



Pulse-mode operation of a diode-pumped alkali laser combining a fiber ring cavity

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Abstract: A diode-pumped alkali laser (DPAL) has potential advantages for high-power laser operation due to the high quantum efficiency of alkali elements and the benefits inherent in gas lasers. Particularly, pulse-mode DPALs can be applied potentially in various fields such as range finding and materials processing, but pulse generation in DPALs without using active devices has been largely unexplored. In this study, we report passive pulse generation in a cesium DPAL that integrates a fiber ring resonator. When a narrowband pump wave is coupled into a fiber ring resonator spanning several tens of meters, Brillouin scattering induces the generation of a counter-propagating Stokes wave. Under these conditions, owing to the narrow linewidth characteristics of the cesium gain medium, it was confirmed that the pump and Stokes waves experience differential absorption, which consequently leads to the amplitude modulation of the pump and Stokes waves within the ring resonator. The modulated pump wave induces laser oscillation at 894 nm through the cesium gain medium, thereby generating pulses with a high repetition rate of up to 3.4 MHz and a minimum pulse width of 123 ns. The results of this study are expected to lead to the realization of a cost-effective and compact alkali gain medium-based pulsed laser.

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1. Introduction

Diode-pumped alkali-vapor laser (DPAL), which uses alkali vapor as the gain medium, is pumped by narrowband laser diodes and exhibits characteristics typical of gas lasers. Due to these properties, the volume of alkali vapor can be readily expanded to increase the amount of gain medium, thereby facilitating an increase in laser output power [1,2]. Moreover, by employing a recirculating system, continuous thermal management is achievable, effectively mitigating thermal lensing issues during high-power laser operation [3]. Additionally, owing to the intrinsic energy-level characteristics of alkali elements, the quantum efficiency exceeds 95%, showing a higher quantum efficiency than conventional solid-state lasers [1,2,4]. Based on these advantages, continuous research has been conducted on DPAL for high-power lasers [1–5].

A pulse-mode DPAL delivering pulsed laser output has the potential to be applied in various fields such as laser cleaning, range-finding systems, and material processing [6–8]. Several studies on pulse-mode DPAL have been conducted to date. For example, by modulating the pump laser diode (LD), a potassium-DPAL with a repetition rate of 100 Hz, an output power of 16 W, and a pulse width of 30 μ s was reported in 2014 [9]; in 2018, a similar method was employed in a cesium-DPAL, which exhibited a repetition rate of 7 kHz, an output power of 0.3 W, and a pulse width of 26 μ s [10]. Besides, approaches that implement pulse-mode DPAL by inserting external modulation devices into the resonator have also been reported. In 2019, a cavity-dumping DPAL using electro-optical modulation, featuring a pulse width of 14 ns, a peak power of 77 W, and a repetition rate of 100 Hz, was reported [11]. Moreover, cesium-DPAL with

a repetition rate of 1 MHz, an output power of 0.2 W, and a pulse width of 238 ns was proposed by employing an acousto-optic modulator into the resonator [12].

Active pulse-mode DPAL allows for relatively easy control of pulse width and repetition rate, but it requires the construction of complex systems incorporating active devices, which can hinder the implementation of a cost-effective and compact laser system. In order to overcome these drawbacks, a passive mode-locking cesium-DPAL utilizing a cesium gain medium as a saturable absorber was proposed for the first time, though the mode-locked laser output is not sufficiently stable [13].

In this study, we propose a novel passive pulse-mode DPAL by combining a fiber ring resonator with a cesium-DPAL. By exploiting the modulation characteristics of the Stokes wave that is generated through stimulated Brillouin scattering (SBS) in a fiber ring resonator [14–17], a cesium gain medium-based laser pulse source was realized, achieving a maximum repetition rate of 3.4 MHz and a minimum pulse width of 123 ns. The fiber cavity coupled passive pulse-mode DPAL developed in this study exhibits a relatively simple structure, excellent output beam profile, higher repetition rates, and narrower pulse widths than conventional active pulse-mode DPAL. We believe that, by combining with an alkali amplifier [18–23], our configuration could contribute to the realization of a high-power pulse-mode DPAL for various applications.

