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0-to-270° wide pattern reconfigurable antenna using 3D-Printed single quasi-yagi antenna with shape memory hinge

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ABSTRACT

This study presents a 0-to-270° wide-pattern reconfigurable antenna incorporating a shape memory hinge. The substrate is 3D-printed using a shape memory polymer (SMP) and high-temperature filaments, with stretchable silver ink applied via screen printing. To enable reconfiguration in response to thermal stimuli, the folding section is fabricated from SMP. Leveraging the end-fire radiation characteristics of a quasi-Yagi antenna, the shape memory hinge adjusts the radiation direction. The antenna's performance was evaluated at folding angles of -180° , -90° , 0° , and 90° . In the flat position (0°), the measured -10 dB bandwidth ranges from 4.26 to 5.48 GHz, with a peak gain of 4.01–7.49 dBi. The measured -10 dB bandwidths at $\alpha = -180^\circ$, -90° , and 90° are 4.22–5.45, 4.26–5.47, and 4.28–5.54 GHz, respectively, with corresponding peak gains of 3.22–6.72, 4.52–7.07, and 5.01–7.24 dBi. These results demonstrate a stable frequency response and gain across different folding angles. With its straightforward design and fabrication process, the proposed antenna enables beam direction adjustment over a wide angular range, offering a novel approach to pattern reconfigurable antennas.

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KEYWORDS

Pattern reconfigurable antenna; shape memory hinge; 3D printing; quasi-Yagi antenna; shape morphing

1. Introduction

With the advancement of wireless communication systems, the use of the frequency spectrum has expanded, leading to increased data transmission. However, this has also resulted in significant interference between transmitted and received signals, reducing communication stability. One extensively researched approach to mitigating interference and enhancing stability is the pattern reconfigurable antenna. Such antennas generate multiple beam radiation patterns from a single structure, either focusing the radiation beam in a specific direction to strengthen the signal or broadening the pattern to transmit signals in multiple directions [1–14]. By dynamically adjusting the radiation pattern, these antennas improve directivity, reduce interference, and enhance energy efficiency.

Commonly used pattern reconfigurable antennas rely on PIN diodes [1–7], varactor diodes [8,9], or radio-frequency microelectromechanical systems (RF-MEMS) [10–12]. However, these designs often involve complex fabrication processes and high production costs, along with the need for high isolation between switches. A

more recent approach [15–19] involves the use of shape memory materials (SMMs) and 3D printing to fabricate reconfigurable antennas, offering a promising alternative to conventional methods.

3D printing, introduced in the latter half of the twentieth century, has gained widespread adoption due to its cost efficiency, rapid production, and versatility across fields such as architecture, engineering, education, and medicine [20]. Various 3D printing processes utilise different materials, including fused deposition modelling (FDM), which employs polymers and composite filaments; selective laser melting, which uses metal powders; selective laser sintering, which utilises polymer and ceramic powders; and stereolithography (SLA), which employs polymer resins. Polymers play a key role in antenna fabrication and are widely used in FDM and SLA-based techniques [20,21]. Additionally, multimaterial 3D printing methods allow the simultaneous use of multiple materials in radio-frequency (RF) applications, falling into three main categories: vapour-based printing, material jetting-based printing, and material extrusion-based printing [22,23]. Among these, material extrusion-based printing, including

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techniques such as direct ink writing and dual or multi-FDM, has been widely applied in RF applications, including antennas and metasurfaces [18,24]. By incorporating multi-nozzle technology into conventional FDM printing, complex structures composed of different filaments can be fabricated [25].

The integration of 3D printing with SMMs has enabled the development of rigid structures that can alter their shape and performance over time or in response to external stimuli. SMMs are smart materials capable of returning to their original shape after deformation when exposed to stimuli such as temperature, current, light, pressure, stress, or magnetic fields [26,27]. This reversible shape memory effect is driven by phase transitions that allow temporary deformation while preserving the original structure [28]. Several materials exhibit shape-memory effects, including shape memory polymers (SMPs) [29–38], shape memory alloys (SMAs) [39–43], shape memory metals [44], shape memory ceramics [45,46], liquid-crystal elastomers [47], and hydrogels [48]. Among these, SMPs and SMAs have received considerable attention for their RF applications [49]. In RF systems, antennas [15–19,50–54], absorbers [24,55,56], and metasurfaces [57–59] incorporating SMAs and SMPs have been extensively studied. SMPs, in particular, are thermally responsive materials widely used in shape memory hinges and actuators [17,18,53] to enable pattern reconfigurability and frequency tuning in antennas.

The antenna proposed in this study is a pattern reconfigurable antenna that adjusts its radiation beam direction using a shape memory hinge, as shown in Figure 1. The antenna substrate is 3D-printed using high-temperature (HT) and SMP filaments. During fabrication, the HT core is encapsulated by SMP, while the hinge is printed entirely from SMP to enable thermal reconfigurability. Stretchable silver ink is then screen-printed onto both surfaces. To reconfigure the antenna, the SMP is heated above 70 °C, allowing it to be deformed under an external force. Once cooled, the antenna retains its shape until reheated, at which point it can be restored to its original configuration. In a previous study [60], a similar design demonstrated end-fire radiation characteristics, where the radiation direction was determined by the arrangement of the ground, driver, and director. The deformed antenna radiates in the direction set by its altered structure, and after heat application, the antenna can be adjusted to various angles using external forces, returning to its original shape when reheated. The frequency range and radiation pattern are verified through simulations and measurements.

The proposed antenna can be utilised in wireless communication systems such as the Internet of Things and is particularly suitable for wireless alert systems designed for specific temperature conditions. Conventional RF temperature sensors integrate SMM with the antenna or resonant circuit, where the SMM undergoes

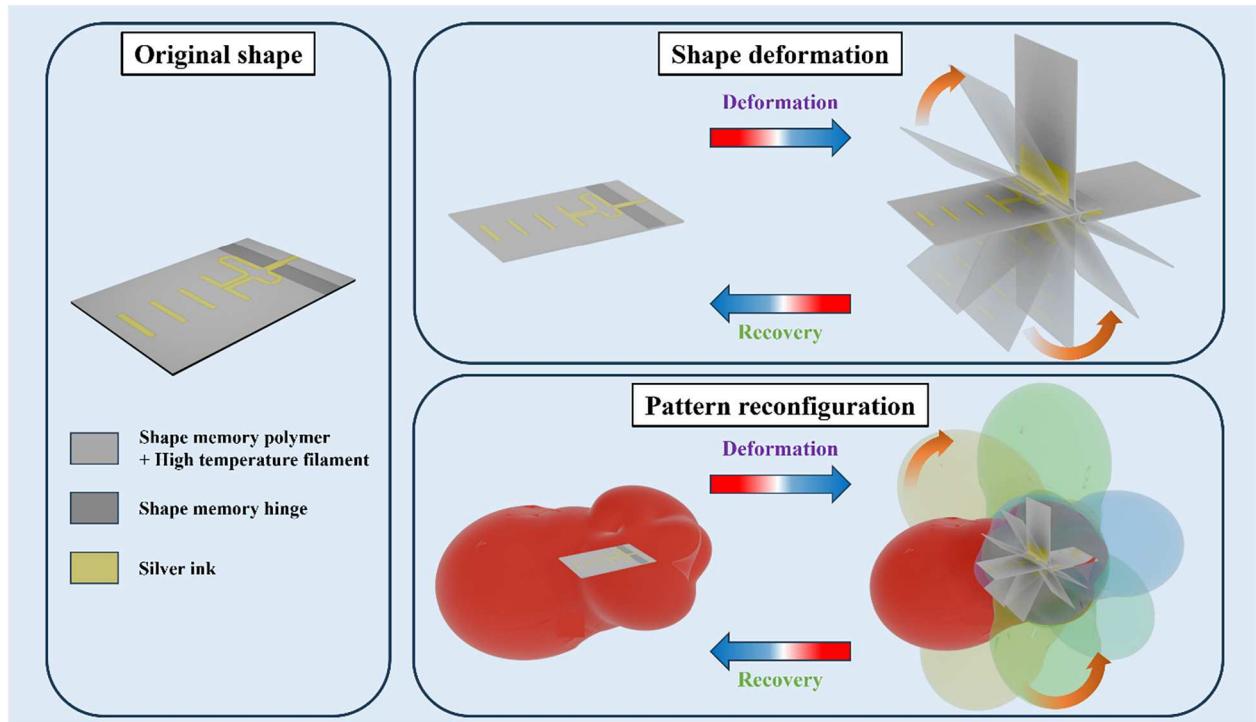


Figure 1. Conceptual illustration of the proposed wide-angle, pattern reconfigurable antenna utilising a shape memory hinge.

shape deformation in response to specific temperature changes [49]. The mechanical and dimensional changes of the SMM influence the resonant frequency and radiation pattern of the RF circuit [17,52,59]. Such characteristics enable SMM-based RF temperature sensors to provide real-time responsiveness to temperature variations. Similar to previous studies [59], this technology can be applied to fire detection and prevention in energy storage systems [61,62]. The remainder of this paper is structured as follows. Section 2 presents the design and analysis of the proposed antenna, including multiphysics analysis results. Section 3 discusses antenna fabrication. Section 4 presents the measurement results and discussion. Finally, Section 5 summarises the findings and conclusions of this study.

2. Design and analysis

2.1. Design of the proposed antenna

Figure 2 illustrates the geometry of the proposed antenna. Figure 2(a) shows the top view, while Figure 2(b) presents the bottom view. The quasi-Yagi antenna, a planar adaptation of the Yagi-Uda antenna, shares a similar configuration. In the quasi-Yagi design, the ground plane functions as the reflector in the Yagi-Uda antenna. The conventional quasi-Yagi antenna typically includes a driver, coplanar strip (CPS) line, balun, reflector, and director. The design of the proposed antenna follows the traditional quasi-Yagi configuration but incorporates additional directors to enhance the directivity further.

The proposed antenna consists of a driver, CPS line, balun, reflector, and three directors. The driver acts as

a dipole antenna, while the balun introduces a 180° phase shift. To achieve this phase difference, the length difference between points L_3 and L_4 must correspond to a quarter wavelength. The directors are designed to be shorter than the driver to ensure that radiation is directed forward rather than backward. The specific dimensional parameters of the antenna are provided in Table 1.

The antenna substrate was fabricated using dual-extrusion FDM 3D printing, employing HT and SMP filaments, while the hinge was exclusively made from SMP. The permittivity and loss tangent of the SMP are 3.0 and 0.03, respectively, while those of the HT filament are 2.5 and 0.02. Conductive materials were applied to both the front and back surfaces of the substrate using screen printing.

For the shape memory hinge to function correctly, its length must be at least π times the thickness of the material. If the hinge length is shorter than this, it cannot fold to 180° , and parts of the antenna other than the hinge may also bend. Moreover, the hinge length must exceed this minimum threshold to avoid contact between the silver ink and other parts of the antenna.

Electromagnetic (EM) simulations were conducted using Ansys High-Frequency Structure Simulator (HFSS) version 16. These simulations optimised the antenna parameters, fine-tuning them to achieve a wide bandwidth of around 5 GHz.

2.2. Analysis of the proposed antenna

This section presents the structural design and simulation results for the proposed antenna, starting with

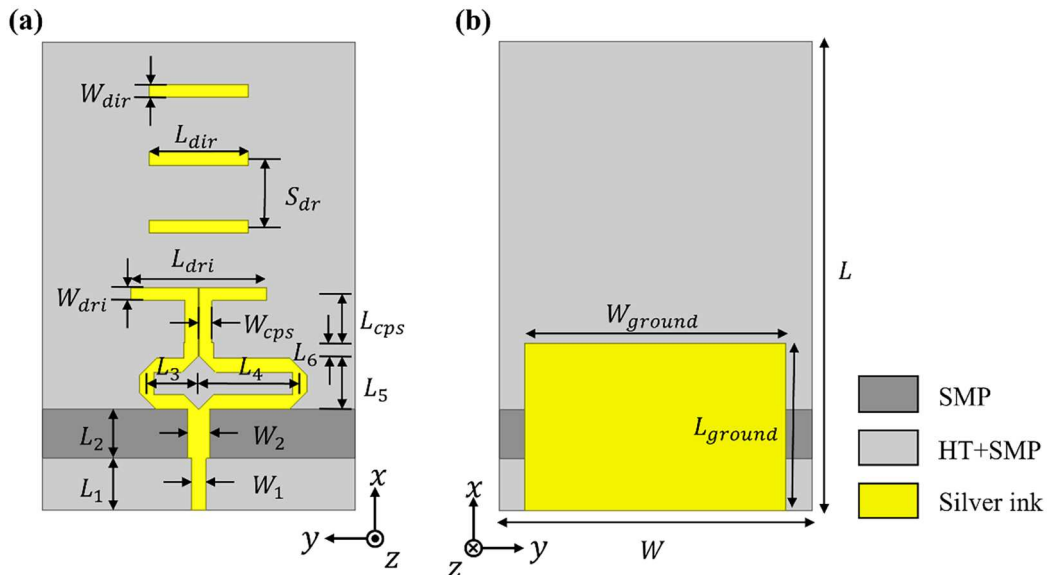


Figure 2. Geometry of the proposed antenna: (a) top view and (b) bottom view.

