems, particularly

in areas like conductivity, metallisation patterning precision, environmental stability challenge, and other critical characteristics specific to RF applications. Addressing these difficulties is crucial for maximising the potential of printed RF devices.

One of the primary difficulties printed RF circuits face is achieving very high electrical conductivity. Conductive inks, which are often made from silver, copper, carbon nanoparticles, or nanowires, and conductive polymers primarily determine the performance of RF components. In addition, printed conductive electrodes have lower conductivity compared to bulk materials because of organic binders, insufficient sintering, and layer porosity. In high-frequency applications, slight variations in conductivity can result in substantial signal losses, which decreases the efficiency of RF devices. Furthermore, it is still difficult to maintain good conductivity under varying environmental conditions, including humidity, oxidation, and temperature fluctuations.

Metallisation (the process of depositing metallic layers) is a key step in the fabrication of RF electronics, enabling the formation of conductive lines and components. However, printed conductive electrodes or circuits often exhibit non-uniformity and porosity, unlike those produced by traditional methods such as thermal evaporation, sputtering, or electroplating, which yield dense and uniform structures. Fig. 11. shows the cross-sectional structures of thermally evaporated and printed conductive lines [211]. The thermally evaporated conductive lines exhibited a dense and smooth structure, whereas the printed conductive lines showed porosity and multiple junctions. Thermal-evaporated lines had smooth current paths and higher conductivity, while printed conductive lines featured complex current paths (because of nanoparticles) with lower conductivity. Although copper-based inks are inexpensive, they are very prone to oxidation, which gradually decreases conductivity. Furthermore, sintering methods that can be used to increase the conductivity of printed metal layers often require high temperatures, which makes them unsuitable for flexible or low-cost substrates and increases the complexity of their application.

Accurate patterning is crucial for RF applications because the component dimensions strongly impact performance. However, printing methods like screen printing and inkjet printing sometimes cannot provide the high resolution required for certain sophisticated radio frequency designs, especially as devices become smaller to meet modern demands. Problems such as layer misalignment during multi-layer printing or uneven ink application can result in irregular patterns, which impact impedance matching and compromise signal integrity.

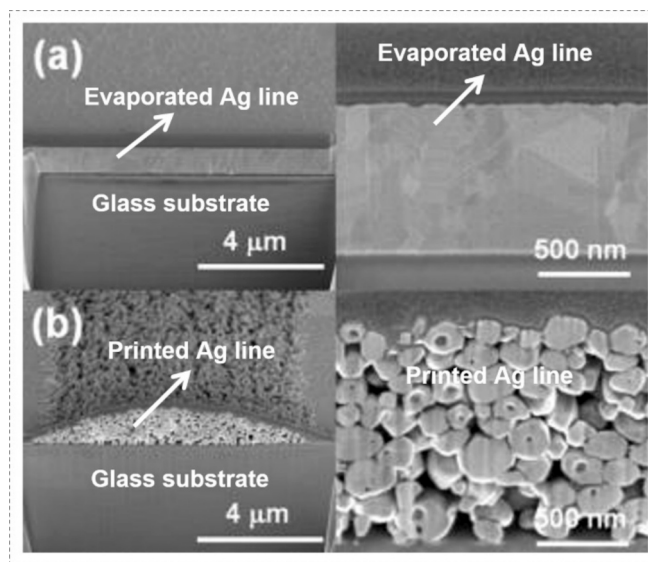


Fig. 11. FIB cross-sectional images of Ag lines prepared using different methods: (a) thermally evaporated Ag line, and (b) printed Ag line. Reprinted with permission from [211] (Copyright 2022, American Chemical Society).

Furthermore, maintaining constant thickness over very large areas remains problematic, as it results in differences in conductivity and impacts overall performance.

Another problem is the long-term stability of printed conductive electrodes or circuits. Electromigration, thermomigration, moisture, humidity, UV exposure, corrosion stability and mechanical stress can degrade printed materials and decrease both conductivity and device performance in saline environments. Hence, developing long-lasting inks and protective coatings is crucial for extending the life of these printed conductive electrodes or circuits [212,213].

6. Future directions

Over the past five years, many studies have explored transparent RF devices utilising printing technology. Various printing methods, such as screen printing, inkjet printing, direct writing, aerosol-jet printing, and EHD printing, have been employed to develop transparent RF devices with various structural designs. Research on transparent RF devices utilising printing technology is expected to continue to increase as some challenges remain. For example, while several types of successfully producing transparent antennas using printing technology have been reported, they showed only low gain. Specifically, they only had a maximum gain of 1.7 dBi and low radiation efficiency. This shortcoming is due to the high sheet resistance of the transparent electrodes typically used with printed structures. Recently, transparent antennas that use a metal mesh (which is both transparent and features low sheet resistance) have been reported [214–217]. For example, the authors fabricated a metal mesh with a linewidth of 5 μm , achieving a sheet resistance of less than 0.18 Ω/sq and an optical transmittance exceeding 60 % [214,215]. On the other hand, the lowest sheet resistance of transparent electrodes used in transparent-antenna research using printing technology to date is only 1.1 Ω/sq . Therefore, more research is needed to reduce the sheet resistance while maintaining high optical transmittance when printing is applied.

Printing RF electronics is already transforming high-frequency applications using advanced hybrid materials, scalable manufacturing, and multifunctional design options. To enable even better performance, research in this field focuses on developing highly conductive inks, such as MXenes, graphene, metal nanomaterials, nanowires, and conductive polymers, to reduce resistive losses, as well as low-loss dielectric substrates and printable magnetic components. Advancements in high-performance printed antennas, including wideband and multiband designs for 5G, 6G, and IoT, are driving the development of next-generation communication systems. Moreover, transparent and flexible antennas are increasingly significant as they facilitate applications in wearable electronics, aerospace, and visually appealing technology. At the same time, efforts are being directed toward improving passive components such as filters, couplers, and high-Q inductors to increase RF circuit efficiency. In addition, advancements in energy harvesting technologies, including printed rectennas and wireless power systems, aim to power IoT devices and support sustainable electronics.

The combination of passive and active components on flexible substrates has opened new possibilities for printed RF systems. In order to create wearable and intelligent textile applications, researchers are aiming to develop fully integrated systems on foil that combine sensors, antennae, and communication circuits. High-frequency advancements are focused on millimetre-wave and terahertz technologies for telecommunications, radar, and high-resolution imaging. Reconfigurable components for electromagnetic manipulation, such as stimuli-responsive materials and printed metasurfaces, enable adaptive RF systems with enhanced functionality. Overall, large-scale production is becoming more feasible because of scalable manufacturing processes such as roll-to-roll printing and additive manufacturing, while the adoption of biodegradable materials supports sustainable practices and reduces environmental impact. Coupled with IoT integration, design optimisation, and lightweight solutions for aeronautical and satellite

communications, printed RF electronics have the potential to transform industries with innovative, cost-effective, and sustainable solutions.

CRedit authorship contribution statement

Prabhakar Jepiti: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Junghyeon Kim:** Writing – original draft, Investigation, Formal analysis, Conceptualization. **Sumin Bark:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **Sungjoon Lim:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research was supported by the National Research Foundation of Korea (NRF) grant, funded by the Korean government (MSIT: Ministry of Science and ICT) (2021R1A2C3005239, RS-2024-00405510).

Data availability

No data was used for the research described in the article.

References

- [1] D. Won, J. Bang, S.H. Choi, K.R. Pyun, S. Jeong, Y. Lee, S.H. Ko, Transparent Electronics for Wearable Electronics Application, *Chem. Rev.* 123 (2023) 9982–10078, <https://doi.org/10.1021/acs.chemrev.3c00139>.
- [2] D. McCoul, W. Hu, M. Gao, V. Mehta, Q. Pei, Recent advances in Stretchable and Transparent Electronic Materials, *Adv. Electron. Mater.* 2 (2016), <https://doi.org/10.1002/aem.201500407>.
- [3] D. Li, W.Y. Lai, Y.Z. Zhang, W. Huang, Printable Transparent Conductive Films for Flexible Electronics, *Adv. Mater.* 30 (2018), <https://doi.org/10.1002/adma.201704738>.
- [4] S. Pang, Y. Hernandez, X. Feng, K. Müllen, Graphene as transparent electrode material for organic electronics, *Adv. Mater.* 23 (2011) 2779–2795, <https://doi.org/10.1002/adma.201100304>.
- [5] L. Yu, C. Shearer, J. Shapter, Recent Development of Carbon Nanotube Transparent Conductive Films, *Chem. Rev.* 116 (2016) 13413–13453, <https://doi.org/10.1021/acs.chemrev.6b00179>.
- [6] A.A.F. Husain, W.Z.W. Hasan, S. Shafie, M.N. Hamidon, S.S. Pandey, A review of transparent solar photovoltaic technologies, *Renew. Sustain. Energy Rev.* 94 (2018) 779–791, <https://doi.org/10.1016/j.rser.2018.06.031>.
- [7] L. Meng, W. Wang, B. Xu, J. Qin, K. Zhang, H. Liu, Solution-Processed Flexible Transparent Electrodes for Printable Electronics, *ACS Nano* 17 (2023) 4180–4192, <https://doi.org/10.1021/acsnano.2c10999>.
- [8] T. Wang, K. Lu, Z. Xu, Z. Lin, H. Ning, T. Qiu, Z. Yang, H. Zheng, R. Yao, J. Peng, Recent developments in flexible transparent electrode, *Crystals (basel)* 11 (2021), <https://doi.org/10.3390/cryst11050511>.
- [9] Y. Hwang, H. Yim, K. Oh, J. Park, S. Kim, H.W. Jang, J.W. Choi, Highly conductive Ag-SiNx composite thin film anode engineering for transparent battery, *Compos. B Eng.* 262 (2023), <https://doi.org/10.1016/j.compositesb.2023.110829>.
- [10] Z. Nie, W. Yan, X. Han, H. Yu, Y. Zhang, M. Tian, X. Zhang, Y. Xiong, P. Cao, G. Zhang, Damage-free non-mechanical transfer strategy for highly transparent, stretchable embedded metallic micromesh electrodes, *Compos. B Eng.* 289 (2025), <https://doi.org/10.1016/j.compositesb.2024.111934>.
- [11] K.S. Lee, J. Shim, M. Park, H.Y. Kim, D.I. Son, Transparent nanofiber textiles with intercalated ZnO@graphene QD LEDs for wearable electronics, *Compos. B Eng.* 130 (2017) 70–75, <https://doi.org/10.1016/j.compositesb.2017.07.046>.
- [12] X. Yu, T.J. Marks, A. Facchetti, Metal oxides for optoelectronic applications, *Nat. Mater.* 15 (2016) 383–396, <https://doi.org/10.1038/nmat4599>.
- [13] W. Cao, J. Li, H. Chen, J. Xue, Transparent electrodes for organic optoelectronic devices: a review, *J. Photonics Energy* 4 (2014) 040990, <https://doi.org/10.1117/1.jpe.4.040990>.
- [14] C. Cui, S. Cui, L. Cui, The discovery of p-type transparent oxide semiconductors, 2004.
- [15] A. Facchetti, T.J. Marks, *Transparent Electronics From Synthesis to Applications* Edited by, n.d.
- [16] H. Hosono, D.C. Paine, D.S. Ginley, *Handbook of Transparent Conductors*, n.d.

