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# Pulse operation of linearly polarized diode-pumped cesium-vapor laser based on acousto-optical modulation

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**Abstract:** We present a pulse linearly polarized diode-pumped cesium-vapor laser (Cs-DPAL) based on an acousto-optical modulator (AOM) for the first time. The continuous wave (CW) performance of the Cs-DPAL was first investigated, and ~1.05 W linearly polarized CW laser was obtained. Next, we applied a rectangular signal to modulate the AOM. The Cs-DPAL realized a pulse laser output with a maximum repetition rate of 1 MHz and minimum pulse duration of 238 ns. To the best of our knowledge, this is the highest repetition rate reported thus far for a diode-pumped alkali-vapor laser (DPAL). The maximum output power of the pulse laser reached ~0.20 W, and the corresponding $M_x^2$ and $M_y^2$ factors were 1.31 and 1.19, respectively. Finally, we realized code modulation of the Cs-DPAL, with a maximum bit rate of 2 Mb/s.



## 1. Introduction

Diode-pumped alkali-vapor lasers (DPALs) have the advantages of both gas lasers and solid lasers, such as a high quantum-efficiency, large stimulated-emission cross-section, small refractive index perturbance, good optical characteristics, easy heat elimination and rich laser wavelengths, which can be used to obtain near-infrared laser output with high efficiency, high power and high beam quality [1–6]. Usually, DPALs operate in the continuous-wave (CW) regime pumped by CW pump laser diodes (LDs) [7,8]. However, pulse lasers, especially high-power high-repetition-rate pulse lasers, are often used in laser communication, light detection and ranging systems (LIDARs), material processing, laser cleaning, and so on [9–12]. Therefore, it is necessary to develop pulse DPALs for expanding their application fields.

The most common method used for generating the pulse laser output of DPALs is based on employing temporally or spectrally modulated LDs as the pump source. In this regard, Zhdanov et al. demonstrated a pulse cesium-vapor DPAL (Cs-DPAL) transversely pumped by pulse LD arrays. Using an unstable resonator, the maximum output power reached 49 W with a pulse width of 500 μs and repetition frequency of 20 Hz [13]. Subsequently, they presented a potassium-vapor DPAL (K-DPAL) pumped by a pulse diode laser stack with a duration of 30 μs and repetition rate of 100 Hz. The maximum output power obtained was ~16 W [14]. Hong et al. realized pulse modulation in a Cs-DPAL by fast spectral modulation of a pump LD, in which a wavelength near the D2 line of the Cs atom provided periodic absorption. The highest repetition rate reached 7.0 kHz with a short pulse width of 26 μs [15]. Previously, we have also reported a pulse Cs-DPAL pumped by a pulse LD. A stable pulsed laser with a maximum average output power of 2.6 W is obtained. The maximum repetition rate can reach 1 kHz with a pulse width of 18 μs [16]. By intracavity frequency doubling, a 447.3 nm pulse laser was investigated theoretically and experimentally, with a maximum repetition rate of 1 kHz achieved [17,18]. However, in all these approaches, subject to the modulation rate of the

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pump LDs, the above DPALs can hardly output a high-repetition-rate pulse laser beam. Meanwhile, for high-power LDs, the high-speed modulated technical scheme is complex and the corresponding cost is high.

Electro-optical modulation is also an effective method for obtaining pulse laser output of DPALs. Recently, Endo demonstrated a pulse Cs-DPAL using an electro-optical cavity-dumping technique. A pulse width of 14 ns with a peak power of 77 W was generated, with a repetition rate of 100 Hz. The peak power was 25 times the CW output power, which indicated that electro-optical cavity-dumping DPALs can enable one to obtain enhanced pulse output [19]. However, the Pockels cell used in electro-optical modulation should be driven by a high-voltage signal. Usually, it is hard to modulate a high-voltage signal with a high repetition rate, which limits the repetition rate of electro-optically modulated DPALs.

To achieve high-power, high-repetition-rate pulse laser output for DPALs, a master oscillator power amplifier (MOPA) structure can be considered. The seed laser source generates a high-repetition-rate pulse laser, and the power can be amplified by the alkali vapor amplifier. In 2019, Cai et al. proposed a temporally modulated Cs vapor amplifier. The master oscillator adopted a low-power distributed feedback (DFB) laser modulated by a sinusoidal signal with a repetition rate of 1 MHz. The highest average power amplification factor obtained was 2359, which proved the high gain of the alkali medium. However, due to the low seed power (60 μW), the amplified spontaneous emission (ASE) became much stronger with higher cell temperature and higher pump power. As a result, the laser output from the amplifier nearly became a CW laser. Therefore, more stages of amplifiers should be applied to solve this problem; such a configuration would be complicated [10].