Table 1. Dimensions of the geometric parameters.

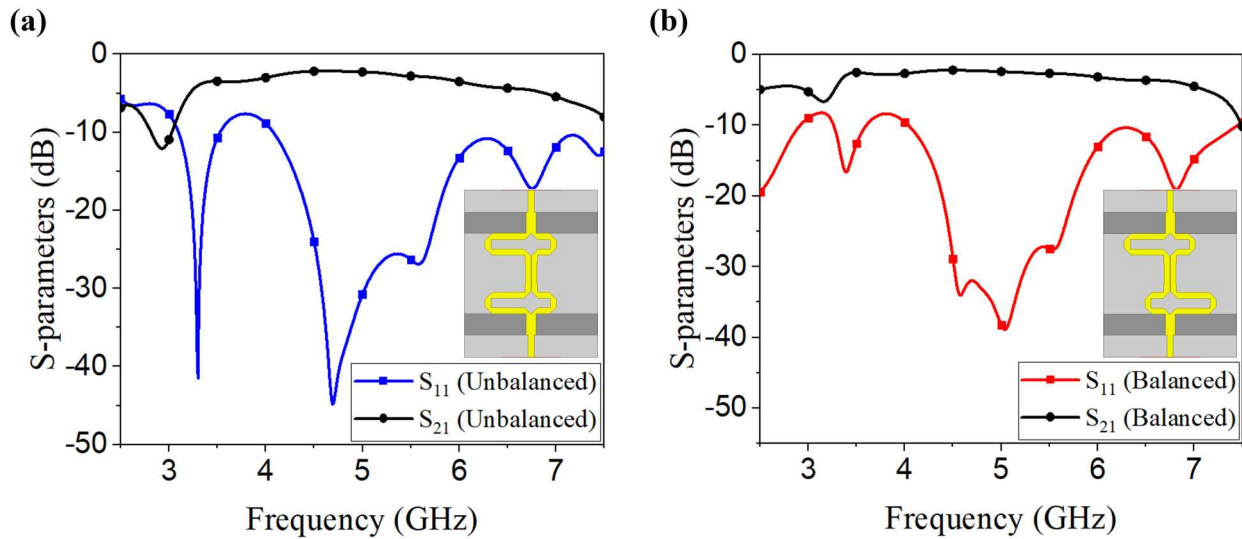
Parameter	Dimension (mm)	Parameter	Dimension (mm)	Parameter	Dimension (mm)
L	90	L_6	3.7	W_{cps}	2.5
W	60	L_{cps}	9.37	W_{dri}	2.5
L_1	10	L_{dri}	26	W_{dir}	2.5
L_2	9.47	L_{dir}	19	W_{ground}	50
L_3	10	L_{ground}	32.9	S_{dr}	13.1
L_4	19.37	W_1	2.73	thickness	1
L_5	9.73	W_2	4.31		

an overview of the balun. In the driver of the quasi-Yagi antenna, a 180° phase shift is required, which is achieved using the balun. The performance of the balun can be evaluated through both balanced and unbalanced back-to-back configurations. The substrate is fabricated using SMP and HT filaments, with shape memory hinges made of SMP positioned at both ends. The conductors are created using stretchable silver ink.

For both the balanced and unbalanced back-to-back configurations, the insertion loss should be close to 0 dB, while the return loss should remain high across the operating frequency range. Additionally, a wide bandwidth is essential for the balun to ensure an adequate -10 dB bandwidth for the antenna. Figure 3 shows the simulated return loss and insertion loss results. Table 2 provides the frequency ranges and insertion losses for return losses exceeding 10 and 20 dB.

Figure 3(a) illustrates the simulation results for the unbalanced back-to-back configuration. The frequency ranges with return losses exceeding 20 dB, indicating 99% signal transmission, are 3.26–3.35 GHz and 4.43–5.78 GHz, with insertion losses of 3.69–4.52 dB and 2.15–3.0 dB, respectively. At 5 GHz, the return loss is 30.76 dB, and the insertion loss is 2.26 dB.

Figure 3(b) presents the simulation results for the balanced back-to-back configuration of the balun. The frequency range with a return loss exceeding 20 dB is 4.39–5.75 GHz, with insertion losses ranging from 2.2 to 2.82 dB. At 5 GHz, the return loss is 38.24 dB, and the insertion loss is 2.41 dB. When comparing the balanced and unbalanced back-to-back configurations, both configurations demonstrate a return loss exceeding 20 dB across the 4.43–5.75 GHz range. In addition, the insertion loss remains between 2.15 and 3 dB within this frequency

**Figure 3.** Simulated return loss and insertion loss results for (a) unbalanced and (b) balanced back-to-back transitions of the balun.**Table 2.** Frequency ranges and insertion losses of the balun with return losses exceeding 10 and 20 dB.

Return Loss (dB)	Unbalanced back-to-back transition		Balanced back-to-back transition	
	Frequency (GHz)	Insertion loss (dB)	Frequency (GHz)	Insertion loss (dB)
>10	3.1–3.52, 4.08–7.5	3.45–7.71, 2.15–8.05	2.5–2.91, 3.27–3.6, 4.04–7.44	4.5–4.95, 2.54–5.04, 2.2–8.55
>20	3.26–3.35, 4.43–5.78	3.69–4.52, 2.15–3.0	4.39–5.75	2.2–2.82

range. The relatively high loss tangents of the HT and SMP, 0.02 and 0.03, respectively, contribute to insertion losses that exceed 2 dB. Upon reviewing both sets of simulation results, it is evident that the return loss is high across a broad frequency range, while the insertion loss remains low across a similar range.

Figure 4 presents the simulation results for the proposed antenna. Figure 4(a) displays the reflection coefficient, while Figure 4(b) illustrates the radiation efficiency and peak gain. The simulated antenna exhibits a frequency range with a reflection coefficient below -10 dB, spanning from 4.38 to 5.51 GHz. Within this frequency range, the radiation efficiency varies between a minimum of 53.4% and a maximum of 73.8%. Likewise, the peak gain ranges from 5.16 to 8.13 dBi. At 5 GHz, the radiation efficiency is 72.66%, and the peak gain is 7.92 dBi. Figure 4(c) represents the xy-plane, corresponding to the E-plane, while Figure 4(d) represents the xz-plane, corresponding to the H-plane.

Figure 5 presents the results of parametric studies on the geometrical parameters influencing the reflection coefficient and gain of the antenna. The parameters

investigated include the lengths of the driver and director. Figure 5(a) shows the variation in the reflection coefficient with respect to L_{dri} . When L_{dri} is 26 mm, the antenna operates at a centre frequency of 5 GHz. As the driver length increases, the centre frequency shifts to a lower value. Figure 5(b) illustrates the relationship between peak gain and L_{dri} . Regardless of the L_{dri} value, the peak gain remains within the range of 7.9–8 dBi across the frequency range of 5–5.5 GHz, after which a sharp decrease occurs. Furthermore, an increase in L_{dri} results in a higher peak gain at lower frequencies. Figure 5(c) shows the variation in the reflection coefficient with respect to L_{dir} . When L_{dir} is 19 mm, the -10 dB bandwidth spans from 4.38 to 5.51 GHz. As L_{dir} increases, the -10 dB bandwidth narrows. Figure 5(d) displays the change in peak gain with respect to L_{dir} . When L_{dir} is set to 19 mm, the maximum gain of 8.1 dBi occurs at 5.2 GHz. As L_{dir} increases, the frequency corresponding to the maximum gain shifts to a lower value. Through this optimisation process, the optimal lengths for the driver and director were determined as 26 and 19 mm, respectively.

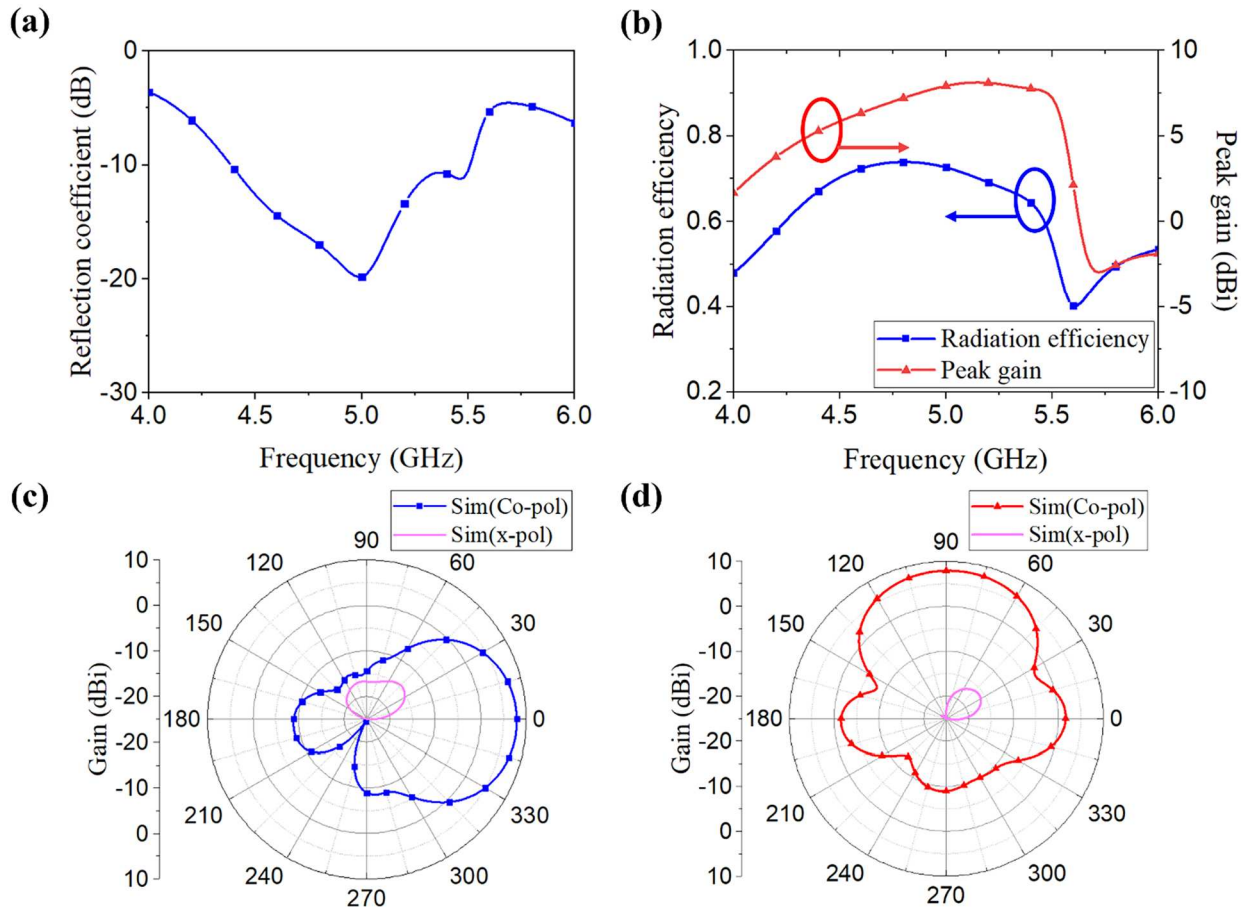


Figure 4. Simulation results of the proposed antenna: (a) reflection coefficient, (b) radiation efficiency and peak gain, (c) E-plane ($\theta = 90^\circ$), and (d) H-plane ($\phi = 0^\circ$) at 5 GHz.