- [17] J. Li, Q. Jiang, N. Yuan, J. Tang, A review on flexible and transparent energy storage system, *Materials* 11 (2018), <https://doi.org/10.3390/ma11112280>.
- [18] I. International Committee on Electromagnetic Safety SCC, IEEE Std C95.1™. 2005 IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz IEEE International Committee on Electromagnetic Safety (SCC39), 2006.
- [19] E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M.S. Alouini, R. Zhang, Wireless communications through reconfigurable intelligent surfaces, *IEEE Access* 7 (2019) 116753–116773, <https://doi.org/10.1109/ACCESS.2019.2935192>.
- [20] Q. Wu, R. Zhang, Towards Smart and Reconfigurable Environment: Intelligent reflecting Surface aided Wireless Network, *IEEE Commun. Mag.* 58 (2020) 106–112, <https://doi.org/10.1109/MCOM.001.1900107>.
- [21] L. Song, A.C. Myers, J.J. Adams, Y. Zhu, Stretchable and reversibly deformable radio frequency antennas based on silver nanowires, *ACS Appl. Mater. Interfaces* 6 (2014) 4248–4253, <https://doi.org/10.1021/am405972e>.
- [22] M. Grande, G.V. Bianco, D. Laneve, P. Capezzuto, V. Petruzzelli, M. Scalora, F. Prudeniano, G. Bruno, A. D'Orazio, Optically transparent wideband CVD graphene-based microwave antennas, *Appl. Phys. Lett.* 112 (2018), <https://doi.org/10.1063/1.5037409>.
- [23] R.B. Green, M. Guzman, N. Izyumskaya, B. Ullah, S. Hia, J. Pitchford, R. Timsina, V. Avrutin, U. Ozgur, H. Morkoc, N. Dhar, E. Topsakal, Optically transparent antennas and filters: a smart city concept to alleviate infrastructure and network capacity challenges, *IEEE Antennas Propag. Mag.* 61 (2019) 37–47, <https://doi.org/10.1109/MAP.2019.2907895>.
- [24] M. Gustafsson, A. Karlsson, A.P.P. Rebelo, B. Widenberg, Design of frequency selective windows for improved indoor outdoor communication, *IEEE Trans. Antennas Propag.* 54 (2006) 1897–1900, <https://doi.org/10.1109/TAP.2006.875926>.
- [25] G.I. Kiani, L.G. Olsson, A. Karlsson, K.P. Esselle, M. Nilsson, Cross-dipole bandpass frequency selective surface for energy-saving glass used in buildings, *IEEE Trans. Antennas Propag.* 59 (2011) 520–525, <https://doi.org/10.1109/TAP.2010.2096382>.
- [26] M. Mantash, A. Kesavan, T.A. Denidni, Highly Transparent Frequency Selective Surface based on Electrotetextiles for On-Chip applications, *IEEE Antennas Wirel. Propag. Lett.* 18 (2019) 2351–2354, <https://doi.org/10.1109/LAWP.2019.2931364>.
- [27] Y. Yang, W. Li, K.N. Salama, A. Shamim, Polarization Insensitive and Transparent Frequency Selective Surface for dual Band GSM Shielding, *IEEE Trans. Antennas Propag.* 69 (2021) 2779–2789, <https://doi.org/10.1109/TAP.2020.3032827>.
- [28] S.W. Kim, K.S. Kim, M. Park, W. Nah, D.U. Kim, C.R. Lee, S.B. Jung, J.W. Kim, 1.4 μm -Thick Transparent Radio Frequency Transmission Lines based on Instant Fusion of Polyethylene Terephthalate through Surface of Ag Nanowires, *Electron. Mater.* 14 (2018) 599–609, <https://doi.org/10.1007/s13391-018-0069-3>.
- [29] Y.J. Choi, S.C. Gong, D.C. Johnson, S. Gollledge, G.Y. Yeom, H.H. Park, Characteristics of the electromagnetic interference shielding effectiveness of Al-doped ZnO thin films deposited by atomic layer deposition, in: *Appl Surf Sci*, Elsevier B.V., 2013, pp. 92–97, <https://doi.org/10.1016/j.apsusc.2012.09.159>.
- [30] Y. Han, Y. Liu, L. Han, J. Lin, P. Jin, High-performance hierarchical graphene/metal-mesh film for optically transparent electromagnetic interference shielding, *Carbon* 115 (2017) 34–42, <https://doi.org/10.1016/j.carbon.2016.12.092>.
- [31] D.A. Lampasi, A. Tamburrano, S. Bellini, M. Tului, A. Albolino, M.S. Sarto, Effect of grain size and distribution on the shielding effectiveness of transparent conducting thin films, *IEEE Trans. Electron. Comput.* 56 (2014) 352–359, <https://doi.org/10.1109/TEMC.2013.2282085>.
- [32] H. Wang, C. Ji, C. Zhang, Y. Zhang, Z. Zhang, Z. Lu, J. Tan, L.J. Guo, Highly Transparent and Broadband Electromagnetic Interference Shielding based on Ultrathin Doped Ag and Conducting Oxides Hybrid Film Structures, *ACS Appl. Mater. Interfaces* 11 (2019) 11782–11791, <https://doi.org/10.1021/acsami.9b00716>.
- [33] H. Sheokand, S. Ghosh, G. Singh, M. Saikia, K.V. Srivastava, J. Ramkumar, S. A. Ramakrishna, Transparent broadband metamaterial absorber based on resistive films, *J. Appl. Phys.* 122 (2017), <https://doi.org/10.1063/1.5001511>.
- [34] D. Yi, X.C. Wei, Y.L. Xu, Transparent Microwave Absorber based on Patterned Graphene: Design, Measurement, and Enhancement, *IEEE Trans Nanotechnol* 16 (2017) 484–490, <https://doi.org/10.1109/TNANO.2017.2688415>.
- [35] Y. Shen, J. Zhang, Y. Pang, J. Wang, H. Ma, S. Qu, Transparent broadband metamaterial absorber enhanced by water-substrate incorporation, *Opt. Express* 26 (2018) 15665, <https://doi.org/10.1364/oe.26.015665>.
- [36] A.R. Chishti, A. Aziz, M.A. Qureshi, M.N. Abbasi, A.M. Algarni, A. Zerguine, N. Hussain, R. Hussain, Optically Transparent Antennas: a Review of the State-of-the-Art, innovative Solutions and Future Trends, *Applied Sciences (switzerland)* 13 (2023), <https://doi.org/10.3390/app13010210>.
- [37] H. Qiu, H. Liu, X. Jia, Z.Y. Jiang, Y.H. Liu, J. Xu, T. Lu, M. Shao, T.L. Ren, K. J. Chen, Compact, flexible, and Transparent Antennas based on embedded Metallic Mesh for Wearable Devices in 5G Wireless Network, *IEEE Trans. Antennas Propag.* 69 (2021) 1864–1873, <https://doi.org/10.1109/TAP.2020.3035911>.
- [38] S. Bark, J. Kim, M. Lee, S. Lim, Optically Transparent Dual-Band Metamaterial Absorber using Ag Nanowire Screen-Printed Second-Order Cross-Fractal Structures, *Fractal and Fractional* 8 (2024), <https://doi.org/10.3390/fractalfract8030153>.
- [39] A. Desai, T. Upadhyaya, J. Patel, R. Patel, M. Palandoken, Flexible CPW fed transparent antenna for WLAN and sub-6 GHz 5G applications, *Microw. Opt. Technol. Lett.* 62 (2020) 2090–2103, <https://doi.org/10.1002/mop.32287>.
- [40] M. Hussain, H. Zahra, S.M. Abbas, Y. Zhu, Flexible Dielectric Materials: potential and applications in Antennas and RF Sensors, *Adv. Electron. Mater.* (2024), <https://doi.org/10.1002/aelm.202400240>.
- [41] J. Kim, P. Jepiti, M. Lee, E. Park, R. Phon, S. Lim, Screen-printing high/low resistance using only a single silver nanowire ink: Resistance-gradient metasurface application for broadband microwave absorption and optical transparency, *Mater. Des.* 247 (2024), <https://doi.org/10.1016/j.matdes.2024.113451>.
- [42] F.C. Krebs, Fabrication and processing of polymer solar cells: a review of printing and coating techniques, *Sol. Energy Mater. Sol. Cells* 93 (2009) 394–412, <https://doi.org/10.1016/j.solmat.2008.10.004>.
- [43] W. Wu, Inorganic nanomaterials for printed electronics: a review, *Nanoscale* 9 (2017) 7342–7372, <https://doi.org/10.1039/c7nr01604b>.
- [44] Z.J. Silva, C.R. Valenta, G.D. Durgin, Optically Transparent Antennas: a Survey of Transparent Microwave Conductor Performance and applications, *IEEE Antennas Propag. Mag.* 63 (2021) 27–39, <https://doi.org/10.1109/MAP.2020.2988526>.
- [45] S.W. Kim, K. Kim, W. Nah, C.R. Lee, S.B. Jung, J.W. Kim, Transparent and flexible high frequency transmission lines based on composite structure comprising silver nanowires and polyvinyl butyral, *Compos. Sci. Technol.* 159 (2018) 25–32, <https://doi.org/10.1016/j.compscitech.2018.02.023>.
- [46] L.C. Jia, D.X. Yan, X. Liu, R. Ma, H.Y. Wu, Z.M. Li, Highly Efficient and Reliable Transparent Electromagnetic Interference Shielding Film, *ACS Appl. Mater. Interfaces* 10 (2018) 11941–11949, <https://doi.org/10.1021/acsami.8b00492>.
- [47] W. Li, S. Yang, A. Shamim, Screen printing of silver nanowires: balancing conductivity with transparency while maintaining flexibility and stretchability, *npj Flexible Electron.* 3 (2019), <https://doi.org/10.1038/s41528-019-0057-1>.
- [48] J. Jung, H. Lee, I. Ha, H. Cho, K.K. Kim, J. Kwon, P. Won, S. Hong, S.H. Ko, Highly Stretchable and Transparent Electromagnetic Interference Shielding Film based on Silver Nanowire Percolation Network for Wearable Electronics applications, *ACS Appl. Mater. Interfaces* 9 (2017) 44609–44616, <https://doi.org/10.1021/acsami.7b14626>.
- [49] B.S. Kim, K.Y. Shin, J.B. Pyo, J. Lee, J.G. Son, S.S. Lee, J.H. Park, Reversibly Stretchable, Optically Transparent Radio-Frequency Antennas based on Wavy Ag Nanowire Networks, *ACS Appl. Mater. Interfaces* 8 (2016) 2582–2590, <https://doi.org/10.1021/acsami.5b10317>.
- [50] W. Li, E. Yarali, A. Bakytbekov, T.D. Anthopoulos, A. Shamim, Highly transparent and conductive electrodes enabled by scalable printing-and-sintering of silver nanowires, *Nanotechnology* 31 (2020), <https://doi.org/10.1088/1361-6528/ab9c53>.
- [51] G.M. Weng, J. Li, M. Alhabeb, C. Karpovich, H. Wang, J. Lipton, K. Maleski, J. Kong, E. Shaulsky, M. Elimelech, Y. Gogotsi, A.D. Taylor, Layer-by-Layer Assembly of Cross-Functional Semi-transparent MXene-Carbon Nanotubes Composite Films for Next-Generation Electromagnetic Interference Shielding, *Adv. Funct. Mater.* 28 (2018), <https://doi.org/10.1002/adfm.201803360>.
- [52] I. Puchades, J.E. Rossi, C.D. Cress, E. Naglich, B.J. Landi, Carbon Nanotube Thin-Film Antennas, *ACS Appl. Mater. Interfaces* 8 (2016) 20986–20992, <https://doi.org/10.1021/acsami.6b05146>.
- [53] S. Sadat, M. Shokooh-Saremi, M.M. Mirsalehi, M.M. Bagheri-Mohagheghi, Electromagnetic characterisation of multi-wall carbon nanotube-doped fluorine tin oxide for transparent antenna applications, *IET Microwaves Antennas Propag.* 13 (2019) 859–863, <https://doi.org/10.1049/iet-map.2018.5877>.
- [54] K. Guerchouche, E. Herth, L.E. Calvet, N. Roland, C. Loyez, Conductive polymer based antenna for wireless green sensors applications, *Microelectron. Eng.* 182 (2017) 46–52, <https://doi.org/10.1016/j.mee.2017.08.007>.
- [55] H. Rmili, J.L. Miane, H. Zangar, T. Olinga, Design of microstrip-fed proximity-coupled conducting-polymer patch antenna, *Microw. Opt. Technol. Lett.* 48 (2006) 655–660, <https://doi.org/10.1002/mop.21435>.
- [56] W. Li, Z. Akhter, M. Vaseem, A. Shamim, Optically Transparent and Flexible Radio Frequency Electronics through Printing Technologies, *Adv. Mater. Technol.* 7 (2022), <https://doi.org/10.1002/admt.202101277>.
- [57] E.R. Escobar, N.J. Kirsch, G. Kontopidis, B. Turner, 5.5 GHz optically transparent mesh wire microstrip patch antenna, *Electron. Lett.* 51 (2015) 1220–1222, <https://doi.org/10.1049/el.2015.1594>.
- [58] C. Ding, L. Liu, K.M. Luk, An optically transparent dual-polarized stacked patch antenna with metal-mesh films, *IEEE Antennas Wirel. Propag. Lett.* 18 (2019) 1981–1985, <https://doi.org/10.1109/LAWP.2019.2935694>.
- [59] K. Skarżyński, M. Słoma, Printed Electronics in Radiofrequency Energy Harvesters and Wireless Power transfer Rectennas for IoT applications, *Adv. Electron. Mater.* 9 (2023), <https://doi.org/10.1002/aelm.202300238>.
- [60] A. Eid, J. Hester, Y. Fang, B. Tehrani, S.A. Nauroze, R. Bahr, M.M. Tentzeris, Nanotechnology-Empowered Flexible Printed Wireless Electronics: a Review of Various applications of Printed Materials, *IEEE Nanotechnol. Mag.* 13 (2019) 18–29, <https://doi.org/10.1109/MNANO.2018.2869233>.
- [61] A.S.M. Sayem, A. Lalbakhsh, K.P. Esselle, J.L. Buckley, B. O'Flynn, R.B.V. B. Simorangkir, Flexible Transparent Antennas: Advancements, challenges, and prospects, *IEEE Open Journal of Antennas and Propagation* 3 (2022) 1109–1133, <https://doi.org/10.1109/OJAP.2022.3206909>.
- [62] X. Zhou, L. Ren, Z. Song, G. Li, J. Zhang, B. Li, Q. Wu, W. Li, L. Ren, Q. Liu, Advances in 3D/4D printing of mechanical metamaterials: from manufacturing to applications, *Compos. B Eng.* 254 (2023), <https://doi.org/10.1016/j.compositesb.2023.110585>.
- [63] K. Markandan, C.Q. Lai, Fabrication, properties and applications of polymer composites additively manufactured with filler alignment control: a review, *Compos. B Eng.* 256 (2023), <https://doi.org/10.1016/j.compositesb.2023.110661>.