2. Operation principle

Figure 1(a) illustrates a schematic diagram of a pulsed DPAL that combines a fiber ring resonator. When a narrow bandwidth pump beam (852 nm) is coupled to the fiber resonator counterclockwise, the SBS [24] generates a Stokes wave that propagates in the direction opposite to the pump beam. In this process, part of the pump beam energy is converted into the Stokes wave, and then the remaining energy absorbed by the cesium gain medium induces laser emission at 894 nm (Cesium D_1 transition). Figure 1(b) presents a schematic diagram in the spectral domain, illustrating the absorption and emission characteristics of the cesium gain medium as well as the features of the Stokes wave. In the experiment, the absorption linewidth of the 500 torr buffer gas-filled cesium gain medium was measured to be 38 GHz at 852 nm (D_2 line) for pump absorption and 46 GHz at 894 nm (D_1 line) for laser emission. In addition, the Stokes wave has an absorption linewidth of approximately 90 MHz at the frequency shifted by about 20 GHz from the pump wavelength [25]. Thus, although the Stokes wave undergoes partial absorption at the cesium gain, due to the nature of the narrow spectral linewidth of the cesium gain, some remaining Stokes signal is coupled into the fiber cavity again, providing feedback. It is known that when the feedback signal is weak enough, the Stokes wave is modulated into pulses with a repetition rate matching that of the laser resonator, which leads to a pulsed Brillouin laser [14–17]. The pulsed Stokes wave periodically depletes the pump beam, eventually leading to the pulsed-mode operation of DPAL.

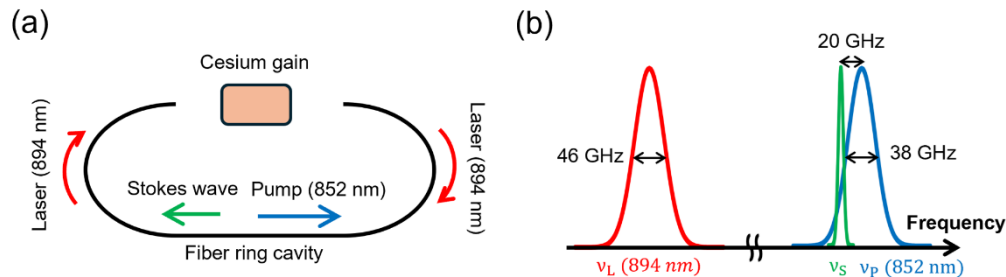


Fig. 1. Schematic diagram of the operating principle of pulsed DPAL. (a) Schematic of a fiber ring resonator combined with a cesium gain medium. (b) Profile of the absorption and emission of the cesium gain medium and the absorption of the Stokes wave in the frequency domain.

3. Experimental setup

Figure 2 shows a schematic of the laser experiment setup consisting of a fiber laser and a cesium vapor gain medium. A distributed Bragg reflector (DBR) laser (Photodigm) with a linewidth of approximately 5 MHz was amplified using a tapered amplifier (Thorlabs) to generate the pump beam. The pump beam then enters the laser resonator through the fiber-type wavelength division multiplexers (WDM) coupler. The maximum available power of the pump beam coupled to the fiber cavity is measured at 320 mW. After passing through the 9:1 output coupler (OC), the pump beam is incident on the long-length fiber spool, where pump energy is partially converted into Stokes waves. The pump beam is directed through a lens (Focal length: 10 cm) after a collimator and then passes through a 9:1 beam splitter (BS). Here, a 10% port (Port1) is used to monitor the characteristics of the pump beam. The remainder is directed into a cesium cell (buffer gas: 500 torr ethane, length: 2 cm, quartz cell) and absorbed. The inset in Fig. 2 shows a photographic image of the free-space section of the laser resonator. To maintain the cesium cell at a constant temperature, the heating wire wrapped the cesium cell, as depicted in the inset, and temperature control and monitoring were performed. An isolator was used to ensure unidirectional laser oscillation in the ring resonator, and a fiber polarization controller (PC) was employed to adjust the polarization of the light in the resonator. The laser output (894 nm) and the Stokes beam were monitored at port 2 through a 9:1 output coupler (OC). In our laser configuration, the pump beam (852 nm) and the laser beam (894 nm) propagate together in the fiber ring resonator, which facilitates the spatial coupling between the pump and signal in the laser [22,23]. In addition, an excellent beam profile can be obtained in our DPAL because the laser output is delivered through a single-mode optical fiber (780 HP) at the operating wavelength.