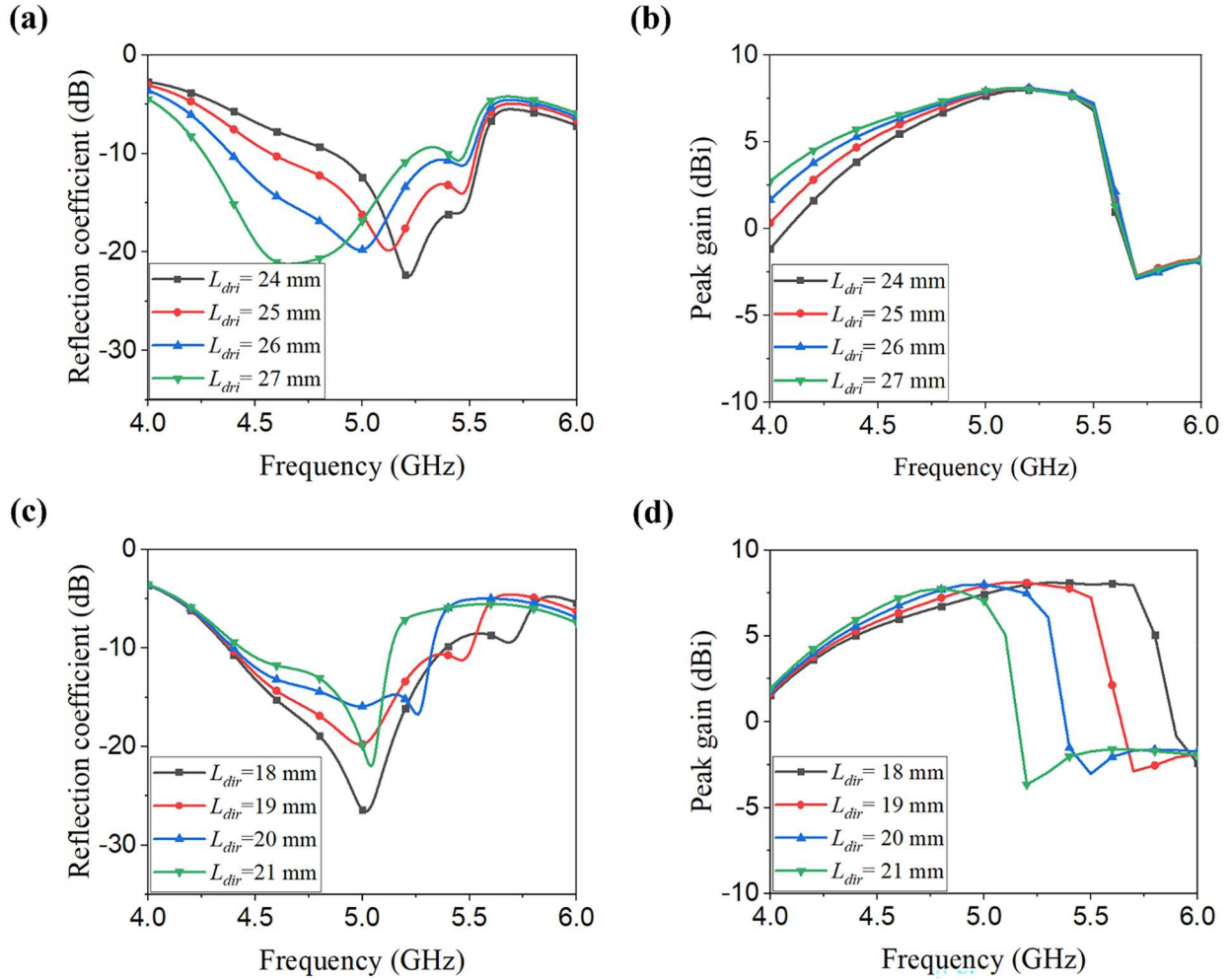


Figure 5. Parametric studies of the antenna's geometrical parameters focusing on (a) reflection coefficient of L_{dri} , (b) peak gain of L_{dri} , (c) reflection coefficient of L_{dir} , and (d) peak gain of L_{dir} .

The driver, functioning as a dipole antenna, generates an electric field that excites the nearest director. This initial director then receives the incident electric field and excites the subsequent director in the forward direction, creating a cascade effect that improves the antenna's directivity as more directors are added. To further enhance the directivity of the quasi-Yagi antenna, additional directors were incorporated. However, due to the coupling between each director, the impedance of the antenna changes with the number of directors, which in turn affects the -10 dB frequency bandwidth. There is a trade-off between the -10 dB bandwidth and the gain, making it essential to optimise the length and number of directors. Figure 6 presents the simulation results for the antenna with varying numbers of directors.

Figure 6(a) shows the reflection coefficients based on the number of directors. When no directors are present, the -10 dB bandwidth spans from 4.34 to 5.52 GHz. With one director, the bandwidth becomes 4.42–5.28

GHz. For two directors, the -10 dB bandwidth is 4.32–5.24 GHz. When three directors are added, the bandwidth extends to 4.38–5.51 GHz, and with four directors, it narrows to 4.38–5.28 GHz. Figure 6(b) illustrates the peak gain as a function of the number of directors. With no directors, the peak gain is 4.04 dBi. As the number of directors increases, the peak gain rises sequentially to 6.22, 7.11, 7.92, and 8.4 dBi. The configuration with three directors offers the broadest -10 dB bandwidth and a relatively high peak gain at 5 GHz. While adding more directors increases the peak gain at 5 GHz, it also narrows the -10 dB bandwidth and elongates the antenna. The increased length results in a higher antenna weight, which in turn makes it more difficult for the shape memory hinge to recover its original shape.

The folding angle, denoted as α in Figure 7(a), represents the angle between the flat surface and the folded surface. A flat position corresponds to 0° , with upward folding assigned positive angles and downward folding assigned negative angles. The fully folded

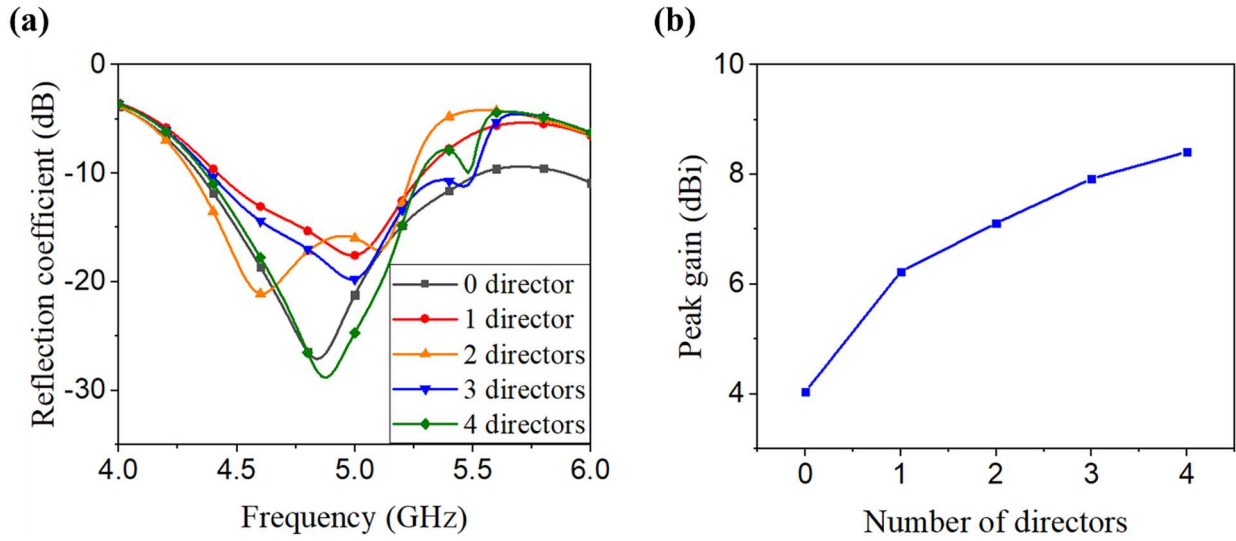


Figure 6. Simulation results with varying numbers of directors: (a) reflection coefficients and (b) peak gain at 5 GHz.

position in the opposite direction is defined as -180° . Figures 7(b) to (e) show the proposed antenna structure variations. The antenna incorporates a shape memory hinge, allowing it to fold. In the simulations, the folding angle α was set to -180° , -90° , 0° , and 90° , and the antenna was designed and simulated for each angle. Specifically, Figure 7(b) corresponds to 0° , Figure 7(c) to -180° , Figure 7(d) to -90° , and Figure 7(e) to

90° . In the fabricated antenna, cracks appeared when folded to 180° , which could create additional resonances. Consequently, the 180° -fold was not pursued further. The cause of this issue is likely the uneven printing of the SMP material, due to differences in the shrinkage rates of the materials during the cooling process. The overall dimensions of the antenna are $90 \text{ mm} \times 60 \text{ mm} \times 1 \text{ mm}$.

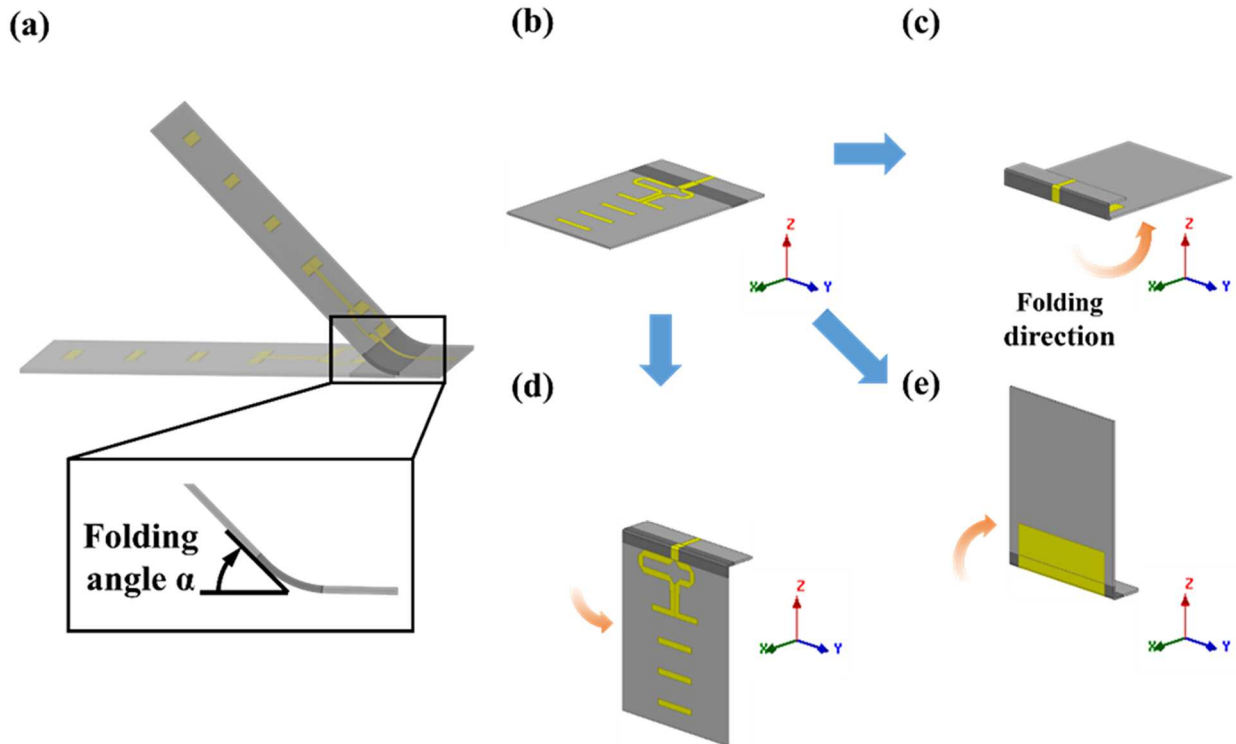


Figure 7. Folding angle (a) of the proposed antenna structure: (a) definition of the folding angle α , and antenna configurations for $\alpha =$ (b) 0° , (c) -180° , (d) -90° , and (e) 90° .

Figure 8 presents the simulated radiation patterns for the modified antenna configurations at different folding angles, shown in the xz -plane. Figure 8(a) illustrates the radiation pattern when α is 0° , with the main beam directed toward $\theta = 90^\circ$ and a gain of 7.92 dBi. Figure 8(b) shows the radiation pattern when α is -180° , with the main beam directed toward $\theta = 270^\circ$ and a gain of 7.99 dBi. Figure 8(c) presents the radiation pattern when α is -90° , with the main beam directed toward $\theta = 180^\circ$ and a gain of 7.98 dBi. Finally, Figure 8(d) depicts the radiation pattern when α is 90° , with the main beam directed toward $\theta = 0^\circ$ and a gain of 8.47 dBi. As the folding angle changes, the radiation pattern also shifts, indicating that the direction of the main beam is altered accordingly.