An alternative method is based on the use of acousto-optically modulated pulse DPALs as the seed laser source. Compared with a DFB laser, the acousto-optically modulated DPALs can reach higher output power and are not sensitive to the backward ASE from the amplifiers. The modulated frequency range of the acousto-optical modulator (AOM) is wide and the technology is very mature. Therefore, the AOM has been extensively applied in pulse solid-state lasers [20,21], fiber lasers [22,23] and gas lasers [24]. On the other hand, if the AOM is controlled by a coded signal, the acousto-optically modulated laser can also output a coded pulse laser [25]. However, there is no public report for the experimental investigation of acousto-optically modulated pulse DPALs.

Against this backdrop, in this paper, we proposed an acousto-optically modulated Cs-DPAL to obtain a pulse laser output for the first time. The pump source was a CW LD, and the Cs-DPAL was linearly polarized. An AOM was used for modulating the intensity of the linearly polarized laser. When the AOM was closed, the performance of the linearly polarized CW Cs-DPAL was first investigated. Then, we applied a high-repetition rate rectangular signal to modulate the AOM; a pulse laser was obtained with a maximum repetition rate of 1 MHz and minimum pulse duration of 238 ns. To the best of our knowledge, this is the highest repetition rate reported thus far in DPALs. The maximum output power of the pulse laser reached ~0.20 W, and the corresponding $M_x^2$ and $M_y^2$ factors were 1.31 and 1.19, respectively. Finally, we realized high-speed coded pulse laser output for the acousto-optically modulated Cs-DPAL. The maximum bit rate of the coded pulse laser reached up to 2 Mb/s. Further, by using a MOPA structure, the pulse Cs-DPAL can act as a seed source and a high-power pulse laser with high beam quality can be obtained by amplifying the pulse seed laser.

## 2. Experimental setup

The schematic of the acousto-optically modulated Cs-DPAL is shown in Fig. 1. The pump source was a fiber-coupled CW LD operating at a wavelength of 852.25 nm with a line-width of 0.17 nm. The numerical aperture of the fiber was 0.22 with a diameter of 400 μm. The pump beam was coupled into the Cs vapor cell by a coupling system, which comprised two aspheric plano-convex lenses, $L_1$ and $L_2$. The focal lengths of the plano-convex lens were 20

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mm and 50 mm, respectively, corresponding to a pump beam waist radius of 500 μm at the center of the cell. Both lenses were antireflection-coated at 852.3 nm with the transmission greater than 98%. The Cs vapor cell was filled with metallic cesium and buffer gases including ethane at 20 kPa and helium at 60 kPa. The diameter of the cell was 15 mm with an intracavity optical length of 5 mm. Both ends of the cell were antireflection-coated at both 852.3 nm and 894.6 nm and the transmissions were greater than 99.5%. The temperature of the cell was controlled by an oven operating at 110 °C. The length of the stable laser resonator was 200 mm, and the cavity consisted of a flat dichroic mirror and an output coupler. The dichroic mirror was antireflection-coated at 852.3 nm with 97.5% transmission, and high-reflection-coated at 894.6 nm with 99.9% transmission. The output coupler was a concave mirror with a curvature radius of 500 mm and 48.79% reflection at 894.6 nm. The AOM (I-QS041-1C10G-3-HI11, Gooch&Housego) was designed to modulate the intensity of linearly polarized light vertical to the base, i.e., p-polarized light, as shown in Fig. 1. Therefore, a polarized beam splitter (PBS) was used as a polarizer, which makes the DPAL output a p-polarized laser. The interaction material of the AOM was composed of a crystal quartz with a transmission of more than 96% at 894.6 nm, and the active aperture of the AOM was 1 mm. The AOM was powered by a radio frequency (RF) driver, the operating mode of which was controlled by a modulated signal from a signal generator (33500B, Agilent). When the signal voltage became low, the RF driver switched on and the AOM started running. On the other hand, when the signal voltage was high, the RF driver switched off, and the AOM stopped running.