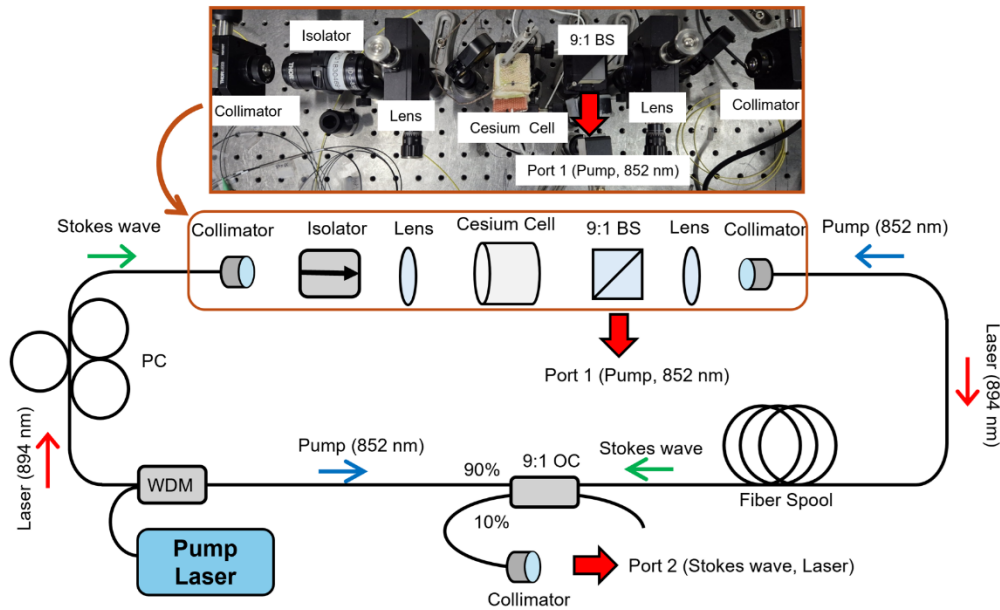


Fig. 2. Experimental schematic of a DPAL incorporating an optical fiber. Blue, green, and red arrows indicate the direction pump, Stokes, and laser beam propagation in the cavity, respectively. PC (Polarization controller), WDM (Wavelength division multiplexers), BS (Beam splitter), OC (Output coupler). (inset: photograph of the free space part).

4. Results and discussion

4.1. Stokes beam modulation in the fiber resonator

When a narrowband pump beam propagates in the long fiber ring resonator that constitutes the DPAL, a Stokes wave traveling in the opposite direction is generated via Brillouin scattering. If the Stokes wave undergoes substantial losses while providing feedback, it is known to exhibit periodic modulation phenomena [14–17]. To experimentally verify this, we maintained the cesium cell at room temperature to minimize the absorption of both the pump and Stokes waves in the configuration shown in Fig. 2. The fiber spool used in the experiment was approximately 75 m long. As the pump power increased, we observed the amplitude modulation of the Stokes wave, which became apparent from a pump power of 130 mW. Figure 3(a) displays the pump and Stokes wave profiles measured at Port 1 and Port 2 using an oscilloscope under an applied pump power of 320 mW. Stable pulse formation was observed in both the Stokes and pump waves. The repetition rate was approximately 2.3 MHz, matching the free spectral range (FSR) calculated from the total resonator length of ~89 m. The modulated Stokes wave exhibited a pulse width of 37 ns, while the depleted pump wave had a pulse width of 162 ns.