2.3. Multiphysics analysis result

COMSOL Multiphysics software was utilised to simulate the mechanical deformation of the proposed 3D-printed substrate for the antenna. This software models physical phenomena based on partial differential equations. The same substrate, previously modelled in HFSS, was extracted and analysed within COMSOL Multiphysics. The structure with a folding angle of $\alpha = -180^\circ$ was simulated.

The proposed antenna's substrate is composed of SMP, which has a temperature-dependent Young's

modulus. Figure 9 illustrates the state when $T > T_g$, where the SMP's mechanical properties are as follows: Young's modulus of 1 MPa, Poisson's ratio of 0.4, and a density of 1073 kg/m^3 [63]. For the HT, Young's modulus is 1500 MPa, Poisson's ratio is 0.35, and the density is 1180 kg/m^3 . Figure 9(a) shows the original shape of the antenna, where the centre of the hinge was fixed to facilitate folding by 180° . A load of 0.4 N was applied in the x and z directions at one end, while a load of 0.068 N was applied in the $-x$ and z directions at the opposite end.

Figure 9(b) illustrates the analytically derived deformation of the proposed shape memory hinge. During the deformation process, the changes in stress, displacement, and force positions were analysed. The maximum von Mises stress of $0.9 \times 10^6 \text{ N/m}^2$ was observed at the hinge of the antenna. This result confirms that the parts containing the HT core remain unfolded while folding occurs only at the shape memory hinge, which is entirely composed of SMP. When the external load is removed above T_g , the shape memory hinge recovers its original shape due to stress.

3. Fabrication process

The heat deflection temperature (HDT) is a critical factor when selecting materials. The materials used in this study were chosen based on the following criteria: the

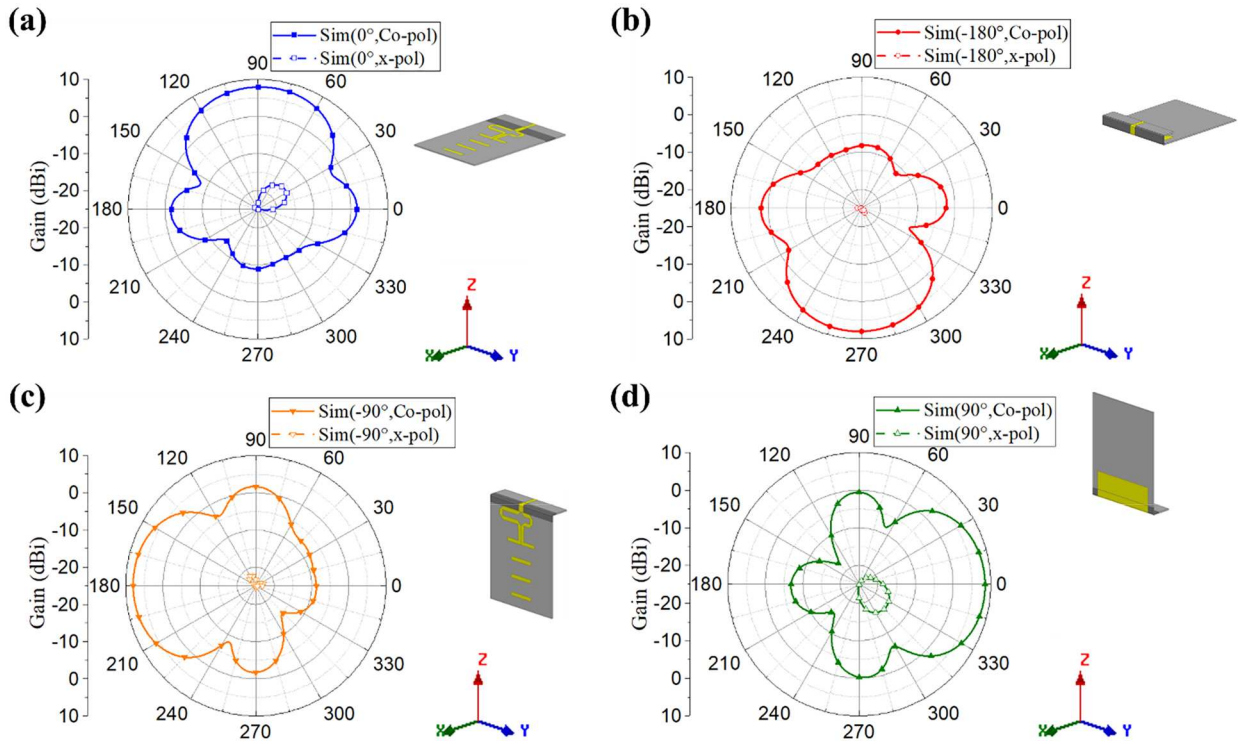


Figure 8. Simulated radiation patterns ($\phi = 0^\circ$) at 5 GHz according to the shape deformation of the antenna: $\alpha =$ (a) 0° , (b) -180° , (c) -90° , and (d) 90° .

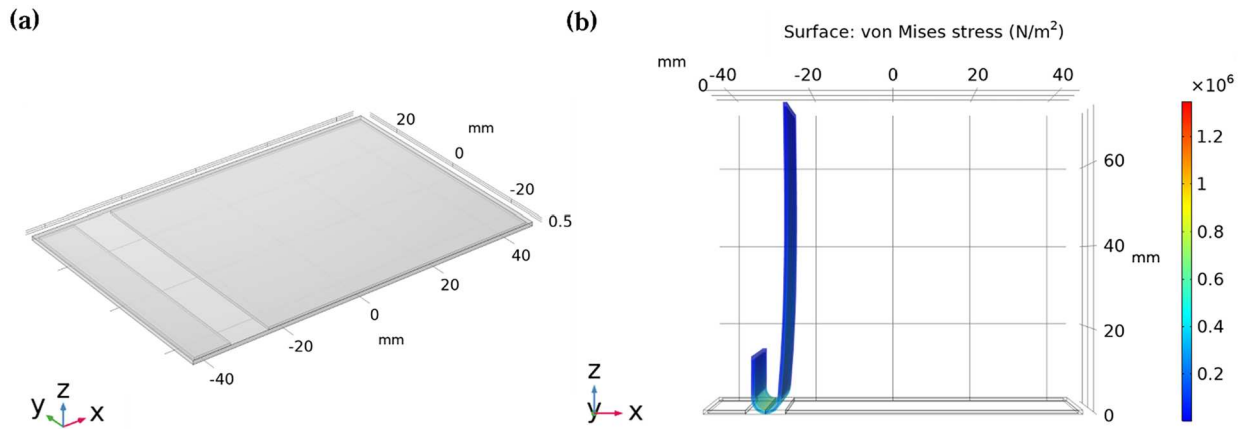


Figure 9. Mechanical deformation of the substrate in COMSOL Multiphysics: (a) original shape and (b) simulated von Mises stress.

HDTs of the fixed components must exceed the temperature induced by the applied heat, while the HDT of the shape-deformation and recovery component should be lower than the temperatures induced by the applied heat. The glass transition temperature (T_g) of the SMP (SMP Technologies, Tokyo, Japan) is 55 °C, and its elastic modulus significantly decreases between 35 and 75 °C. Experimental results indicated that the deformation temperature required to ensure deformation and recovery in the SMP structure was 70 °C [18]. The HDTs of PLA (Sindoh, Seoul, South Korea) and ABS (Sindoh, Seoul, South Korea) are 52 and 73 °C, respectively, making them unsuitable as fixed components due to their proximity to the SMP's HDT. In contrast, the HT filament (HT CLEAR, colorFabb, Belfeld, Netherlands) has an HDT of 90 °C, which is higher than

the SMP's deformation temperature, making it suitable as the core material of the antenna substrate. Figure S1 illustrates the properties of the structure combining SMP and HT core.

The shape memory effect within the SMP is explained in Figure 10. The shape memory hinge is fabricated from an SMP, a type of SMM. SMP consists of hard and soft segments, with the key difference being their response to thermal stimuli. The hard segments do not react to heat, while the soft segments respond via changes in their elasticity. In Figure 10, the soft segments are represented by blue and orange colours, depicted by arbitrary lines. The blue colour corresponds to the soft segments when the temperature is below the T_g , while the orange colour represents the soft segments above T_g .

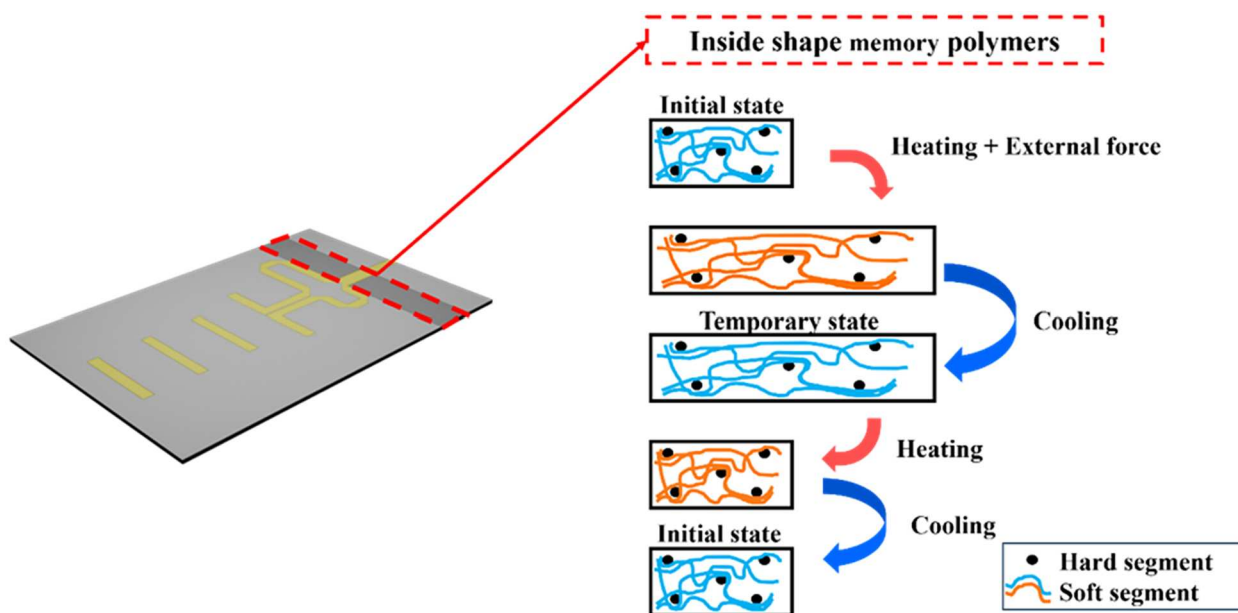


Figure 10. Deformation process of the shape memory polymer.

At temperatures below T_g , the SMP maintains high strength and rigidity, behaving like a solid. When the temperature exceeds T_g , the soft segments enter a rubber-like, deformable state, causing them to deform when subjected to external force. If the temperature is then lowered, the stretched soft segment becomes fixed, locking the material in the deformed shape. When heat above T_g is reapplied, the material becomes deformable once again, and the stretched soft segment returns to its original shape. Lowering the temperature after this recovery fixes the material in its original form.

The proposed antenna structure consists of an upper conductor layer, a lower conductor layer, and a dielectric substrate. The antenna substrate is fabricated using HT and SMP filaments, with the conductor made of stretchable silver ink. The fabrication process is illustrated in Figure 11. The first step involves dual-extrusion FDM 3D printing using a Sindoh 3DWOX 7X dual-extruder FDM printer. The nozzle diameter is 0.4 mm, and the printable layer thickness ranges from 0.05 to 0.4 mm. The total substrate height is 1 mm, with a printed layer height of 0.1 mm. HT filament, known for its rigidity at high temperatures, serves as the core material to ensure that only the hinges remain flexible. The SMP layers on the top and bottom are each 0.2 mm thick, while the HT layer is printed to a thickness of 0.6 mm. During 3D printing, the bed temperature is maintained at 65 °C, with nozzle temperatures set to 250 °C for the HT filament and 200 °C for the SMP filament. The print and travel speeds for the HT filament are 70 and 110 mm/s, respectively, whereas for the SMP filament, they

are 10 and 20 mm/s. The printing process begins with the outer walls and then fills the interior. Once the substrate is fully printed, it is cooled at room temperature before being removed from the print bed. The raft used for securing the substrate to the bed is also removed. The bottom surface of the printed substrate is smoother than the top, making it more suitable for detailed patterning of the driver, directors, and balun. Figure S2 illustrates why the top surface is not used for this purpose.