- [64] H. Zhai, X. Li, S. Yu, J. Wang, Y. Chang, J. Li, X. Cheng, L. Zhou, Y. Fang, T. Liu, X. Yu, M. Zhu, B. Li, W. Li, Review on the 3D printing technology and application of magnetic materials: Material-Process-Structure-Application, *Compos B Eng* (2025) 112387, <https://doi.org/10.1016/j.compositesb.2025.112387>.
- [65] B. Chen, Y. Jia, F. Narita, H. Kurita, Y. Shi, Screen-printed piezoelectric composites for vibrational energy harvesting in combination with structural composite laminates for powering a sensing node, *Compos. B Eng.* 273 (2024), <https://doi.org/10.1016/j.compositesb.2024.111274>.
- [66] B. Zhang, X. Pei, P. Song, H. Sun, H. Li, Y. Fan, Q. Jiang, C. Zhou, X. Zhang, Porous bioceramics produced by inkjet 3D printing: effect of printing ink formulation on the ceramic macro and micro porous architectures control, *Compos. B Eng.* 155 (2018) 112–121, <https://doi.org/10.1016/j.compositesb.2018.08.047>.
- [67] X. Qi, J. Zhou, X. Zhu, H. Li, G. Zhang, L. Sun, R. Wang, Y. Huang, W. Yang, Y. F. Zhang, Z. Li, H. Zhang, J. Zhao, Q. Xu, H. Lan, Microscale hybrid 3D printed ultrahigh aspect ratio embedded silver mesh for flexible transparent electrodes, *Mater. Today Phys.* 33 (2023), <https://doi.org/10.1016/j.mtphys.2023.101044>.
- [68] Y. Zhang, L. Chen, M. Xie, Z. Zhan, D. Yang, P. Cheng, H. Duan, Q. Ge, Z. Wang, Ultra-fast programmable human-machine interface enabled by 3D printed degradable conductive hydrogel, *Mater. Today Phys.* 27 (2022), <https://doi.org/10.1016/j.mtphys.2022.100794>.
- [69] H. Wang, T.N. Lamichhane, M.P. Paranthaman, Review of additive manufacturing of permanent magnets for electrical machines: a prospective on wind turbine, *Mater. Today Phys.* 24 (2022), <https://doi.org/10.1016/j.mtphys.2022.100675>.
- [70] Z. Peng, Z. Zhai, R. Yang, H. Xu, Y. Wu, Fabrication and property research of a new 3D-printable magnetorheological elastomer (MRE), *Mater. Today Phys.* 45 (2024), <https://doi.org/10.1016/j.mtphys.2024.101467>.
- [71] M. Choi, Y.J. Park, B.K. Sharma, S.-R. Bae, S.Y. Kim, J.-H. Ahn, Flexible active-matrix organic light-emitting diode display enabled by MoS₂ thin-film transistor, 2018, <https://www.science.org>.
- [72] S. Niu, N. Matsuhisa, L. Beker, J. Li, S. Wang, J. Wang, Y. Jiang, X. Yan, Y. Yun, W. Burnett, A.S.Y. Poon, J.B.H. Tok, X. Chen, Z. Bao, A wireless body area sensor network based on stretchable passive tags, *Nat. Electron.* 2 (2019) 361–368, <https://doi.org/10.1038/s41928-019-0286-2>.
- [73] E. Sowade, E. Ramon, K.Y. Mitra, C. Martínez-Domingo, M. Pedró, J. Pallarès, F. Loffredo, F. Villani, H.L. Gomes, L. Terés, R.R. Baumann, All-inkjet-printed thin-film transistors: Manufacturing process reliability by root cause analysis, *Sci. Rep.* 6 (2016), <https://doi.org/10.1038/srep33490>.
- [74] S. Bellani, E. Petroni, A.E. Del Rio Castillo, N. Curreli, B. Martín-García, R. Oropesa-Núñez, M. Prato, F. Bonaccorso, Scalable production of Graphene Inks via Wet-Jet Milling Exfoliation for Screen-Printed Micro-Supercapacitors, *Adv. Funct. Mater.* 29 (2019), <https://doi.org/10.1002/adfm.201807659>.
- [75] S. Nam, M. Song, D.H. Kim, B. Cho, H.M. Lee, J.D. Kwon, S.G. Park, K.S. Nam, Y. Jeong, S.H. Kwon, Y.C. Park, S.H. Jin, J.W. Kang, S. Jo, C.S. Kim, Ultrasoft, extremely deformable and shape recoverable Ag nanowire embedded transparent electrode, *Sci. Rep.* 4 (2014), <https://doi.org/10.1038/srep04788>.
- [76] Y. Khan, F.J. Pavinatto, M.C. Lin, A. Liao, S.L. Swisher, K. Mann, V. Subramanian, M.M. Maharbiz, A.C. Arias, Inkjet-Printed Flexible Gold Electrode Arrays for Bioelectronic Interfaces, *Adv. Funct. Mater.* 26 (2016) 1004–1013, <https://doi.org/10.1002/adfm.201503316>.
- [77] Y. Wang, Y. Huang, Y. ze Li, P. Cheng, S. yuan Cheng, Q. Liang, Z. quan Xu, H. jun Chen, Z. sheng Feng, A facile process combined with roll-to-roll flexographic printing and electroless deposition to fabricate RFID tag antenna on paper substrates, *Compos B Eng* 224 (2021), <https://doi.org/10.1016/j.compositesb.2021.109194>.
- [78] P. Galliker, J. Schneider, H. Eghlidi, S. Kress, V. Sandoghdar, D. Poulidakos, Direct printing of nanostructures by electrostatic autofocussing of ink nanodroplets, *Nat. Commun.* 3 (2012), <https://doi.org/10.1038/ncomms1891>.
- [79] Y. Kim, S. Jang, J.H. Oh, High-resolution electrohydrodynamic printing of silver nanoparticle ink via commercial hypodermic needles, *Appl. Phys. Lett.* 106 (2015), <https://doi.org/10.1063/1.4905387>.
- [80] G. Miskovic, R. Kaufhold, Additive Manufacturing for Nano-Feature applications: Electrohydrodynamic Printing as a Next-Generation Enabling Technology, *IEEE Open Journal of Nanotechnology* 3 (2022) 191–198, <https://doi.org/10.1109/OJNANO.2022.3224229>.
- [81] S. Khan, L. Lorenzelli, R.S. Dahiya, Technologies for printing sensors and electronics over large flexible substrates: a review, *IEEE Sens. J.* 15 (2015) 3164–3185, <https://doi.org/10.1109/JSEN.2014.2375203>.
- [82] E. Cantatore, ed., *Applications of Organic and Printed Electronics*, Springer US, Boston, MA, 2013, <https://doi.org/10.1007/978-1-4614-3160-2>.
- [83] W.J. Hyun, E.B. Secor, M.C. Hersam, C.D. Frisbie, L.F. Francis, High-resolution patterning of graphene by screen printing with a silicon stencil for highly flexible printed electronics, *Adv. Mater.* 27 (2015) 109–115, <https://doi.org/10.1002/adma.201404133>.
- [84] M. Hösel, R.R. Søndergaard, M. Jørgensen, F.C. Krebs, Comparison of UV-curing, hotmelt, and pressure sensitive adhesive as roll-to-roll encapsulation methods for polymer solar cells, *Adv. Eng. Mater.* 15 (2013) 1068–1075, <https://doi.org/10.1002/adem.201300172>.
- [85] N.J. Wilkinson, M.A.A. Smith, R.W. Kay, R.A. Harris, A review of aerosol jet printing—a non-traditional hybrid process for micro-manufacturing, *Int. J. Adv. Manuf. Technol.* 105 (2019) 4599–4619, <https://doi.org/10.1007/s00170-019-03438-2>.
- [86] H. Abdulmaleki, P. Kidmose, S. Agarwala, Droplet-based Techniques for Printing of Functional Inks for Flexible Physical Sensors, *Adv. Mater.* 33 (2021), <https://doi.org/10.1002/adma.202006792>.