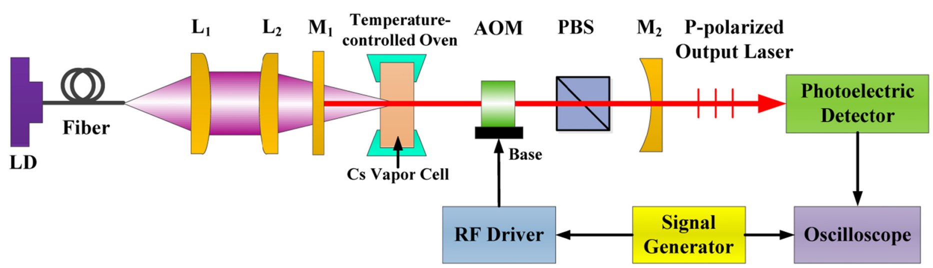


Fig. 1. Schematic of a linearly polarized diode-pumped cesium-vapor laser (Cs-DPAL) based on acousto-optical modulation.

## 3. Experimental results and discussion

### *3.1. CW operation*

In our study, we first investigated the characteristics of the CW Cs-DPAL. Without the AOM and the PBS, we measured the output power of the p-polarized and s-polarized laser, and the result is depicted in Fig. 2. With a maximum pump power of 8.57 W, the output power of the p-polarized laser and s-polarized laser was 0.77 W and 0.80 W, respectively. The corresponding maximum total output power was 1.57 W, with an optical-to-optical conversion efficiency of 18.3%. Compared with our previously reported result [16], the conversion efficiency was lower. The reason for this was the fact that the length of the Cs-DPAL resonator was longer for placing the AOM and the PBS.

Then, we inserted the AOM and the PBS into the cavity, as shown in Fig. 1. When the AOM was closed, the output power of the p-polarized and s-polarized laser as a function of pump power is depicted in Fig. 3. With a maximum pump power of 8.57 W, the output power of the p-polarized laser and s-polarized laser was 1.055 W and ~8 mW, respectively, which indicated that the polarization ratio was >20 dB. Therefore, the output laser became linearly polarized with p-polarization due to the PBS. Because of the insertion loss of the AOM and the PBS, the corresponding optical-to-optical conversion efficiency was reduced to 12.3%.

The spectrum of the Cs-DPAL was recorded by a fiber optical spectral analyzer. As shown in Fig. 3, the central wavelength of the Cs-DPAL was 894.57 nm.

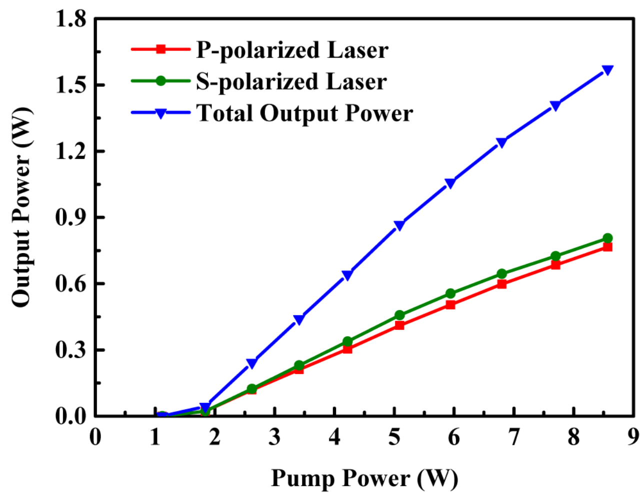


Fig. 2. Output power of the Cs-DPAL as a function of pump power without the AOM and the PBS.

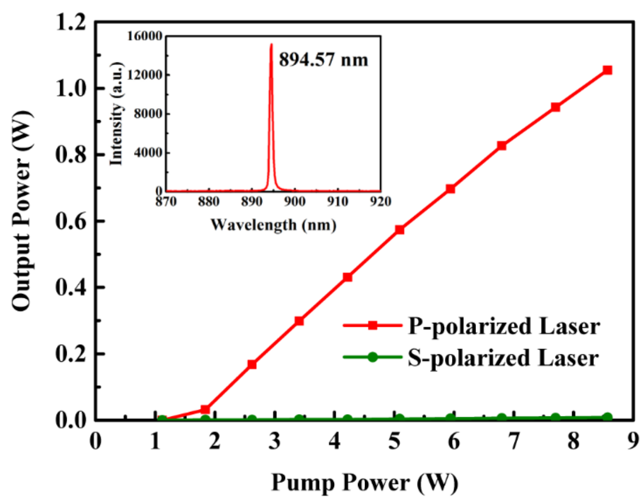


Fig. 3. Output power of the p-polarized and s-polarized laser as a function of pump power when inserting the AOM and the PBS; the laser spectrum is shown in the inset.