The second step is screen printing, carried out using an auto-align screen printer (SJ-7320SA, Sungjin Technology, Gimhae, Republic of Korea). This process involves passing conductive ink through the stencil area of a mask to print onto the substrate. Both copper and silver inks can be used; however, copper inks require a complex sintering process, such as treatment in a reducing gas atmosphere or laser and flash lamp sintering. In contrast, silver inks can be sintered at high temperatures with fewer processing steps. Although silver ink has slightly lower conductivity than copper, the difference is negligible. The chosen conductor, Dycotec DM-SIP-2006, has a stretchability of up to 170%. Since breaking the conductive pattern during shape-shifting could introduce additional resonances or render the antenna non-functional, stretchable silver ink was selected. After securing the substrate in place, screen printing is performed, applying multiple layers of ink to improve conductivity. The third step is sintering, which dries and hardens the silver ink. This process is conducted using a hot-air dryer (S-HOV90, SERIMA, Pocheon, Republic of Korea) at 60 °C for approximately 10–15 min.

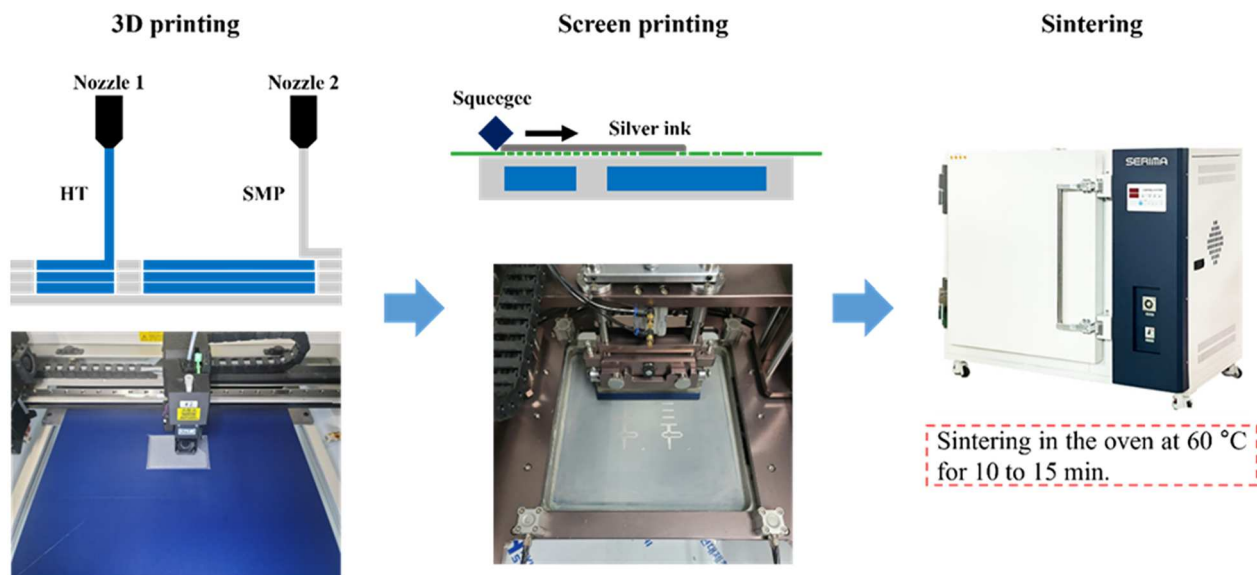


Figure 11. Fabrication process: FDM 3D printing with SMP and HT filaments, followed by screen printing with stretchable silver ink and final sintering.

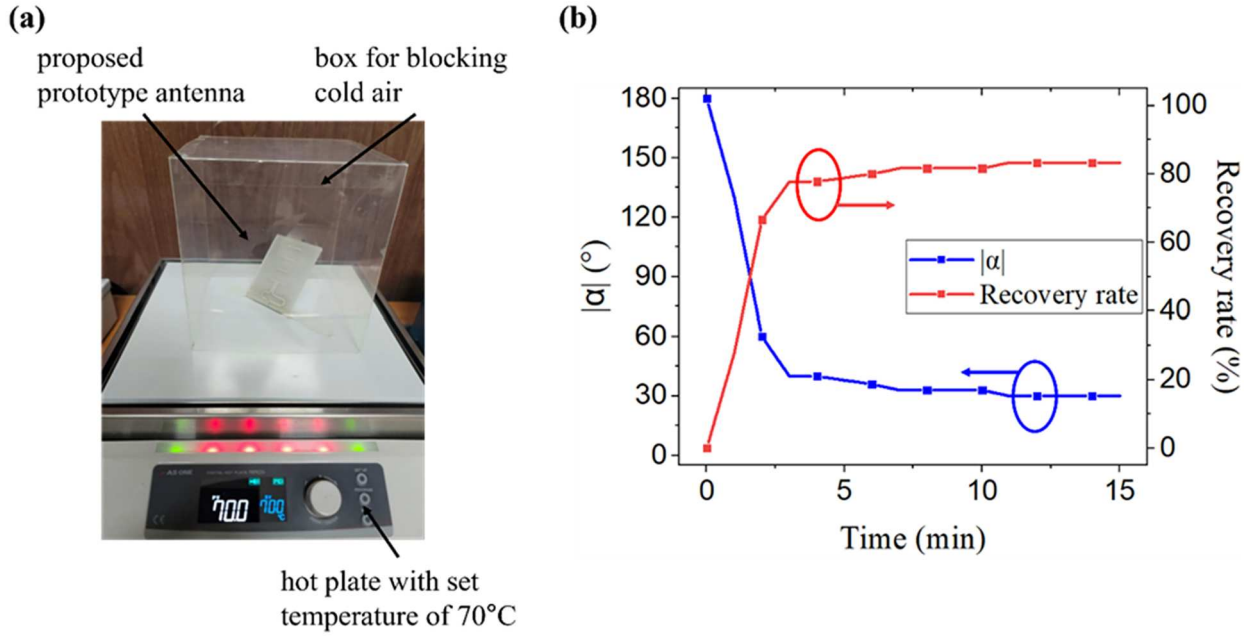


Figure 12. Shape recovery test of the antenna substrate: (a) measurement setup and (b) shape recovery rate of the substrate vs. heating time.

Through the hinge recovery process, the antenna substrate is restored to its original shape. Figure 12 presents the recovery rate (R_r) of the hinge and the measurement setup. A recovery test was conducted to evaluate the hinge's performance by applying heat to an antenna substrate folded at 180° and measuring the recovery angle over time. The test assessed both the maximum recovery rate and the recovery time of the proposed hinge structure. A hot plate (NDK-2A-F, AS ONE, Osaka, Japan) set to 70 °C was used for heating. Figure 12(a) illustrates the measurement setup

for hinge recovery. The angle of the antenna substrate was recorded at 1-min intervals. The R_r , representing the extent to which the antenna substrate returns to its original shape, was calculated using Equation (1), where α_d is the deformed α and α_r is the recovered α :

$$R_r = \frac{|\alpha_d - \alpha_r|}{|\alpha_d|} \times 100 (\%). \quad (1)$$

As heating progressed, the folded antenna substrate gradually unfolded, reducing the absolute angle $|\alpha|$. The graphs in Figure 12(b) show the hinge angle and

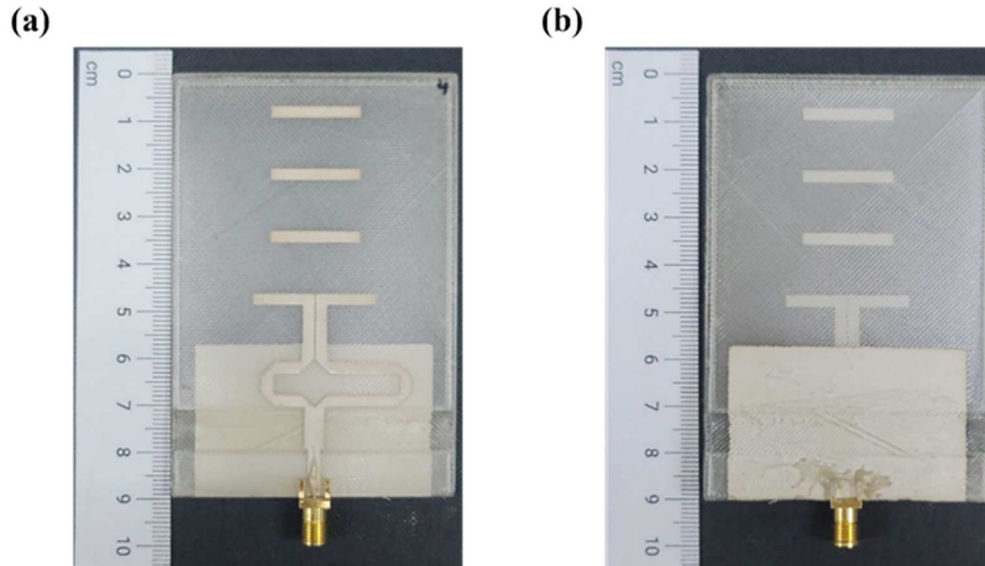


Figure 13. Fabricated prototype antenna: (a) top view and (b) bottom view.

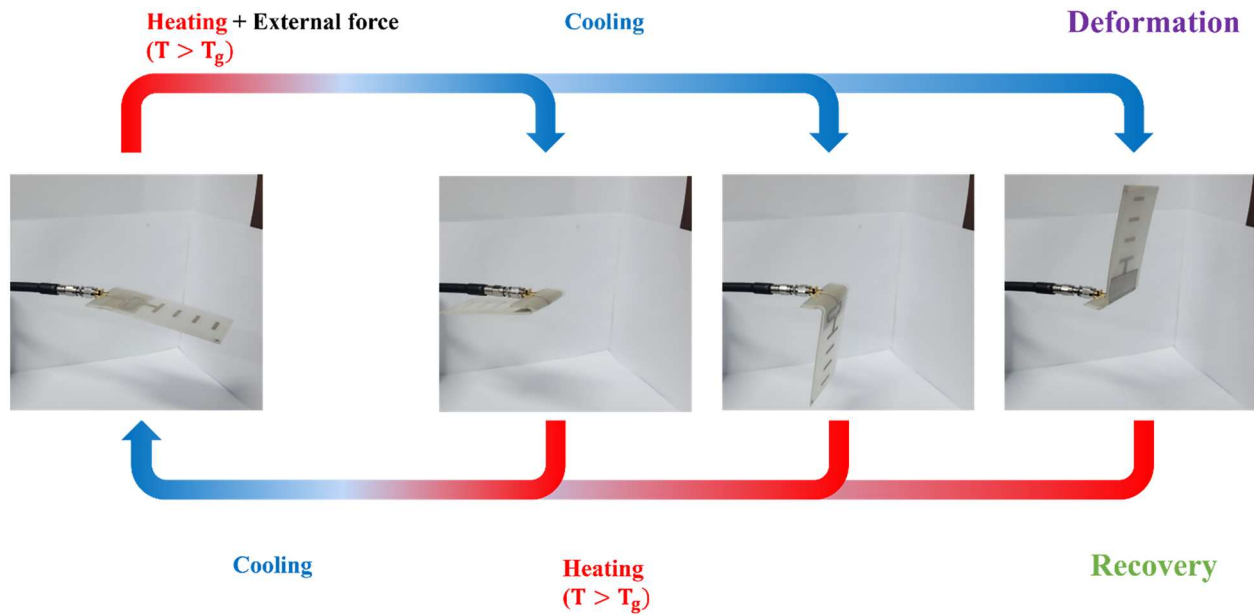


Figure 14. Shape morphing process of the fabricated antenna.

recovery rate as functions of heating time. After 2.5 min, the hinge had recovered approximately 50% of its original shape. The recovered angle was 150° , and the maximum recovery rate was 83.33%. The total recovery time was 11 min.

Figure 13 shows the fabricated prototype antenna with an attached SMA connector, with Figure 13(a) displaying the top view and Figure 13(b) the bottom view. The antenna was produced using the fabrication process described earlier and has dimensions of $90 \text{ mm} \times 60 \text{ mm} \times 1 \text{ mm}$, excluding the SMA connector.

Figure 14 illustrates the shape-morphing process of the fabricated antenna. The antenna is heated above T_g using an oven or hot plate, and an external force is applied to bend it. During this process, the angle α can be adjusted within a range of -180° to 90° . After bending, the temperature is reduced to fix the antenna in a deformed shape. Once fixed, the antenna can either be reshaped into a different configuration or restored to its original form. To deform the antenna into another shape, heat above T_g and external forces are applied, similar to the initial deformation process. To restore it to its original shape, heat is applied without any external force. Upon heating, the antenna returns to its original shape, and cooling solidifies this form; this process is referred to as recovery. As shown in Figure 14, the antenna can be transformed into configurations with angles of -180° , -90° , 90° , etc., through deformation and restored to its original shape through recovery. **Video S1** demonstrates the shape-morphing process.