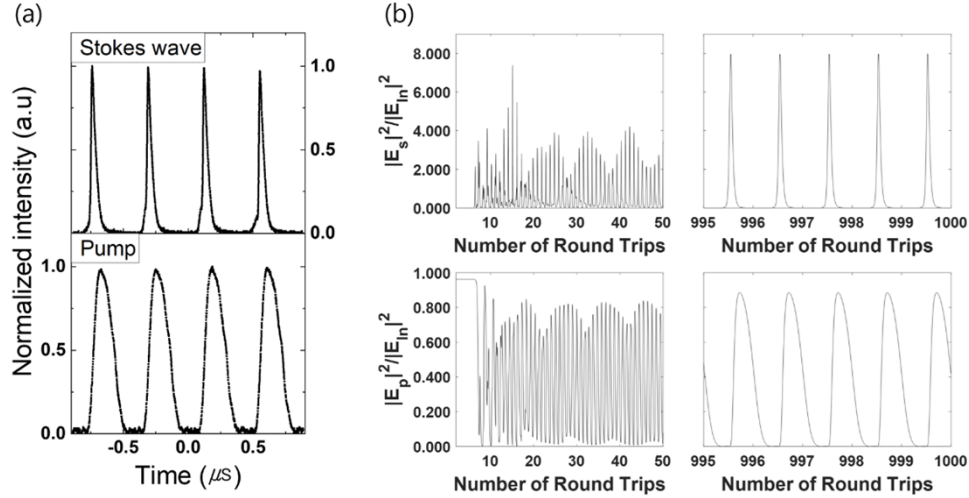


Fig. 3. Temporal dynamics of the pump and Stokes waves in the fiber ring resonator under an applied pump power of 320 mW pump power. (a) Experimental results. (b) Simulation results.

In addition, we performed a computational simulation of the modulation behavior of the Stokes and pump waves in the fiber ring resonators. The governing equations can be expressed as below [14].

$$\begin{aligned}
 \left(\partial_t + \frac{c}{n} \partial_x + \gamma_e \right) E_p &= -K E_s E_a + i K_r [|E_p|^2 + 2|E_s|^2] E_p \\
 \left(\partial_t - \frac{c}{n} \partial_x + \gamma_e \right) E_s &= K E_p E_a^* + i K_r [2|E_p|^2 + |E_s|^2] E_s \\
 (\partial_t + \gamma_a) E_a &= K E_p E_s^* + f_n
 \end{aligned} \tag{1}$$

Here E_p , E_s , and E_a represent the amplitudes of the pump, Stokes, and acoustic waves, respectively. c denotes the speed of light, and n ($=1.455$) is the refractive index of the optical fiber. K ($= 30 \text{ m}^{-1} \text{ s}^{-1} \text{ V}^{-1}$) is the SBS coupling constant, K_r ($= 1.5 \times 10^{-7} \text{ m}^2 \text{ V}^{-2} \text{ s}^{-1}$) is the Kerr constant, γ_e ($= 4.7 \times 10^4 \text{ s}^{-1}$) is the damping coefficient for the optical wave, γ_a ($= 3 \times 10^8 \text{ s}^{-1}$) is the damping coefficient for the acoustic wave, and f_n is the Langevin source term associated

with spontaneous Brillouin scattering. The boundary conditions for the fiber ring laser are given by the following equation [14].

$$E_p(0, t) = E_{cw}, \quad E_s(L, t) = \sqrt{R}E_s(0, t) \quad (2)$$

Here E_{cw} is the amplitude of the electric field of the continuous wave (CW) pump wave, and $R (= 9.9 \times 10^{-5})$ denotes the fraction of the Stokes wave that feeds back into the resonator. Equation (1) was numerically calculated using the characteristic method [14] and a fourth-order Runge-Kutta algorithm. Figure 3(b) shows the temporal dynamics of the pump and Stokes wave profiles as the number of round trips in the fiber ring resonator increases. When the number of round trips was low (10~50), unstable modulation of both the Stokes and pump waves, caused by SBS-induced modulation instability, was observed. The pulse mode Stokes wave is observed to be stable as the number of round trips increases (> 600). The modulation of the Stokes wave subsequently causes the pump wave to be periodically depleted, as shown in the figure. Numerical simulations reveal pulse widths of 170 ns for the pump wave and 28 ns for the Stokes wave, with pulses recurring every round trip at a repetition rate of 2.3 MHz. These simulation results show reasonable agreement with the experimental observations.