- [87] F. Mattei, D. Vurro, D. Spoltore, M. Pavesi, P.R. Kalvani, S. Pasini, G. Foti, P. D'Angelo, A. Bosio, A. Baraldi, F. Mezzadri, P. Mazzolini, S. Vantaggio, M. Bosi, L. Seravalli, G. Taraballa, A. Parisini, R. Fornari, Planar hybrid UV-C photodetectors based on aerosol-jet printed PEDOT:PSS on different Ga₂O₃ thin films, *Mater. Today Phys.* 51 (2025), <https://doi.org/10.1016/j.mtphys.2025.101663>.
- [88] Y. Wei, R. Torah, Y. Li, J. Tudor, Dispenser printed capacitive proximity sensor on fabric for applications in the creative industries, *Sens Actuators A Phys* 247 (2016) 239–246, <https://doi.org/10.1016/j.sna.2016.06.005>.
- [89] C.C. Ho, J.W. Evans, P.K. Wright, Direct write dispenser printing of a zinc microbattery with an ionic liquid gel electrolyte, *J. Micromech. Microeng.* 20 (2010), <https://doi.org/10.1088/0960-1317/20/10/104009>.
- [90] M. De Vos, R. Torah, J. Tudor, Dispenser printed electroluminescent lamps on textiles for smart fabric applications, *Smart Mater. Struct.* 25 (2016), <https://doi.org/10.1088/0964-1726/25/4/045016>.
- [91] M. Pudas, J. Hagberg, S. Leppävuori, Printing parameters and ink components affecting ultra-fine-line gravure-offset printing for electronics applications, *J. Eur. Ceram. Soc.* 24 (2004) 2943–2950, <https://doi.org/10.1016/j.jeurceramsoc.2003.11.011>.
- [92] K.H. Shin, H.A.D. Nguyen, J. Park, D. Shin, D. Lee, Roll-to-roll gravure printing of thick-film silver electrode micropatterns for flexible printed circuit board, *J. Coat. Technol. Res.* 14 (2017) 95–106, <https://doi.org/10.1007/s11998-016-9844-y>.
- [93] Y.Y. Kim, T.Y. Yang, R. Suhonen, M. Välimäki, T. Maaninen, A. Kempainen, N. J. Jeon, J. Seo, Gravure-Printed Flexible Perovskite Solar Cells: Toward Roll-to-Roll Manufacturing, *Adv. Sci.* 6 (2019), <https://doi.org/10.1002/advs.201802094>.
- [94] D.P. Banks, C. Grivas, J.D. Mills, R.W. Eason, I. Zergioti, Nanodroplets deposited in microarrays by femtosecond Ti:sapphire laser-induced forward transfer, *Appl. Phys. Lett.* 89 (2006), <https://doi.org/10.1063/1.2386921>.
- [95] M. Kandyla, S. Chatzandroulis, I. Zergioti, Laser Induced Forward Transfer of Conducting Polymers (2010), <https://doi.org/10.2478/s11772-010-0045-4>.
- [96] C.W. Visser, R. Pohl, C. Sun, G.W. Römer, B. Huis In 't Veld, D. Lohse, Toward 3D Printing of Pure Metals by Laser-Induced Forward Transfer, *Advanced Materials* 27 (2015) 4087–4092, <https://doi.org/10.1002/adma.201501058>.
- [97] N. Kooy, K. Mohamed, L.T. Pin, O.S. Guan, A review of roll-to-roll nanoimprint lithography, 2014, <http://www.nanoscaleslett.com/content/9/1/320>.
- [98] M.D. Austin, H. Ge, W. Wu, M. Li, Z. Yu, D. Wasserman, S.A. Lyon, S.Y. Chou, Fabrication of 5 nm linewidth and 14 nm pitch features by nanoimprint lithography, *Appl. Phys. Lett.* 84 (2004) 5299–5301, <https://doi.org/10.1063/1.1766071>.
- [99] T.M. Lee, J.H. Noh, I. Kim, D.S. Kim, S. Chun, Reliability of gravure offset printing under various printing conditions, *J. Appl. Phys.* (2010), <https://doi.org/10.1063/1.3510466>.
- [100] A. Sneek, T. Makela, A. Alastalo, Reverse-offset for roll-to-roll high-resolution printing, *Flexible Printed Electron.* 3 (2018), <https://doi.org/10.1088/2058-8585/aa9f00>.
- [101] Y.M. Choi, J. Jo, E. Lee, Y. Jang, I. Kim, J.H. Park, C.M. Yang, W.C. Kim, T.M. Lee, S. Kwon, Reverse offset printing of transparent metal mesh electrodes using an imprinted disposable cliché, *Int. J. Precis. Eng. Manuf.* 16 (2015) 2347–2352, <https://doi.org/10.1007/s12541-015-0302-z>.
- [102] A. Sneek, H. Ailas, F. Gao, J. Leppäniemi, Reverse-Offset Printing of Polymer resist Ink for Micrometer-Level Patterning of Metal and Metal-Oxide Layers, *ACS Appl. Mater. Interfaces* 13 (2021) 41782–41790, <https://doi.org/10.1021/acsaami.1c08126>.
- [103] Y.T. Cho, Y. Jeong, Y.J. Kim, S. Kwon, S.H. Lee, K.Y. Kim, D. Kang, T.M. Lee, Printing speed and quality enhancement by controlling the surface energy of cliché in reverse offset printing, *Applied Sciences (switzerland)* 7 (2017), <https://doi.org/10.3390/app7121302>.
- [104] T. Cheng, Y.Z. Zhang, J.P. Yi, L. Yang, J.D. Zhang, W.Y. Lai, W. Huang, Inkjet-printed flexible, transparent and aesthetic energy storage devices based on PEDOT:PSS/Ag grid electrodes, *J Mater Chem A Mater* 4 (2016) 13754–13763, <https://doi.org/10.1039/c6ta05319j>.
- [105] D. Lim, S. Lim, Optically Transparent and Rollable Metafilm for Electromagnetic Absorption using Screen Printed Metal Mesh, *IEEE Antennas Wirel. Propag. Lett.* 24 (2025) 686–690, <https://doi.org/10.1109/LAWP.2024.3512587>.
- [106] A. Shimoni, S. Azoubel, S. Magdassi, Inkjet printing of flexible high-performance carbon nanotube transparent conductive films by “coffee ring effect”, *Nanoscale* 6 (2014) 11084–11089, <https://doi.org/10.1039/c4nr02133a>.
- [107] A. Capasso, A.E. Del Rio Castillo, H. Sun, A. Ansaldi, V. Pellegrini, F. Bonaccorso, Ink-jet printing of graphene for flexible electronics: an environmentally-friendly approach, *Solid State Commun* 224 (2015) 53–63, <https://doi.org/10.1016/j.ssc.2015.08.011>.
- [108] J. Liang, K. Tong, Q. Pei, A Water-based Silver Nanowire Screen Print Ink for Fabrication of A Stretchable Conductor and Wearable Thin Film Transistors, n.d.
- [109] W.J. Scheideler, J. Smith, I. Deckman, S. Chung, A.C. Arias, V. Subramanian, A robust, gravure-printed, silver nanowire/metal oxide hybrid electrode for high-throughput patterned transparent conductors, *J Mater Chem C Mater* 4 (2016) 3248–3255, <https://doi.org/10.1039/c5tc04364f>.
- [110] D.J. Finn, M. Lotya, J.N. Coleman, Inkjet printing of silver nanowire networks, *ACS Appl. Mater. Interfaces* 7 (2015) 9254–9261, <https://doi.org/10.1021/acsaami.5b01875>.
- [111] B. Deng, P.C. Hsu, G. Chen, B.N. Chandrashekar, L. Liao, Z. Ayitumuda, J. Wu, Y. Guo, L. Lin, Y. Zhou, M. Aisijiang, Q. Xie, Y. Cui, Z. Liu, H. Peng, Roll-to-Roll Encapsulation of Metal Nanowires between Graphene and Plastic Substrate for High-Performance Flexible Transparent Electrodes, *Nano Lett.* 15 (2015) 4206–4213, <https://doi.org/10.1021/acs.nanolett.5b01531>.