4. Measurement results and discussion

4.1. Measurement results

Figure 15 presents the simulation and measurement results of the proposed antenna. Although the substrate thickness was designed to be 1 mm, measurements revealed a thickness of 1.05 mm, with some areas exceeding this due to printing inaccuracies. Additionally, in the fabricated antenna, silver ink was screen-printed onto the uneven surface of the 3D-printed substrate, introducing printing tolerances of up to 0.4 mm and reducing conductivity. These fabrication errors in both the 3D-printed substrate and screen-printed conductive patterns contributed to discrepancies between the simulated and measured results. To account for these variations, a new simulation was conducted using the actual dimensions of the fabricated sample.

Figure 15(a) compares the simulated and measured reflection coefficients of the proposed antenna. A Keysight FieldFox N9951A network analyser (Santa Rosa, CA, USA) was used for the measurements. The simulated frequency range extends from 4.31 to 5.49 GHz, while the measured frequency range spans 4.26–5.48 GHz. Despite minor deviations, the -10 dB bandwidths.

The gain and radiation pattern of the antenna were measured in an anechoic chamber. Figure 15(b) compares the simulated and measured peak gains of the antenna. Within the -10 dB bandwidth, the simulated peak gain ranges from 3.22 to 6.55 dBi, while the measured peak gain varies from 4.01 to 7.49 dBi. At 5 GHz, the simulated and measured peak gains are 6.55

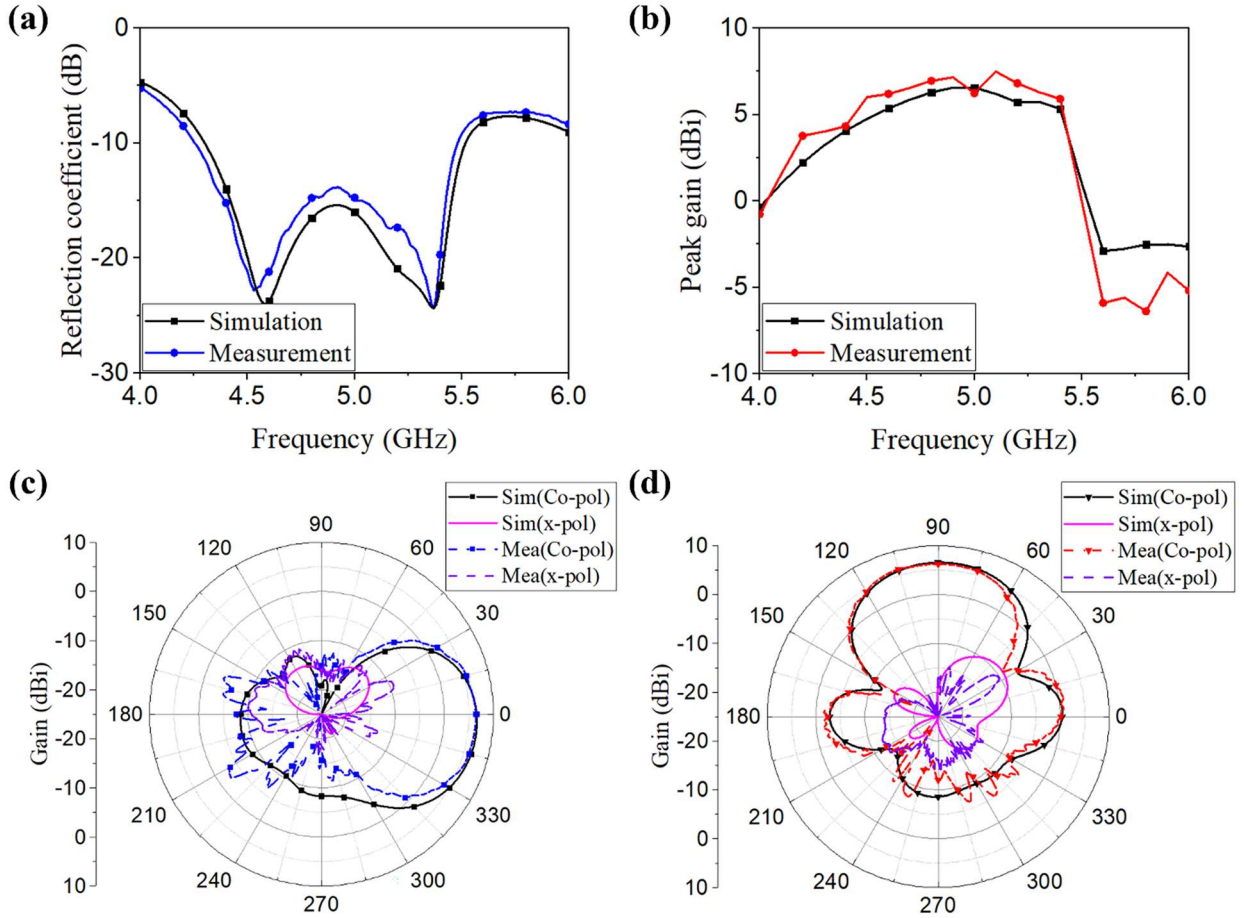


Figure 15. Simulation and measurement results of the proposed antenna: (a) reflection coefficient, (b) peak gain vs. frequency, (c) E-plane ($\theta = 90^\circ$), and (d) H-plane ($\phi = 0^\circ$) at 5 GHz.

and 6.24 dBi, respectively, indicating a small difference of 0.31 dBi. In simulation, the radiation efficiency ranges from 32% to 58.5% within the -10 dB bandwidth, reaching 56.5% at 5 GHz.

Figure 15(c) and Figure 15(d) illustrate the xy-plane and xz-plane radiation patterns at 5 GHz, corresponding to the E-plane and H-plane, respectively. The measured radiation pattern exhibits a slightly smaller amplitude than the simulated pattern, but the overall shape remains consistent. The results confirm that the simulation and measurement trends align well in terms of reflection coefficients, peak gains, and radiation patterns.

Figure 16 presents the reflection coefficients and peak gains from both the simulation and measurements. In Figure 16(a), the simulated and measured reflection coefficients of the proposed antenna are shown. The same network analyser, as previously mentioned, was used for these measurements. The measured -10 dB bandwidths at different angles ($\alpha = -180^\circ$, -90° , and 90°) are 4.22–5.45, 4.26–5.4, and 4.28–5.54 GHz, respectively. For configurations at $\alpha = -180^\circ$, -90° , and 90° , the

reflection coefficient slightly varies due to differences in the length of the quarter-wave impedance line. When comparing these results to the bandwidth measured at $\alpha = 0^\circ$, the differences are minimal, with the measured bandwidths being similar to the result obtained at $\alpha = 0^\circ$.

Figure 16(b) displays the peak gains from both simulation and measurement. For $\alpha = -180^\circ$, the peak gain within the -10 dB bandwidth ranges from 3.22 to 6.72 dBi. For $\alpha = -90^\circ$, the peak gain ranges from 4.52–7.07 dBi, and for $\alpha = 90^\circ$, the peak gain ranges from 5.01 to 7.24 dBi. Both the simulated and measured results exhibit similar trends. Notably, when comparing the peak gains measured for the antenna at $\alpha = 0^\circ$ with those measured at $\alpha = -180^\circ$, -90° , and 90° , it is clear that the antenna maintains a consistent gain even when deformed across a wide range of angles.

Figure 17 illustrates the simulated and measured radiation patterns at 5 GHz for various values of α . The antenna was folded by applying heat to the shape-memory hinge using a hot plate, and measurements were conducted at 5 GHz for each configuration. Figures 17(a)–(d) correspond to the cases where α is -180° ,

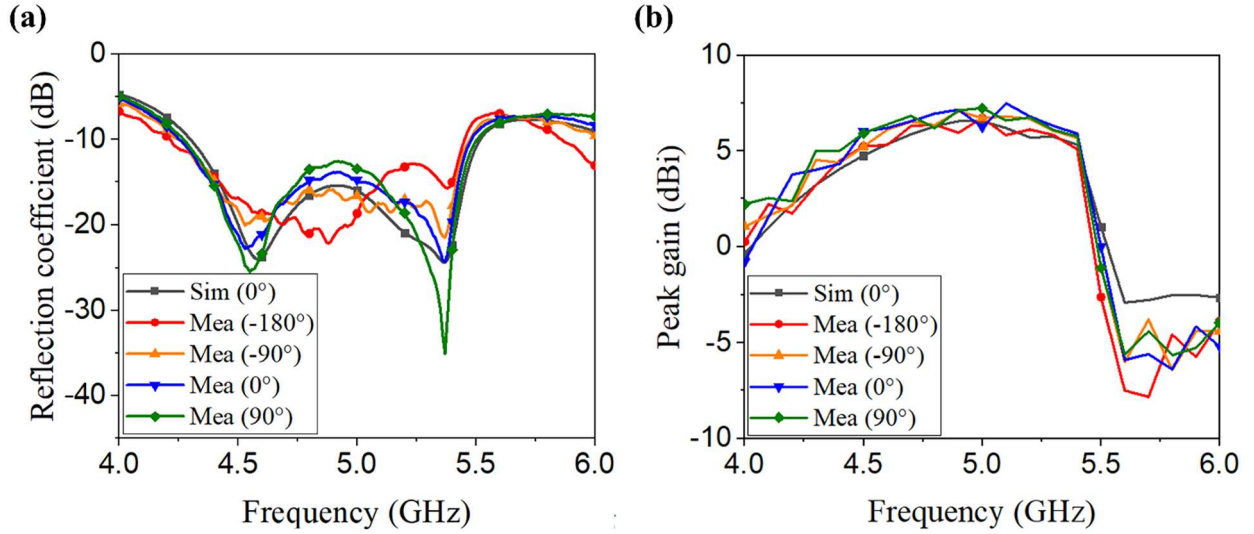


Figure 16. Simulation and measurement results: (a) reflection coefficients and (b) peak gains of the antenna with respect to α .

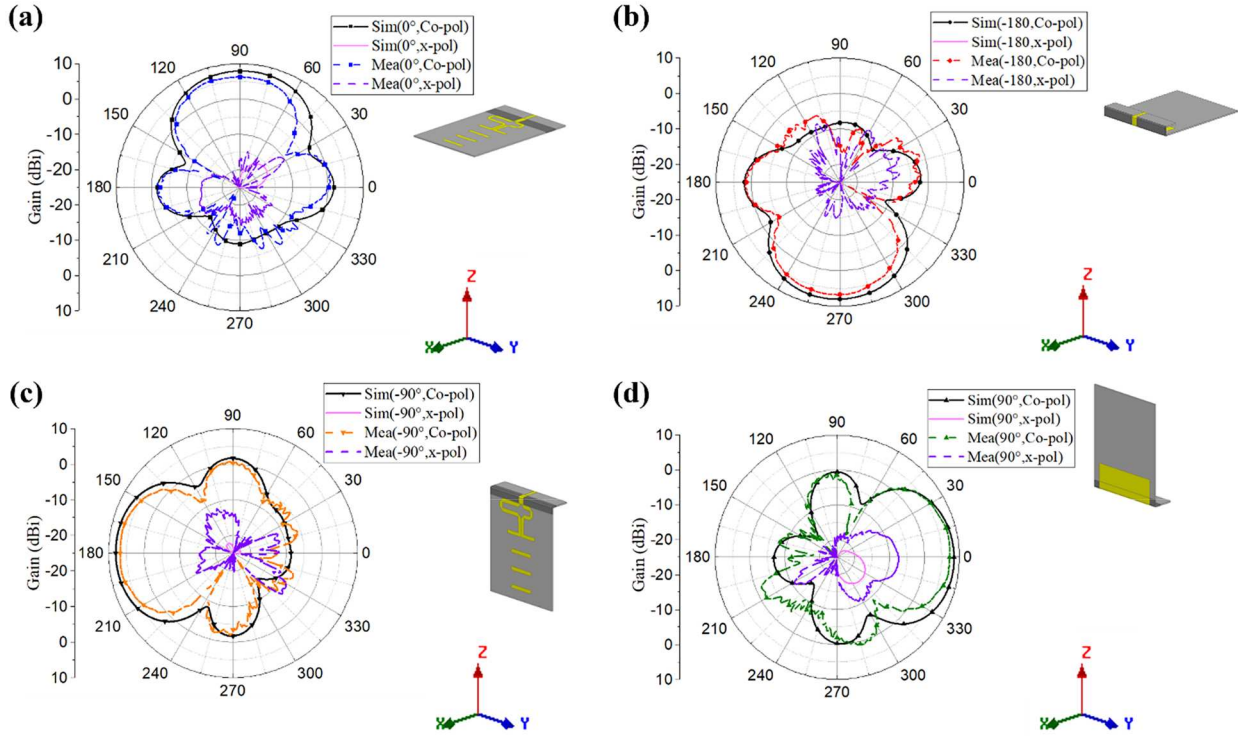


Figure 17. Simulated and measured radiation patterns ($\phi = 0^\circ$) at 5 GHz for different shape deformations of the antenna: $\alpha =$ (a) 0° , (b) -180° , (c) -90° , and (d) 90° .