### *3.2. High-repetition-rate pulse operation*

As a next step, the high-repetition-rate pulse modulation of the Cs-DPAL was investigated in our experiments. The switch mode of the AOM was controlled by a modulated signal, the waveform of which was rectangular with a repetition rate chosen from 10 kHz to 1 MHz with a duty cycle of 20%. The temporal waveform of the output laser was measured by using a photoelectric detector (APD110C/M, Thorlabs) and oscilloscope (DSO-X 4104A, Keysight).

When the pump power was 8.57 W, the waveforms of the modulated signal and the laser intensity with different repetition rates is shown in Fig. 4. We observed that the output laser of the Cs-DPAL was modulated by the AOM. When the modulated signal voltage became high, the AOM switched off and the intensity of the p-polarized laser was high. With the signal voltage falling, the AOM turned on and the p-polarized laser was suppressed by the diffraction loss of the AOM. Therefore, the laser intensity fell to nearly zero.

The repetition rate of the pulse laser was the same as that of the modulated signal. The maximum repetition rate of the acousto-optically modulated Cs-DPAL could reach 1 MHz, which is much higher than schemes based on LD pump modulation [13–16] and electro-optical modulation [19]. By controlling the modulated signal, we can obtain a Cs-DPAL pulse laser with a repetition rate that is tunable over a wide range.

The laser pulse duration was also related to the modulated signal. As shown in Fig. 4, when the repetition rate was 10 kHz, 100 kHz, 400 kHz, and 1 MHz, the pulse width of the modulated signal was 20 μs, 2 μs, 500 ns, and 200 ns, respectively, and the corresponding laser pulse duration was 20.1 μs, 1.98 μs, 566 ns, and 238 ns, respectively. This result suggested that the minimum pulse duration of the acousto-optically modulated Cs-DPAL was far smaller than that obtained using methods based on LD pump modulation [13–16]. We can also adjust the pulse duration over a wide range by controlling the modulated signal.

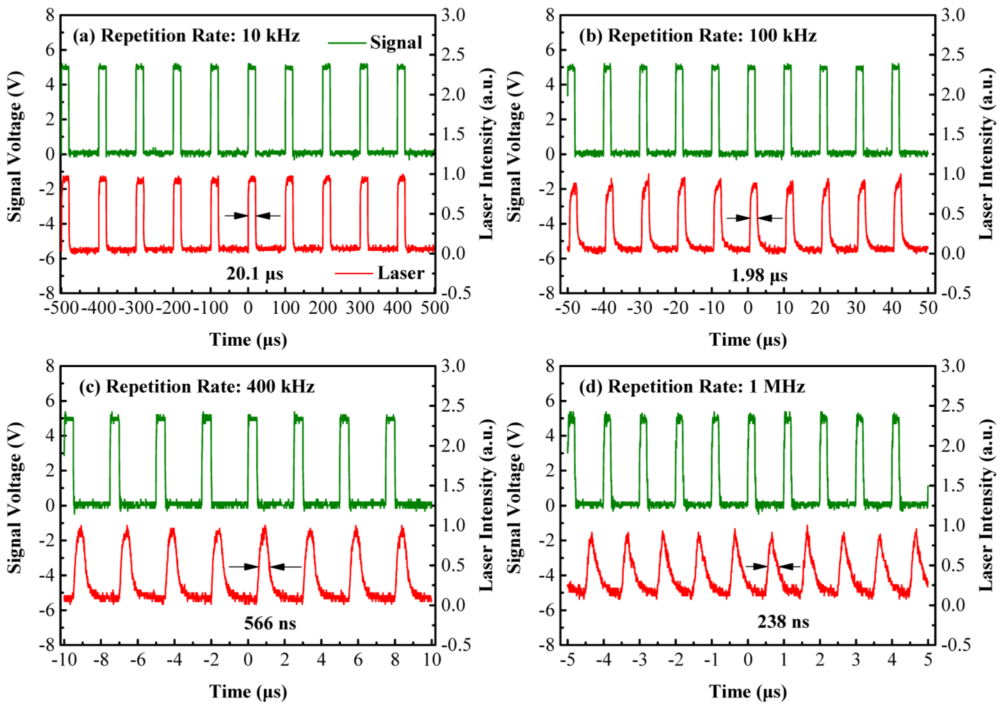


Fig. 4. Waveforms of the modulated signals and output laser operating at (a) 10 kHz, (b) 100 kHz, (c) 400 kHz, and (d) 1 MHz.