- [112] A. Singh, M. Katiyar, A. Garg, Understanding the formation of PEDOT:PSS films by ink-jet printing for organic solar cell applications, *RSC Adv.* 5 (2015) 78677–78685, <https://doi.org/10.1039/c5ra11032g>.
- [113] G. Haacke, New figure of merit for transparent conductors, *J. Appl. Phys.* 47 (1976) 4086–4089, <https://doi.org/10.1063/1.323240>.
- [114] N. Sharma, N.M. Nair, G. Nagasavari, D. Ray, P. Swaminathan, A review of silver nanowire-based composites for flexible electronic applications, *Flexible Printed Electron.* 7 (2022), <https://doi.org/10.1088/2058-8585/ac5214>.
- [115] A. Madeira, D.T. Papanastasiou, T. Toupance, L. Servant, M. Tréguer-Delapierre, D. Bellet, I.A. Goldthorpe, Rapid synthesis of ultra-long silver nanowires for high performance transparent electrodes, *Nanoscale Adv.* 2 (2020) 3804–3808, <https://doi.org/10.1039/d0na00032a>.
- [116] T.T. Nge, M. Nogi, K. Suganuma, Electrical functionality of inkjet-printed silver nanoparticle conductive tracks on nanostructured paper compared with those on plastic substrates, *J. Mater. Chem. C Mater* 1 (2013) 5235–5243, <https://doi.org/10.1039/c3tc31220h>.
- [117] J. Choi, D. Lim, S. Lim, Screen-Printed Metamaterial Absorber using Fractal Metal Mesh for Optical Transparency and Flexibility, *Fractal and Fractional* 8 (2024), <https://doi.org/10.3390/fractalfract8050284>.
- [118] H.S. Kim, S.R. Dhage, D.E. Shim, H.T. Hahn, Intense pulsed light sintering of copper nanoink for printed electronics, *Appl. Phys. A Mater. Sci. Process.* 97 (2009) 791–798, <https://doi.org/10.1007/s00339-009-5360-6>.
- [119] I. Reinhold, C.E. Hendriks, R. Eckardt, J.M. Kranenburg, J. Perelaer, R. Baumann, U.S. Schubert, Argon plasma sintering of inkjet printed silver tracks on polymer substrates, *J. Mater. Chem.* 19 (2009) 3384–3388, <https://doi.org/10.1039/b823329b>.
- [120] Y. Farraj, A. Smooha, A. Kamyshny, S. Magdassi, Plasma-Induced Decomposition of copper complex Ink for the Formation of Highly Conductive Copper Tracks on Heat-Sensitive Substrates, *ACS Appl. Mater. Interfaces* 9 (2017) 8766–8773, <https://doi.org/10.1021/acsami.6b14462>.
- [121] J. Perelaer, B.J. De Gans, U.S. Schubert, Ink-jet printing and microwave sintering of conductive silver tracks, *Adv. Mater.* 18 (2006) 2101–2104, <https://doi.org/10.1002/adma.200502422>.
- [122] S. Wünscher, R. Abbel, J. Perelaer, U.S. Schubert, Progress of alternative sintering approaches of inkjet-printed metal inks and their application for manufacturing of flexible electronic devices, *J. Mater. Chem. C Mater* 2 (2014) 10232–10261, <https://doi.org/10.1039/c4tc01820f>.
- [123] Q. Huang, Y. Zhu, Printing Conductive Nanomaterials for flexible and Stretchable Electronics: a Review of Materials, Processes, and applications, *Adv. Mater. Technol.* 4 (2019), <https://doi.org/10.1002/admt.201800546>.
- [124] O.R. Alobaidi, P. Chelvanathan, S.K. Tiong, B. Bais, M.A. Uzzaman, N. Amin, Transparent Antenna for Green Communication Feature: a Systematic Review on Taxonomy Analysis, Open challenges, Motivations, Future Directions and Recommendations, *IEEE Access* 10 (2022) 12286–12321, <https://doi.org/10.1109/ACCESS.2020.3044435>.
- [125] D. Ye, H. Xie, Y. Tian, J.M. Wen, Z.Y. Shi, K. An, Y.P. Zhang, Y.A. Huang, Electrohydrodynamic lithography of metallic mesh for optically transparent flexible and conformal antennas, *Sci. China Technol. Sci.* 66 (2023) 2–12, <https://doi.org/10.1007/s11431-022-2240-6>.
- [126] L.F. Engel, L. González-García, T. Kraus, Flexible and transparent electrodes imprinted from metal nanostructures: morphology and opto-electronic performance, *Nanoscale Adv.* 4 (2022) 3370–3380, <https://doi.org/10.1039/d2na00259k>.
- [127] W.K. Kim, S. Lee, D. Hee Lee, I. Hee Park, J. Seong Bae, T. Woo Lee, J.Y. Kim, J. Hun Park, Y. Chan Cho, C. Ryong Cho, S.Y. Jeong, Cu mesh for flexible transparent conductive electrodes, *Sci Rep* 5 (2015), <https://doi.org/10.1038/srep10715>.
- [128] Z. Chen, S. Yang, J. Huang, Y. Gu, W. Huang, S. Liu, Z. Lin, Z. Zeng, Y. Hu, Z. Chen, B. Yang, X. Gui, Flexible, Transparent and Conductive Metal Mesh Films with Ultra-High FoM for Stretchable heating and Electromagnetic Interference Shielding, *Nanomicro Lett* 16 (2024), <https://doi.org/10.1007/s40820-023-01295-z>.
- [129] M.N. Abbasi, A. Aziz, K. AlJaloud, A.R. Chishti, A.H. Alqahtani, D. Abbasi, F. A. Tahir, Z.U. Khan, R. Hussain, Design and optimization of a transparent and flexible MIMO antenna for compact IoT and 5G applications, *Sci. Rep.* 13 (2023), <https://doi.org/10.1038/s41598-023-47458-1>.
- [130] Y. Goliya, A. Rivadeneyra, J.F. Salmeron, A. Albrecht, J. Mock, M. Haider, J. Russer, B. Cruz, P. Eschlwech, E. Biebl, M. Becherer, M.R. Bobinger, Next Generation Antennas based on Screen-Printed and Transparent Silver Nanowire Films, *Adv. Opt. Mater.* 7 (2019), <https://doi.org/10.1002/adom.201900995>.
- [131] W. Li, A. Meredov, A. Shamim, Coat-and-print patterning of silver nanowires for flexible and transparent electronics, *npj Flexible Electron.* 3 (2019), <https://doi.org/10.1038/s41528-019-0063-3>.
- [132] N.M. Nair, J.K. Pakkathillam, K. Kumar, K. Arunachalam, D. Ray, P. Swaminathan, Printable Silver Nanowire and PEDOT:PSS Nanocomposite Ink for Flexible Transparent Conducting applications, *ACS Appl. Electron. Mater.* 2 (2020) 1000–1010, <https://doi.org/10.1021/acsaelm.0c00061>.
- [133] M. Vaseem, Z. Akhter, W. Li, E. Yarali, T.D. Anthopoulos, A. Shamim, High-conductivity screen-printable silver nanowire Ink for optically transparent flexible radio frequency electronics, *Flexible Printed Electron.* 7 (2022), <https://doi.org/10.1088/2058-8585/ac97a4>.
- [134] S. Glinsek, L. Song, M. Gerard, O. Bouton, S. Girod, M. El Hachemi, B. Mandal, E. Defay, T. Granzow, J. Polesel-Marais, Autonomous low-energy communication module based on inkjet-printed transparent antenna, *Cell Rep. Phys. Sci.* 4 (2023), <https://doi.org/10.1016/j.xcrp.2023.101685>.
- [135] P. Li, J. Fleischer, E. Quinn, D. Park, Fabrication of an Optically Transparent Planar Inverted-F Antenna using PEDOT-Based Silver Nanowire Clear Ink with Aerosol-Jet Printing Method towards Effective Antennas, *Journal of Manufacturing and Materials Processing* 8 (2024), <https://doi.org/10.3390/jmmp8010039>.
- [136] S.I. Hussain Shah, S. Lim, RF advancements enabled by smart shape memory materials in the microwave Regime: a state-of-the-art review, *Mater. Today Phys.* 44 (2024) 101435, <https://doi.org/10.1016/j.mtphys.2024.101435>.
- [137] J. Liu, Z. Jia, Y. Dong, J. Li, X. Cao, G. Wu, Structural engineering and compositional manipulation for high-efficiency electromagnetic microwave absorption, *Mater. Today Phys.* 27 (2022) 100801, <https://doi.org/10.1016/j.mtphys.2022.100801>.
- [138] Z. Jia, D. Lan, M. Chang, Y. Han, G. Wu, Heterogeneous interfaces and 3D foam structures synergize to build superior electromagnetic wave absorbers, *Mater. Today Phys.* 37 (2023) 101215, <https://doi.org/10.1016/j.mtphys.2023.101215>.
- [139] H. Chen, H. Chen, X. Xiu, Q. Xue, W. Che, Transparent FSS on Glass Window for Signal selection of 5G Millimeter-Wave Communication, *IEEE Antennas Wirel. Propag. Lett.* 20 (2021) 2319–2323, <https://doi.org/10.1109/LAWP.2021.3110053>.
- [140] Z. Chen, Y. Li, Z. Wang, J. Hu, X. Yao, Energy-Saving Glass Loading Dual-Band Miniaturized FSS for RF Shielding with High Oblique Stability and Optical Transparency, *IEEE Trans. Electromagn. Compat.* 66 (2024) 1094–1103, <https://doi.org/10.1109/TEMC.2024.3377253>.
- [141] D.J. King, K. Hettak, M.R. Chaharmir, S. Gupta, Flexible Ink-Minimized Screen-Printed Frequency Selective Surfaces with increased Optical Transparency for 5G Electromagnetic Interference Mitigation, *IEEE Trans Compon Packaging Manuf Technol* 13 (2023) 110–119, <https://doi.org/10.1109/TCPMT.2023.3235616>.
- [142] J.Y. Lai, Y.C. Lin, M.H. Lin, C.C. Chang, S.C. Lin, S.F. Chang, Design of Switchable, Polarization-Insensitive, Optically Transparent Window Film for Communication Security, *IEEE Antennas Wirel. Propag. Lett.* (2024), <https://doi.org/10.1109/LAWP.2024.3408641>.
- [143] N.I. Landy, S. Sajuyigbe, J.J. Mock, D.R. Smith, W.J. Padilla, Perfect metamaterial absorber, *Phys. Rev. Lett.* 100 (2008), <https://doi.org/10.1103/PhysRevLett.100.207402>.
- [144] H. Luo, Y. Xiong, Y.Z. Cheng, F. Chen, X.C. Li, Optical transparent metamaterial structure for microwave-infrared-compatible camouflage based on indium tin oxide, *Sci. China Technol. Sci.* 66 (2023) 2850–2861, <https://doi.org/10.1007/s11431-023-2450-0>.
- [145] Z. Li, Y. Cheng, H. Luo, F. Chen, X. Li, Dual-band tunable terahertz perfect absorber based on all-dielectric InSb resonator structure for sensing application, *J. Alloys Compd.* 925 (2022), <https://doi.org/10.1016/j.jallcom.2022.166617>.
- [146] Y. Zhang, H. Dong, N. Mou, H. Li, X. Yao, L. Zhang, Tunable and transparent broadband metamaterial absorber with water-based substrate for optical window applications, *Nanoscale* 13 (2021) 7831–7837, <https://doi.org/10.1039/d0nr08640a>.
- [147] Y. Zhang, H. Dong, N. Mou, L. Chen, R. Li, L. Zhang, High-performance broadband electromagnetic interference shielding optical window based on a metamaterial absorber, *Opt. Express* 28 (2020) 26836, <https://doi.org/10.1364/oe.401766>.
- [148] M.L. Hakim, A. Hanif, T. Alam, M.T. Islam, H. Arshad, M.S. Soliman, S. M. Albadran, M.S. Islam, Ultrawideband Polarization-Independent Nanoarchitectonics: a Perfect Metamaterial Absorber for Visible and Infrared Optical Window applications, *Nanomaterials* 12 (2022), <https://doi.org/10.3390/nano12162849>.
- [149] Y. Okano, S. Ogino, K. Ishikawa, Development of optically transparent ultrathin microwave absorber for ultrahigh-frequency RF identification system, *IEEE Trans. Microw. Theory Tech.* 60 (2012) 2456–2464, <https://doi.org/10.1109/TMTT.2012.2202680>.
- [150] S. Li, L. Liu, Y. Jiang, C. Tang, C. Gu, Z. Li, Ultrathin optically transparent metamaterial absorber for broadband microwave invisibility of solar panels, *J. Phys. D Appl. Phys.* 55 (2022), <https://doi.org/10.1088/1361-6463/ac2bcc>.
- [151] F.Y. Dong, S. Xu, W. Guo, N.R. Jiang, D.D. Han, X.Y. He, L. Zhang, Z.J. Wang, J. Feng, W. Su, H.B. Sun, Solar-energy camouflage coating with varying sheet resistance, *Nano Energy* 77 (2020), <https://doi.org/10.1016/j.nanoen.2020.105095>.
- [152] Y. Wu, Y. Deng, J. Wang, Z. Zong, X. Chen, W. Gu, THz Broadband Absorber Fabricated by EHD Printing Technology with High Error Tolerance, *IEEE Trans. Terahertz Sci. Technol.* 9 (2019) 637–642, <https://doi.org/10.1109/THZ.2019.2943564>.
- [153] H. Jeong, M.M. Tentzeris, S. Lim, Optically transparent metamaterial absorber using inkjet printing technology, *Materials* 12 (2019), <https://doi.org/10.3390/ma12203406>.
- [154] Y. Wu, C. Fu, S. Qian, Z. Zong, X. Wu, Y. Yue, W. Gu, Flexible and Transparent W-Band Absorber Fabricated by EHD Printing Technology, *IEEE Antennas Wirel. Propag. Lett.* 19 (2020) 1345–1349, <https://doi.org/10.1109/LAWP.2020.3000786>.
- [155] D. Lim, S. Lim, Optically Transparent and Rollable Metafilm for Electromagnetic Absorption using Screen Printed Metal Mesh, *IEEE Antennas Wirel. Propag. Lett.* (2024) 1–5, <https://doi.org/10.1109/LAWP.2024.3512587>.
- [156] A. Desai, T. Upadhyaya, R. Patel, Compact wideband transparent antenna for 5G communication systems, *Microw. Opt. Technol. Lett.* 61 (2019) 781–786, <https://doi.org/10.1002/mop.31601>.
- [157] A. Desai, C.D. Bui, J. Patel, T. Upadhyaya, G. Byun, T.K. Nguyen, Compact wideband four element optically transparent MIMO antenna for mm-wave 5G applications, *IEEE Access* 8 (2020) 194206–194217, <https://doi.org/10.1109/ACCESS.2020.3033314>.