-90° , 0° , and 90° , respectively. When α is -180° , the main beam points toward $\theta = 270^\circ$; at $\alpha = -90^\circ$, it shifts to $\theta = 180^\circ$; at $\alpha = 0^\circ$, the beam is directed towards $\theta = 90^\circ$; and at $\alpha = 90^\circ$, the main beam points toward $\theta = 0^\circ$. These results demonstrate that the shape-memory hinge effectively alters the radiation pattern and the direction of the main beam. The measured gains are similar across all configurations, ranging from 6.2 to 7.2 dBi.

Table 3 summarises the performance of the proposed antenna at different angles. This table includes parameters such as the -10 dB bandwidth, peak gain, side-lobe level (SLL), and beamwidth. The measured SLL values at $\alpha = -180^\circ$, -90° , 0° , and 90° are -5.37 , -5.01 , -6.1 , and -6.32 dB, respectively. The simulated SLL is -6.15 dB, with a maximum deviation of 1.14 dB between the simulated and measured values. The

Table 3. Performance of the proposed antenna at various angles.

α	–10 dB bandwidth	Peak gain (dBi) @ 5 GHz	Side-lobe level (dB) @ 5 GHz	Beamwidth @ 5 GHz
Sim (0°)	4.31–5.49 GHz	6.55	–6.15	68° (54–122°)
Mea (0°)	4.26–5.48 GHz	6.24	–5.37	67° (60–127°)
Mea (–180°)	4.22–5.45 GHz	6.77	–5.01	65° (233–298°)
Mea (–90°)	4.26–5.47 GHz	6.8	–6.1	67° (145–212°)
Mea (90°)	4.28–5.54 GHz	7.44	–6.32	64° (–25–39°)

beamwidths for the respective angles are 65°, 65°, 67°, and 64°, with minimal differences observed in the measured beamwidths. The small discrepancy of 1–4° between the measured beamwidths and the simulated beamwidth of 68° is not significant. Overall, there are no substantial differences between the simulation and measurement results in terms of SLL and beamwidth.

Since the recovery of the shape-memory hinge is crucial, a repeatability test was conducted to assess the antenna's performance after multiple cycles of deformation and recovery. This test was carried out up to the 70th cycle, with measurements taken for the reflection coefficient and folded angle. Figure 18 shows the results of the repeatability test for the proposed antenna. Figure 18(a) presents the reflection coefficient as a function of the number of recovery cycles. Initially, the –10 dB bandwidth is 4.26–5.48 GHz, and after 70 cycles of deformation and recovery, it becomes 4.31–5.51 GHz. No significant changes in the reflection coefficient were observed, even after repeated cycles of deformation and recovery.

Figure 18(b) illustrates the recovery rate of the structure as a function of the number of recovery cycles. The recovered angle $|\alpha|$ values show that after the 1st and 5th recovery cycles, the hinge restores to 28°, even when folded to 180°. Over successive cycles, the recovery rate gradually decreases, and the hinge eventually recovers to 30° when folded to 180°. After 50 cycles,

the recovery rate stabilises at a consistent value of 83.33%. The remaining 16.67% corresponds to a $|\alpha|$ of 30°, indicating a deviation of approximately 30° from the original radiation direction. These results demonstrate that the shape-memory hinge remains reliable even under repeated folding, with the silver ink adhering well to the substrate, indicating minimal risk of long-term issues.

4.2. Discussions

Table 4 compares the proposed antenna with other reported pattern reconfigurable antennas, considering the key aspects such as the reconfiguration method, centre frequency, –10 dB bandwidth, peak gain, radiation efficiency, beam scanning angle, number of beams, and overall complexity. Previous studies have employed technologies such as PIN diodes, varactor diodes, and RF-MEMS, while more recent research has explored pattern-reconfigurable antennas using actuators or hinges based on SMMs. Antennas utilising PIN diodes, varactor diodes, and RF-MEMS generally do not offer wide beam scanning across their operational frequency ranges, and their scanning angles are typically not continuous [6–8,12]. For instance, the antenna in reference [7] features a wide scanning angle of 300°, but its bandwidth is narrow, and the design complexity is increased due to the extensive use of diodes for pixel

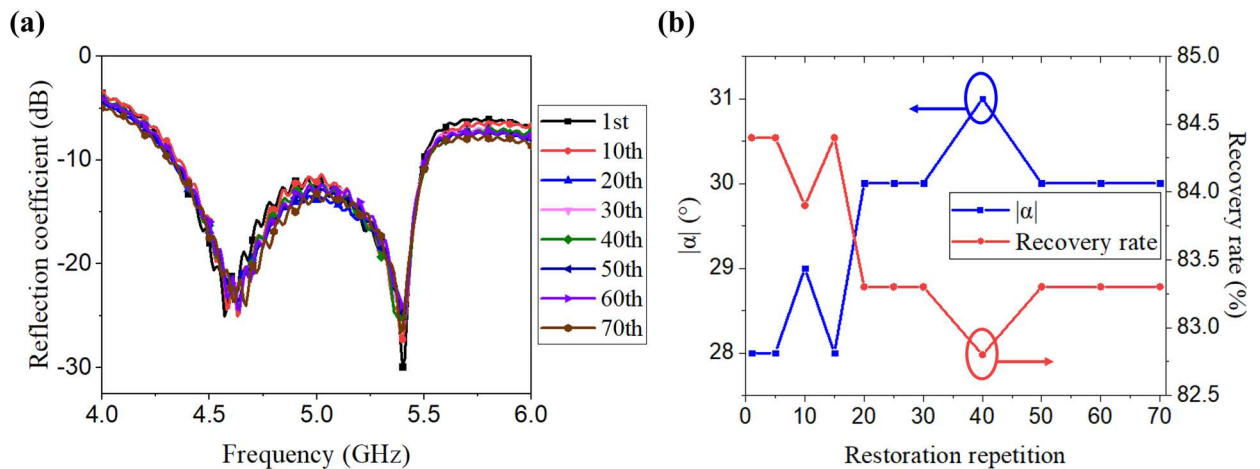


Figure 18. Repeatability test results for the proposed antenna: (a) reflection coefficients and (b) recovery rate vs. restoration repetitions.

Table 4. Performance comparison of the proposed antenna with other pattern-reconfigurable antennas.

Ref	Pattern variation method	Centre Frequency (GHz)	−10 dB bandwidth (GHz)	Peak gain (dBi)	Radiation efficiency (%)	Beam scanning range	Number of beams	Design complexity
[6]	PIN diode	5.2	5–5.43	10	–	40°	3	Complex
[7]	PIN diode	2.5	2.4–2.6	9.5	69	300°	11	Complex
[8]	Varactor diode	2.45	2.43–2.47	3.36	41	80°	17	Complex
[12]	RF-MEMS switch	35	–	–	–	34°	4	Complex
[17]	Shape memory hinge	2.4	2.2–2.6	4.8, 8.5, 11	86–98	270°	9	Simple
This work	Shape memory hinge	5	4.26–5.48	6.24	56.5	270°	Continuous	Simple

control. Antennas incorporating shape memory hinges can achieve beam scanning angles of up to 270°, but their scanning is not continuous, and the peak gain varies across different angles because of the use of reflectors [17].

In contrast, the antenna proposed in this work maintains a consistent −10 dB bandwidth and gain even when the pattern is reconfigured, offering both a wider and continuous beam scanning angle. Moreover, this antenna does not require vias or wires to supply signals to diodes, and it is fabricated using dual-extruded FDM-based 3D printing and screen printing, rather than the more complex multilayer PCB fabrication process. This results in a simplified production process, providing additional advantages.

5. Conclusion

This study presents a combined antenna design incorporating a shape memory hinge and a quasi-Yagi antenna. To assess the mechanical performance and RF characteristics of the proposed antenna, simulations, fabrication, and measurements were carried out. Upon deformation from −180° to 90°, the antenna consistently maintained a −10 dB bandwidth of approximately 4.3–5.4 GHz. Even with the deformation, the peak gain remained stable, ranging from 6.2 to 7.2 dBi. These findings demonstrate that both the bandwidth and gain exhibit minimal variation despite the deformations caused by the shape memory hinge. Thanks to the shape memory hinge, the antenna can autonomously recover to its original form when exposed to a thermal stimulus exceeding 70 °C. The hinge's recovery capability was confirmed through measurements, which showed that the antenna recovers up to 83.33% of its original shape within 11 min. The proposed antenna's ability to adjust its radiation pattern over a wide range of angles, facilitated by the shape memory hinge, holds significant promise for applications in wireless communication systems. Additionally, the antenna benefits from fast processing times and low production costs, as it is fabricated using 3D printing and screen-printing techniques. Future work will focus on enhancing the

antenna's performance by exploring the use of SMP with added fillers or increased thickness, enabling 360° pattern variability and overcoming the limitations of FDM 3D printing, such as recovery issues and uneven printing.

Author contributions

Taehwan Jang: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Validation. **Seyeon Park:** Conceptualization, Methodology, Validation. **Sungjoon Lim:** Conceptualization, Funding acquisition, Writing – review & editing, Resources, Project administration, Supervision.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data that support the findings of this study are available from the corresponding author, [S. Lim], upon reasonable request.