4.2. Pulse-mode DPAL

For the laser operation in DPAL, we set the temperature of the cesium cell to 111°C so that the pump wave (852 nm) was fully absorbed in the cesium gain medium up to our available power of 320 mW in the experimental setup of Fig. 2. The characteristics of the pump wave and laser beam were monitored by Port 1 and Port 2, respectively. At port 2, a long-pass filter with a center wavelength of 875 nm was used to eliminate the Stokes wave. Figure 4(a) displays the pump and laser signal profiles measured by the oscilloscope at various pump power levels. At 107 mW pump power (below the SBS threshold), the DPAL laser operated in continuous-wave (CW) mode without modulation. When the pump power exceeded 156 mW, modulation emerged in both the pump and laser outputs. Further increases in pump power enhanced the modulation depth, producing pulsed output. The observed modulation frequency of approximately 2.3 MHz corresponds to the free spectral range determined by the resonator length. At an applied pump power of 320 mW, the measured pulse widths were 142 ns for the pump wave and 123 ns for the laser beam. Figure 4(b) presents laser output power versus pump power. Below 150 mW pump power, where SBS is absent, the slope efficiency remains constant. Above this threshold, SBS initiation converts part of the pump beam into a Stokes wave, reducing the pump power delivered to the cesium cell and consequently decreasing the slope efficiency.

Figure 4(c) displays the laser output versus cesium cell temperature at 320 mW pump power. The laser output increases gradually with temperature due to enhanced pump power absorption in the cesium gain medium. However, above 111°C, significant reabsorption in the cesium gain occurs, leading to reduced laser output. The maximum output power of 3.5 mW was achieved at the optimal cell temperature of 111°C.

Figure 5(a) presents the operating characteristics of the pulsed DPAL at 320 mW pump power and 111°C cesium cell temperature, with fiber spool lengths varying from 50 m to 125 m in 25 m increments. As the fiber length increases, the resonator's FSR decreases, resulting in corresponding reductions of the laser repetition rate to 3.4, 2.4, 1.9, and 1.5 MHz. Figure 5(b) displays the laser output power and duty cycle variations versus fiber spool length. Increasing the fiber length from 50 m to 125 m reduces the laser output from 5.8 mW to 1.4 mW, due to enhanced pump depletion caused by stronger Stokes wave amplification in longer fibers. We also observed that the pulse width remains almost unchanged with fiber spool length. Concurrently, the pulse mode duty cycle decreases from 51% to 20%. These findings demonstrate that the pulsed DPAL's repetition rate can be effectively tuned through fiber length adjustment.