- [158] R.B. Green, K. Ding, V. Avrutin, U. Ozgur, E. Topsakal, Optically Transparent Antenna Arrays for the Next Generation of Mobile Networks, *IEEE Open Journal of Antennas and Propagation* 3 (2022) 538–548, <https://doi.org/10.1109/OJAP.2022.3171322>.
- [159] A. Desai, M. Palandoken, J. Kulkarni, G. Byun, T.K. Nguyen, Wideband Flexible/Transparent Connected-Ground MIMO Antennas for Sub-6 GHz 5G and WLAN applications, *IEEE Access* 9 (2021) 147003–147015, <https://doi.org/10.1109/ACCESS.2021.3123366>.
- [160] A. Desai, M. Palandoken, I. Elfergani, I. Akdag, C. Zebiri, J. Bastos, J. Rodriguez, R.A. Abd-Alhameed, Transparent 2-Element 5G MIMO Antenna for Sub-6 GHz applications, *Electronics (switzerland)* 11 (2022) 1–20, <https://doi.org/10.3390/electronics11020251>.
- [161] J. Hautcoeur, L. Talbi, K. Hettak, M. Nedil, 60 GHz optically transparent microstrip antenna made of meshed AuGL material, *IET Microwaves Antennas Propag.* 8 (2014) 1091–1096, <https://doi.org/10.1049/iet-map.2013.0564>.
- [162] Z. Weng, J. Liu, Y. Su, X. Wang, B. Yan, A broadband transparent antenna applied in indoor mobile communication system, *Microw. Opt. Technol. Lett.* 66 (2024) 1–7, <https://doi.org/10.1002/mop.34104>.
- [163] J.I. Trujillo-Flores, R. Torrealba-Meléndez, J.M. Muñoz-Pacheco, M.A. Vásquez-Agustín, E.I. Tamariz-Flores, E. Colín-Beltrán, M. López-López, CPW-fed transparent antenna for vehicle communications, *Applied Sciences (switzerland)* 10 (2020) 1–11, <https://doi.org/10.3390/app10176001>.
- [164] A.S. Thampy, S.K. Dhamodharan, Performance analysis and comparison of ITO- and FTO-based optically transparent terahertz U-shaped patch antennas, *Physica E Low Dimens Syst Nanostruct* 66 (2015) 52–58, <https://doi.org/10.1016/j.physe.2014.09.016>.
- [165] A. Anisha, D. Sriram Kumar, Performance analysis of Ta4C3 MXene based optically transparent patch antenna for terahertz communications, *Optik (stuttgart)* (2022) 168959, <https://doi.org/10.1016/j.jiloe.2022.168959>.
- [166] J.H. Lee, S.H. Lee, D. Kim, C.W. Jung, Transparent dual-band monopole antenna using a μ -metal mesh on the rear glass of an automobile for frequency modulation/digital media broadcasting service receiving, *Microw. Opt. Technol. Lett.* 61 (2019) 503–508, <https://doi.org/10.1002/mop.31567>.
- [167] W. Hong, S. Lim, S. Ko, Y.G. Kim, Optically Invisible Antenna Integrated within an OLED Touch Display Panel for IoT applications, *IEEE Trans. Antennas Propag.* 65 (2017) 3750–3755, <https://doi.org/10.1109/TAP.2017.2705127>.
- [168] Y. Morimoto, S. Shiu, I.W. Huang, E. Fest, G. Ye, J. Zhu, Optically Transparent Antenna for Smart Glasses, *IEEE Open Journal of Antennas and Propagation* 4 (2023) 159–167, <https://doi.org/10.1109/OJAP.2023.3238721>.
- [169] M. Kashanianfard, K. Sarabandi, Vehicular Optically Transparent UHF Antenna for Terrestrial Communication, *IEEE Trans. Antennas Propag.* 65 (2017) 3942–3949, <https://doi.org/10.1109/TAP.2017.2717973>.
- [170] T.W. Turpin, R. Baktur, Meshed patch antennas integrated on solar cells, *IEEE Antennas Wirel. Propag. Lett.* 8 (2009) 693–696, <https://doi.org/10.1109/LAWP.2009.2025522>.
- [171] Y. Li, K.M. Luk, A Water Dense Dielectric Patch Antenna, *IEEE Access* 3 (2015) 274–280, <https://doi.org/10.1109/ACCESS.2015.2420103>.
- [172] S. Sheikh, M. Shokoh-Saremi, M.M. Bagheri-Mohagheghi, Transparent microstrip antenna made of fluorine doped tin oxide: a comprehensive study, *J Electromagn Waves Appl* 29 (2015) 1557–1569, <https://doi.org/10.1080/09205071.2015.1050528>.
- [173] M.A. Maged, F. Elhefnawi, H.M. Akah, H.M. El-Hennawy, C-Band Transparent Antenna Design for Intersatellites Communication, *Int. J. Sci. Eng. Res.* 9 (2018) 248–252.
- [174] M. El Halaoui, P. Dupuis, O. Pigaglio, A. Asselman, G. Zissis, L. Canale, Optically Transparent Honeycomb Mesh Antenna Integrated into OLED Light Source, *Electronics (switzerland)* 13 (2024) 1–17, <https://doi.org/10.3390/electronics13020289>.
- [175] J. Park, S.Y. Lee, J. Kim, D. Park, W. Choi, W. Hong, An Optically Invisible Antenna-on-Display Concept for Millimeter-Wave 5G Cellular Devices, *IEEE Trans. Antennas Propag.* 67 (2019) 2942–2952, <https://doi.org/10.1109/TAP.2019.2900399>.
- [176] Y.K. Chang Min Lee, Youngsung Kim, C.W.J. Il Kwon Kim, A Flexible And Transparent Antenna On A Polyamide Substrate For Laptop Computers, *Microw Opt Technol Lett* 57 (2015) 1038–1042, <https://doi.org/10.1002/mop>.
- [177] M. El Halaoui, L. Canale, P. Dupuis, A. Asselman, G. Zissis, An Optically Transparent Mesh-Antenna Integrated in OLEDs for WLAN applications, *Conference Record - IAS Annual Meeting (IEEE Industry Applications Society)* (2021-Octob (2021)) 1–6, <https://doi.org/10.1109/IAS48185.2021.9677344>.
- [178] M. Stanley, Y. Huang, H. Wang, H. Zhou, A. Alieldin, S. Joseph, A Transparent Dual-Polarized Antenna Array for 5G Smartphone applications, in: 2018 IEEE Antennas and Propagation Society International Symposium and USNC/URSI National Radio Science Meeting, 2018, pp. 635–636, <https://doi.org/10.1109/APUSNCURSINRSM.2018.8609096>.
- [179] S. Hong, S.H. Kang, Y. Kim, C.W. Jung, Transparent and Flexible Antenna for Wearable Glasses applications, *IEEE Trans. Antennas Propag.* 64 (2016) 2797–2804, <https://doi.org/10.1109/TAP.2016.2554626>.
- [180] A.S.M. Sayem, R.B.V.B. Simorangkir, K.P. Esselle, A. Lalbakhsh, D.R. Gawade, B. O'Flynn, J.L. Buckley, Flexible and Transparent Circularly Polarized Patch Antenna for Reliable Unobtrusive Wearable Wireless Communications, *Sensors* 22 (2022) 1–22, <https://doi.org/10.3390/s22031276>.
- [181] R.B.V.B. Simorangkir, D.R. Gawade, T. Hannon, P. Donovan, S. Kumar, N. Rather, G. Moloudian, B. O'Flynn, J.L. Buckley, Transparent Epidermal Antenna for Unobtrusive Human-Centric internet of things applications, *IEEE Internet Things J.* 11 (2024) 1164–1174, <https://doi.org/10.1109/IJOT.2023.3288994>.