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References

- [1] Alam MS, Abbosh AM. Wideband pattern-reconfigurable antenna using pair of radial radiators on truncated ground with switchable director and reflector. *IEEE Antennas Wirel Propag Lett.* **2017**;16:24–28. doi:[10.1109/LAWP.2016.2552492](#)
- [2] Xiang BJ, Dai X, Luk KM. A wideband low-cost reconfigurable reflectarray antenna with 1-bit resolution. *IEEE Trans Antennas Propag.* **2022**;70:7439–7447. doi:[10.1109/TAP.2022.3176868](#)
- [3] Han J, Li L, Liu G, et al. A wideband 1 bit 12×12 reconfigurable beam-scanning reflectarray: design, fabrication, and measurement. *IEEE Antennas Wirel Propag Lett.* **2019**;18:1268–1272. doi:[10.1109/LAWP.2019.2914399](#)
- [4] Ren J, Yang X, Yin J, et al. A novel antenna with reconfigurable patterns using H-shaped structures. *IEEE Antennas Wirel Propag Lett.* **2015**;14:915–918. doi:[10.1109/LAWP.2014.2387292](#)
- [5] Shirazi M, Huang J, Li T, Gong Xun, et al. A switchable-frequency slot-ring antenna element for designing a reconfigurable array. *IEEE Antennas Wirel Propag Lett.* **2018**;17:229–233. doi:[10.1109/LAWP.2017.2781463](#)
- [6] Qin PY, Guo YJ, Ding C. A beam switching quasi-yagi dipole antenna. *IEEE Trans Antennas Propag.* **2013**;61:4891–4899. doi:[10.1109/TAP.2013.2274635](#)
- [7] Lotfi P, Soltani S, Murch R. Printed endfire beam-steerable pixel antenna. *IEEE Trans Antennas Propag.* **2017**;65:3913–3923. doi:[10.1109/TAP.2017.2716399](#)
- [8] Khairnar VV, Kadam BV, Ramesha CK, et al. A reconfigurable parasitic antenna with continuous beam scanning capability in H-plane. *AEU Int J Electron Commun.* **2018**;88:78–86. doi:[10.1016/j.aeue.2018.02.014](#)
- [9] Farzami F, Khaledian S, Smida B, Erricolo Danilo, et al. Pattern-reconfigurable printed dipole antenna using loaded parasitic elements. *IEEE Antennas Wirel Propag Lett.* **2017**;16:1151–1154. doi:[10.1109/LAWP.2016.2625797](#)
- [10] Jung C, Lee M, Li GP, et al. Reconfigurable scan-beam single-arm spiral antenna integrated with RF-MEMS switches. *IEEE Trans Antennas Propag.* **2006**;54:455–463. doi:[10.1109/TAP.2005.863407](#)
- [11] Huff GH, Bernhard JT. Integration of packaged RF MEMS switches with radiation pattern reconfigurable square spiral microstrip antennas. *IEEE Trans Antennas Propag.* **2006**;54:464–469. doi:[10.1109/TAP.2005.863409](#)
- [12] Deng Z, Guo X, Wei H, et al. Design, analysis, and verification of Ka-band pattern reconfigurable patch antenna using RF MEMS switches. *Micromachines (Basel).* **2016**;7:144. doi:[10.3390/mi7080144](#)
- [13] Hong S, Nam S, Choi S, et al. Advanced beam estimation for antennas via patterned coupling-line detection board in Ka-band. *J Electromagn Eng Sci.* **2024**;24:524–529. doi:[10.26866/jees.2024.5.r.254](#)
- [14] Lee Y, Choi S-H, Lee B-H, et al. LCP-based low-cost base station antenna for 3.7 GHz 5G band. *J Electromagn Eng Sci.* **2024**;24:276–284. doi:[10.26866/jees.2024.3.r.228](#)
- [15] Wu L, Huang J, Zhai M, et al. Deformable bowtie antenna realized by 4D printing. *Electronics (Switzerland).* **2021**;10:1792. doi:[10.3390/electronics10151792](#)
- [16] Cersoli T, Barnawi M, Johnson K, et al. 4D printed shape memory polymers: morphology and fabrication of a functional antenna. *Recent Prog Mater.* **2022**;4(2):009. doi:[10.21926/rpm.2202009](#)
- [17] Shah SIH, Lim S. Thermally beam-direction- and beam-width-switchable monopole antenna using origami reflectors with smart shape memory polymer hinges. *IEEE Antennas Wirel Propag Lett.* **2019**;18:1696–1700. doi:[10.1109/LAWP.2019.2928333](#)
- [18] Park S, Park E, Lee M, Lim S, et al. Shape-morphing antenna array by 4D-printed multimaterial miura origami. *ACS Appl Mater Interfaces.* **2023**;15:49843–49853. doi:[10.1021/acsami.3c11425](#)
- [19] Zhang J, Zhang L, Wang C. Kresling origami-inspired reconfigurable antenna with spherical cap. *Int J Mech Sci.* **2022**;227:107470. doi:[10.1016/j.ijmecsci.2022.107470](#)
- [20] Carvalho SS, Reis JRV, Caldeirinha RFS. A state-of-the-art review on 4D printed antennas and other adaptable designs. *IEEE Access.* **2024**;12:62861–62881. doi:[10.1109/ACCESS.2024.3394950](#)
- [21] Verma R, Sharma R. Four-element biodegradable substrate-integrated MIMO DRA with radiation diversity. *J Electromagn Eng Sci.* **2024**;24:109–119. doi:[10.26866/jees.2024.2.r.210](#)
- [22] Goh GL, Zhang H, Chong TH, Yeong WY, et al. 3D printing of multilayered and multimaterial electronics: a review. *Adv Electron Mater.* **2021**;7:2100445. doi:[10.1002/aelm.202100445](#)
- [23] Kuang X, Roach DJ, Wu J, et al. Advances in 4D printing: materials and applications. *Adv Funct Mater.* **2018**;29:1805290. doi:[10.1002/adfm.201805290](#)
- [24] Kim K, Kim Y, Park E, et al. Frequency- and bandwidth-controllable electromagnetic absorber using 3D-printed shape memory meta-wires. *Virtual Phys Prototyp.* **2024**;19:1–14. doi:[10.1080/17452759.2024.2351143](#)
- [25] Skylar-Scott MA, Mueller J, Visser CW, Lewis JA. Voxelated soft matter via multimaterial multinozzle 3D printing. *Nature* **2019**;575:330–335. doi:[10.1038/s41586-019-1736-8](#)
- [26] Bogue R. Shape-memory materials: a review of technology and applications. *Assembly Autom.* **2009**;29:214–219. doi:[10.1108/01445150910972895](#)
- [27] Mirasadi K, Rahmatabadi D, Ghasemi I, et al. Investigating the effect of ABS on the mechanical properties, morphology, printability, and 4D printing of PETG-ABS blends. *Macromol Mater Eng.* **2024**;309:2400038. doi:[10.1002/mame.202400038](#)
- [28] Huang WM, Ding Z, Wang CC, Wei J, Zhao Y, Purnawali H, et al. Shape memory materials. *Mater Today.* **2010**;13:54–61. doi:[10.1016/S1369-7021\(10\)70128-0](#)
- [29] Su J-W, Tao X, Deng H, et al. 4D printing of a self-morphing polymer driven by a swellable guest medium. *Soft Matter.* **2018**;14:765–772. doi:[10.1039/c7sm01796k](#)
- [30] Monzón MD, Paz R, Pei E, et al. 4D printing: processability and measurement of recovery force in shape memory polymers. *Int J Adv Manuf Technol.* **2017**;89:1827–1836. doi:[10.1007/s00170-016-9233-9](#)
- [31] Ehrmann G, Ehrmann A. 3D printing of shape memory polymers. *J Appl Polym Sci.* **2021**;138:e50847. doi:[10.1002/app.50847](#)
- [32] Behl M, Lendlein A. Shape-memory polymers. *Mater Today.* **2007**;10:20–28. doi:[10.1016/S1369-7021\(07\)70047-0](#)
- [33] Bakhtiyari A, Baniasadi M, Baghani M. Development of a large strain formulation for multiple shape-memory-

- effect of polymers under bending. *Int J Mech Sci.* **2021**;204:106560. doi:10.1016/j.ijmecsci.2021.106560
- [34] Zeng C, Liu L, Hu Y, et al. Stair-stepping mechanical meta-materials with programmable load plateaus. *Adv Funct Mater.* **2024**;34:2408887. doi:10.1002/adfm.202408887
- [35] Ren L, Wang Z, Liu Q, et al. 4D printing of shape memory composites with remotely controllable local deformation. *Mater Today Chem.* **2023**;29:101470. doi:10.1016/j.mtchem.2023.101470
- [36] Zeng C, Liu L, Du Y, et al. A shape-memory deployable subsystem with a large folding ratio in China's tianwen-1 Mars exploration mission. *Engineering.* **2023**;28:49–57. doi:10.1016/j.eng.2023.01.005
- [37] Soleyman E, Aberoumand M, Rahmatbadi D, et al. Assessment of controllable shape transformation, potential applications, and tensile shape memory properties of 3D printed PETG. *J Mater Res Technol.* **2022**;18:4201–4215. doi:10.1016/j.jmrt.2022.04.076
- [38] Aberoumand M, Rahmatbadi D, Soltanmohammadi K, et al. Stress recovery and stress relaxation behaviors of PVC 4D printed by FDM technology for high-performance actuation applications. *Sens Actuators A Phys.* **2023**;361:114572. doi:10.1016/j.sna.2023.114572
- [39] Yao T, Wang Y, Zhu B, et al. 4D printing and collaborative design of highly flexible shape memory alloy structures: a case study for a metallic robot prototype. *Smart Mater Struct.* **2020**;30:015018. doi:10.1088/1361-665X/abcc0a
- [40] Otsuka K, Ren X. Recent developments in the research of shape memory alloys. *Intermetallics (Barking).* **1999**;7:511–528. doi:10.1016/S0966-9795(98)00070-3
- [41] Huang W. On the selection of shape memory alloys for actuators. *Mater Des.* **2002**;23:11–19. doi:10.1016/S0261-3069(01)00039-5
- [42] Mehrpouya M, Alberto Biffi C, Lemke JN, et al. Additive manufacturing of architected shape memory alloys: a review. *Virtual Phys Prototyp.* **2024**;19:e2414395. doi:10.1080/17452759.2024.2414395
- [43] Lu HZ, Chen T, Liu LH, et al. Constructing function domains in NiTi shape memory alloys by additive manufacturing. *Virtual Phys Prototyp.* **2022**;17:563–581. doi:10.1080/17452759.2022.2053821
- [44] Zhou L-y, Ye J-h, Fu J-z, et al. 4D printing of high-performance thermal-responsive liquid metal elastomers driven by embedded microliquid chambers. *ACS Appl Mater Interfaces.* **2020**;12:12068–12074. doi:10.1021/acsami.9b22433
- [45] Wang F, Liu C, Yang H, et al. 4D printing of ceramic structures. *Additive Manuf.* **2023**;63:103411. doi:10.1016/j.addma.2023.103411
- [46] Scheithauer U, Weingarten S, John R, et al. Ceramic-based 4D components: additive manufacturing (AM) of ceramic-based functionally graded materials (FGM) by thermoplastic 3D printing (T3DP). *Materials (Basel).* **2017**;10:1368. doi:10.3390/ma10121368
- [47] Ren L, Li B, He Y, et al. Programming shape-morphing behavior of liquid crystal elastomers via parameter-encoded 4D printing. *ACS Appl Mater Interfaces.* **2020**;12:15562–15572. doi:10.1021/acsami.0c00027
- [48] Lai J, Ye X, Liu J, et al. 4D printing of highly printable and shape morphing hydrogels composed of alginate and methylcellulose. *Mater Des.* **2021**;205:109699. doi:10.1016/J.MATDES.2021.109699
- [49] Shah SIH, Lim S. Rf advancements enabled by smart shape memory materials in the microwave regime: a state-of-the-art review. *Mater Today Phys.* **2024**;44:101435. doi:10.1016/J.MTPHYS.2024.101435
- [50] Jape S, Garza M, Ruff J, et al. Self-foldable origami reflector antenna enabled by shape memory polymer actuation. *Smart Mater Struct.* **2020**;29:105011. doi:10.1088/1361-665X/abaac2
- [51] Lee M, Lee S, Lim S. Electromagnetic control by actuating kirigami-inspired shape memory alloy: thermally reconfigurable antenna application. *Sensors.* **2021**;21:3026. doi:10.3390/s21093026
- [52] Zeng W, Wang W, Sonkusale S. Temperature sensing shape morphing antenna (ShMoA). *Micromachines (Basel).* **2022**;13:1673. doi:10.3390/mi13101673
- [53] Mazlouman SJ, Mahanfar A, Menon C, et al. Square ring antenna with reconfigurable patch using shape memory alloy actuation. *IEEE Trans Antennas Propag.* **2012**;60:5627–5634. doi:10.1109/TAP.2012.2213053
- [54] Shah SIH, Shah SS, Bernhardsson E, et al. Shape memory alloy-based fluidically reconfigurable metasurfaced beam steering antenna. *IEEE Access.* **2023**;11:102271–8. doi:10.1109/ACCESS.2023.3315318
- [55] Yi J, Wei M, Lin M, et al. Frequency-tunable and magnitude-tunable microwave metasurface absorbers enabled by shape memory polymers. *IEEE Trans Antennas Propag.* **2022**;70:6804–6812. doi:10.1109/TAP.2022.3161560
- [56] Bark S, Jeong H, Park E, et al. Biaxially stretchable meta-material absorber with a four-dimensional printed shape-memory actuator. *Int J Mech Sci.* **2024**;283:109729. doi:10.1016/j.ijmecsci.2024.109729
- [57] Shah SIH, Sarkar A, Phon R, et al. Two-dimensional electromechanically transformable metasurface with beam scanning capability using four independently controllable shape memory alloy axes. *Adv Opt Mater.* **2020**;8:2001180. doi:10.1002/adom.202001180
- [58] Phon R, Kim Y, Park E, et al. Mechanical and self-deformable spatial modulation beam steering and splitting metasurface. *Adv Opt Mater.* **2021**;9:2100821. doi:10.1002/adom.202100821
- [59] Jeong H, Park E, Lim S. Four-dimensional printed shape memory metasurface to memorize absorption and reflection functions. *ACS Appl Mater Interfaces.* **2021**;13:59487–59496. doi:10.1021/acsami.1c17968
- [60] Kaneda N, Deal WR, Yongxi Q, et al. A broad-band planar quasi-yagi antenna. *IEEE Trans Antennas Propag.* **2002**;50:1158–1160. doi:10.1109/TAP.2002.801299
- [61] Feng X, Zheng S, Ren D, et al. Investigating the thermal runaway mechanisms of lithium-ion batteries based on thermal analysis database. *Appl Energy.* **2019**;246:53–64. doi:10.1016/j.apenergy.2019.04.009
- [62] Lopez CF, Jeevarajan JA, Mukherjee PP. Experimental analysis of thermal runaway and propagation in lithium-ion battery modules. *J Electrochem Soc.* **2015**;162:A1905–A1915. doi:10.1149/2.0921509jes
- [63] Kim Y, Phon R, Jeong H, et al. Thermal spiral inductor using 3D printed shape memory kirigami. *Sci Rep.* **2022**;12:22246. doi:10.1038/s41598-022-26923-3