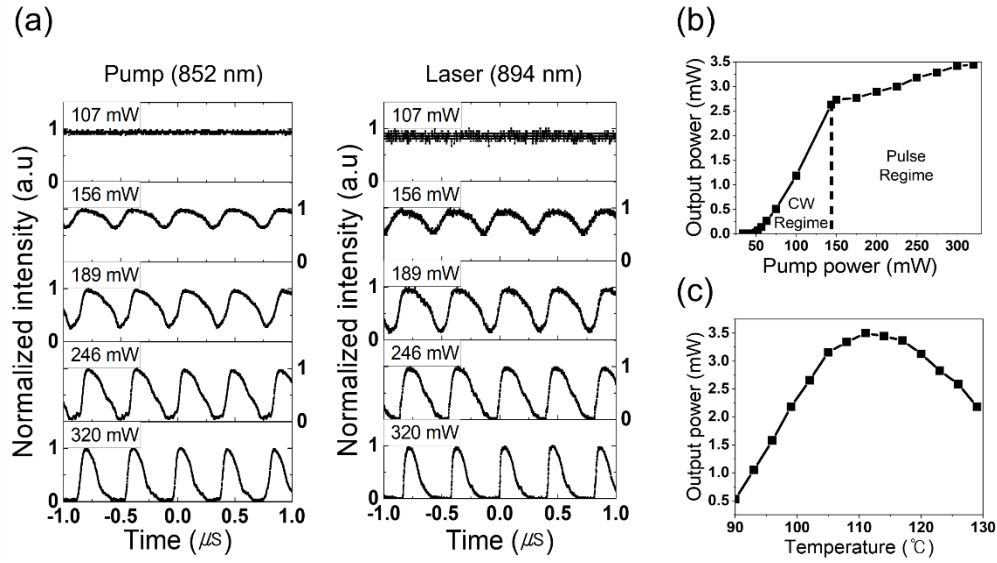


Fig. 4. Experimental results of the pulsed DPAL. (a) Temporal dynamics of the pump (852 nm) and laser (894 nm) profiles with increasing pump power. (b) Laser output power according to the pump power. (c) Laser output power according to the temperature of the cesium cell at the applied pump power of 320 mW.

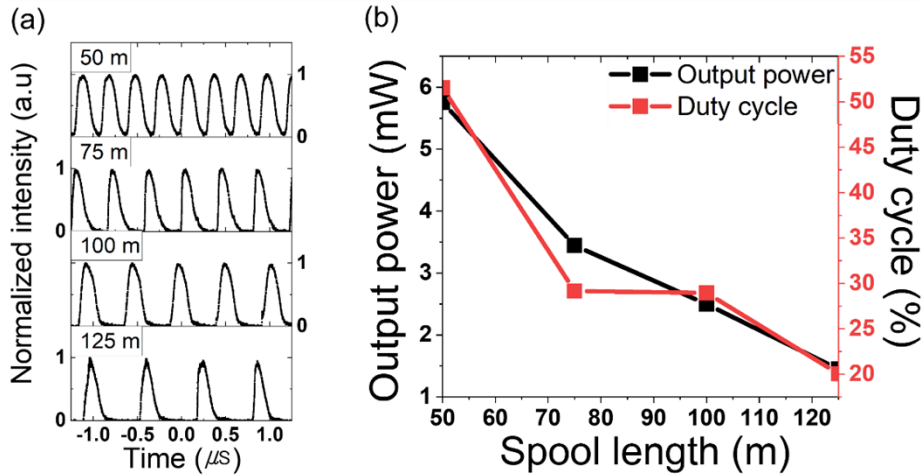


Fig. 5. Pulsed DPAL characteristics at various lengths of fiber. (a) Temporal dynamics of the pulsed DPAL profile. (b) Laser output and duty cycle as a function of fiber spool length.

5. Conclusion

We have developed a novel passively pulsed DPAL system by integrating a fiber ring cavity with a cesium DPAL. Both simulations and experiments demonstrate that the Stokes beam (852 nm) undergoes SBS-induced modulation in the fiber ring resonator, which subsequently generates periodic pump beam modulation and enables pulsed DPAL operation. The system produces pulses with a minimum width of 123 ns and a maximum repetition rate of 3.4 MHz. It should be noted that our DPAL oscillator exhibits relatively low optical conversion efficiency due to

several factors, including coupling loss in a hybrid cavity configuration with fibers and bulk components, and back-scattered loss of Stokes wave during pulse formation. When coupled with an energy-efficient alkali amplifier [18–23], this laser architecture could generate high-power pulsed alkali laser output with superior beam quality and high repetition rates. Such master oscillator power amplifier (MOPA) systems have potential for industrial applications [6,8,26]. Furthermore, the fiber ring resonator approach, while demonstrated here for cesium DPALs, is readily extendable to other alkali elements, offering a versatile platform for achieving pulsed DPAL operation across multiple wavelength regimes

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Data availability. Data will be made available on request.

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