- [182] J. Kim, M. Kim, M.S. Lee, K. Kim, S. Ji, Y.T. Kim, J. Park, K. Na, K.H. Bae, H. K. Kim, F. Bien, C.Y. Lee, J.U. Park, Wearable smart sensor systems integrated on soft contact lenses for wireless ocular diagnostics, *Nat. Commun.* 8 (2017) 14997, <https://doi.org/10.1038/ncomms14997>.
- [183] J. Park, J. Kim, S.-Y. Kim, W.H. Cheong, J. Jang, Y.-G. Park, K. Na, Y.-T. Kim, J. H. Heo, C.Y. Lee, J.H. Lee, F. Bien, J. Jang-Ung Park, Soft, Smart Contact Lenses with Integrations of Wireless Circuits, Glucose Sensors, and Displays, *Sci Adv* 4 (2018) 1–11, <https://www.science.org>.
- [184] Y. Zhang, Z. Huo, X. Wang, X. Han, W. Wu, B. Wan, H. Wang, J. Zhai, J. Tao, C. Pan, Z.L. Wang, High precision epidermal radio frequency antenna via nanofiber network for wireless stretchable multifunction electronics, *Nat. Commun.* 11 (2020) 1–10, <https://doi.org/10.1038/s41467-020-19367-8>.
- [185] N.J. Kirsch, N.A. Vacirca, E.E. Plowman, T.P. Kurzweg, A.K. Fontecchio, K. R. Dandekar, Optically transparent conductive polymer RFID meandering dipole antenna, in: 2009 IEEE International Conference on RFID, RFID, 2009 (2009), pp. 278–282, <https://doi.org/10.1109/RFID.2009.4911205>.
- [186] C.C. Serra, C.R. Medeiros, J.R. Costa, C.A. Fernandes, Mirror-integrated transparent antenna for RFID application, *IEEE Antennas Wirel. Propag. Lett.* 10 (2011) 776–779, <https://doi.org/10.1109/LAWP.2011.2163053>.
- [187] A. Vena, A.A. Babar, L. Sydanheimo, M.M. Tentzeris, L. Ukkonen, A novel near-transparent ask-reconfigurable inkjet-printed chipless RFID tag, *IEEE Antennas Wirel. Propag. Lett.* 12 (2013) 753–756, <https://doi.org/10.1109/LAWP.2013.2270932>.
- [188] Y. Yao, J. Yu, X. Chen, Study on the optically transparent near-field and far-field RFID reader antenna, *Int J Antennas Propag* 2014 (2014), <https://doi.org/10.1155/2014/149051>.
- [189] M.A. Malek, S. Hakimi, S.K. Abdul Rahim, A.K. Evizal, Dual-Band CPW-Fed Transparent Antenna for active RFID Tags, *IEEE Antennas Wirel. Propag. Lett.* 14 (2015) 919–922, <https://doi.org/10.1109/LAWP.2014.2387157>.
- [190] A.S.M. Sayem, D. Le, R.B.V.B. Simorangkir, T. Bjorninen, K.P. Esselle, R. M. Hashmi, M. Zhadobov, Optically Transparent Flexible Rotor Circularly Polarized Antenna for UHF RFID Tags, *IEEE Antennas Wirel. Propag. Lett.* 19 (2020) 2334–2338, <https://doi.org/10.1109/LAWP.2020.3032687>.
- [191] P. Zhang, X. Zhang, L. Li, An Optically Transparent Metantenna for RF Wireless Energy Harvesting, *IEEE Trans. Antennas Propag.* 70 (2022) 2550–2560, <https://doi.org/10.1109/TAP.2021.3137166>.
- [192] M.B. Arboleda, A. Shamim, Self-Powered and Cost-Effective Wireless Sensor Node for Air Quality monitoring with an Optically Transparent Smart Antenna System, *IEEE Sens. J.* 24 (2024) 28457–28471, <https://doi.org/10.1109/JSEN.2024.3435885>.
- [193] J. Hun, S. Chang, W. Jung, Design of Transparent Frequency Selective Surface on Window Glass for 5G Indoor Communications, (2024).
- [194] U. Farooq, A. Iftikhar, A.I. Najam, S.A. Khan, M.F. Shafique, An optically transparent dual-band frequency selective surface for polarization independent RF shielding, *Opt. Commun.* 546 (2023) 129824, <https://doi.org/10.1016/j.optcom.2023.129824>.
- [195] J.Y. Lai, Y.C. Lin, M.H. Lin, C.C. Chang, S.C. Lin, S.F. Chang, Design of Switchable, Polarization-Insensitive, Optically Transparent Window Film for Communication Security, *IEEE Antennas Wirel Propag Lett* 23 (2024) 2807–2811, <https://doi.org/10.1109/LAWP.2024.3408641>.
- [196] A.A. Dewani, S.G. O'Keefe, D.V. Thiel, A. Gahedhar, Window RF Shielding Film using Printed FSS, *IEEE Trans. Antennas Propag.* 66 (2018) 790–796, <https://doi.org/10.1109/TAP.2017.2780893>.
- [197] Y. Yang, W. Li, A. Shamim, in: Polarization Insensitive and Transparent FSS for Flexible Electronics Applications, 2020, pp. 953–954, <https://doi.org/10.1109/IEEECONF35879.2020.9330398>.
- [198] Y. Solunke, D. Patanvariya, A. Kothari, A Compact Transparent FSS for Tri-Band applications with Polarization Insensitive and RCS Reduction, 2024 IEEE Space, Aerospace and Defence Conference, SPACE 2024 (2024) 760–763, <https://doi.org/10.1109/SPACE63117.2024.10668070>.
- [199] V. Sanphuang, W.G. Yeo, J.L. Volakis, N.K. Nahar, THz transparent metamaterials for enhanced spectroscopic and imaging measurements, *IEEE Trans. Terahertz Sci. Technol.* 5 (2015) 117–123, <https://doi.org/10.1109/THZ.2014.2362659>.
- [200] B. Kim, J. Oh, Characterization of Optically Transparent Two-Metal-Layered Refractive Metasurfaces for 6G Upper-Mid Outdoor-to-Indoor Communication, *IEEE Antennas and Propagation Society, AP-S International Symposium (digest)* (2024) 1363–1364, <https://doi.org/10.1109/AP-S/INC-USNC-URSI52054.2024.10686503>.
- [201] A. Bagheri, S. Danesh, F. Wang, S.E. Hosseinienejad, M. Khalily, R. Tafazoli, Enhancing 5G propagation into vehicles and buildings using optically transparent and polarisation insensitive metasurfaces over wide-incidence angles, *Sci. Rep.* 14 (2024) 1–14, <https://doi.org/10.1038/s41598-024-51447-3>.
- [202] B. Liu, Q. Wang, S. Pollin, TAIS: Transparent Amplifying Intelligent Surface for Indoor-To-Outdoor mmWave Communications, *IEEE Trans. Commun.* 72 (2024) 1223–1238, <https://doi.org/10.1109/TCOMM.2023.3328259>.
- [203] G. Oliveri, F. Zardi, G. Gottardi, A. Massa, Optically-Transparent EM Skins for Outdoor-to-Indoor mm-Wave Wireless Communications, *IEEE Access* 12 (2024) 65178–65191, <https://doi.org/10.1109/ACCESS.2024.3397186>.
- [204] M. Lee, J. Park, K. Kim, J. Kim, E. Park, S. Lim, Broadband and Wide-Incidence-Angle Transparent Metamaterial Absorber using Eight-Resistive-arm Cell, *IEEE Antennas Wirel. Propag. Lett.* 23 (2024) 1754–1758, <https://doi.org/10.1109/LAWP.2024.3368610>.
- [205] J.H. Pu, X.J. Zha, L.S. Tang, L. Bai, R.Y. Bao, Z.Y. Liu, M.B. Yang, W. Yang, Human Skin-inspired Electronic Sensor Skin with Electromagnetic Interference Shielding for the Sensation and Protection of Wearable Electronics, *ACS Appl. Mater. Interfaces* 10 (2018) 40880–40889, <https://doi.org/10.1021/acsami.8b15809>.

- [206] S. Han, J. Kim, S.M. Won, Y. Ma, D. Kang, Z. Xie, K.T. Lee, H.U. Chung, A. Banks, S. Min, S.Y. Heo, C.R. Davies, J.W. Lee, C.H. Lee, B.H. Kim, K. Li, Y. Zhou, C. Wei, X. Feng, Y. Huang, J.A. Rogers, Battery-free, wireless sensors for full-body pressure and temperature mapping, *Sci. Transl. Med.* 10 (2018), <https://doi.org/10.1126/scitranslmed.aan4950>.
- [207] D.T. Nguyen, Q. Zeng, X. Tian, P. Chia, C. Wu, Y. Liu, J.S. Ho, Ambient health sensing on passive surfaces using metamaterials, *Sci. Adv.* 10 (2024), <https://doi.org/10.1126/sciadv.adj6613>.
- [208] X. Zhu, K. Wu, X. Xie, S.W. Anderson, X. Zhang, A robust near-field body area network based on coaxially-shielded textile metamaterial, *Nat. Commun.* 15 (2024) 1–12, <https://doi.org/10.1038/s41467-024-51061-x>.
- [209] M. Mirhosseini, A. Sipahigil, M. Kalaei, O. Painter, Superconducting qubit to optical photon transduction, *Nature* 588 (2020) 599–603, <https://doi.org/10.1038/s41586-020-3038-6>.
- [210] Y. Xu, G. Huang, D.I. Santiago, I. Siddiqi, Radio frequency mixing modules for superconducting qubit room temperature control systems, *Rev. Sci. Instrum.* 92 (2021), <https://doi.org/10.1063/5.0055906>.
- [211] P. Jepiti, S. Yoon, J. Kim, Electromigration Reliability in Ag Lines Printed with Nanoparticle Inks: Implications for Printed Electronics, *ACS Appl. Nano Mater.* 5 (2022) 2569–2577, <https://doi.org/10.1021/acsanm.1c04144>.
- [212] G. Nagasarvari, N.M. Nair, S.D. Ranade, L. Neelakantan, P. Swaminathan, PDMS-metal oxide nanocomposites as transparent encapsulants for flexible electronic devices, *Flexible Printed Electron.* 8 (2023), <https://doi.org/10.1088/2058-8585/ad05d7>.
- [213] X. Xu, Y. Lu, C. Tang, Q. Sun, F. Huang, A simple technique to prevent electromigration damage in printed Ag thin wires, *Mater. Lett.* 225 (2018) 21–23, <https://doi.org/10.1016/j.matlet.2018.04.067>.
- [214] S. Hong, Y. Kim, C. Won Jung, Transparent Microstrip Patch Antennas with Multilayer and Metal-Mesh Films, *IEEE Antennas Wirel. Propag. Lett.* 16 (2017) 772–775, <https://doi.org/10.1109/LAWP.2016.2602389>.
- [215] P. Duy Tung, C.W. Jung, Optically Transparent Wideband Dipole and Patch External Antennas using Metal Mesh for UHD TV applications, *IEEE Trans. Antennas Propag.* 68 (2020), <https://doi.org/10.1109/TAP.2019.2950077>.
- [216] B. Wu, X.Y. Sun, H.R. Zu, H.H. Zhang, T. Su, Transparent Ultrawideband Halved Coplanar Vivaldi Antenna with Metal Mesh Film, *IEEE Antennas Wirel. Propag. Lett.* 21 (2022) 2532–2536, <https://doi.org/10.1109/LAWP.2022.3200455>.
- [217] P. Qin, Q. Wang, P. Zhang, G. Huang, Q. Li, B. Liu, L. Li, L. Gui, J. Liu, Z. Deng, A Highly Transparent Flexible Antenna based on Liquid Metal Mesh Film, *Int. J. RF Microwave Comput. Aided Eng.* 2023 (2023), <https://doi.org/10.1155/2023/6369944>.