The average power and peak power of the pulse laser was also investigated for a pump power of 8.57 W. The results for the modulated signal operating from 10 kHz to 1 MHz with a duty cycle of 20% are summarized in Fig. 5. The average power and the peak power were almost unchanged for different repetition rates, with values of ~0.20 W and ~0.95 W, respectively. When the AOM switched off, the resonator immediately changed from a low-Q state to a high-Q state. Then, an enhanced pulse should have been produced. However, in this experiment, the peak power was no more than the CW output power. The main reason for this was that the radiative lifetime of the upper laser level of the Cs atoms is only 34.9 ns [26], but the switching time of the AOM was ~100 ns. The radiative lifetime of the Cs atoms was too short to store energy in the upper laser level when the AOM was running. As a result, there was not enough energy to generate a high-peak-power pulse while the AOM was turned off. For K-DPALs and rubidium-vapor DPALs (Rb-DPALs), the acousto-optically modulated configuration also cannot generate an enhanced pulse output for the same reason. To solve this problem, an alkali-vapor amplifier can be used to improve the pulse peak power, which we will undertake in the future.

The beam quality of the acousto-optically modulated Cs-DPAL operating at 1 MHz was measured by means of the knife-edge method, and the result is summarized in Fig. 6. At the maximum output power, the $M_x^2$ and $M_y^2$ factors were 1.31 and 1.19, respectively. Therefore, by amplifying the Cs-DPAL, we can obtain a high-power pulse laser with high beam quality.

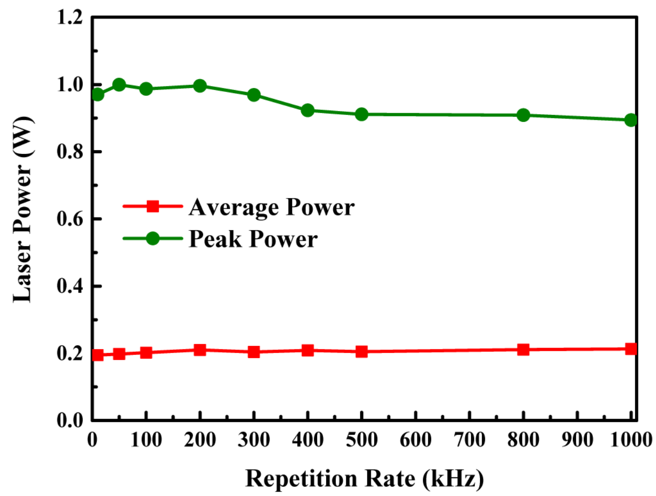


Fig. 5. Average power and peak power for different repetition rates with a duty cycle of 20% for a pump power of 8.57 W.

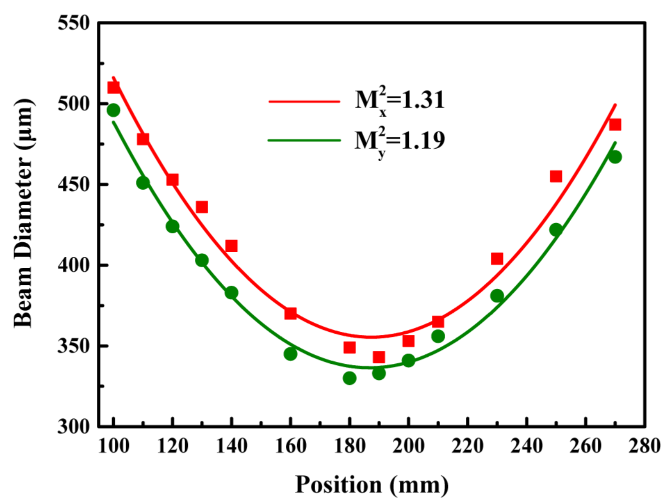


Fig. 6. $M^2$ factors for the pulse laser operating at 1 MHz at maximum output power.

### 3.3. Code modulation

The above results indicated that the temporal waveforms of the acousto-optically modulated Cs-DPAL were tunable by changing the modulated signal. Therefore, by applying a digital coded modulated signal, the Cs-DPAL can also be used to realize code modulation, which has the potential to be applied for free-space laser communication in view of the high atmospheric transmittance [27,28]. We used the signal generator to output a pseudo-random binary sequence (PRBS). The bit rate of the PRBS signal was varied as 200 kb/s, 500 kb/s, 1 Mb/s, and 2 Mb/s. The other experimental conditions remained unchanged. The waveforms for the PRBS signal and the laser intensity at different bit rates are shown in Fig. 7. It can be observed that the laser intensity was coded by the PRBS signal with a maximum bit rate of 2 Mb/s. The temporal waveforms of the coded laser accurately corresponded to the PRBS signals. In this paper, the RF driver was modulated by the transistor-transistor logic (TTL) level. Therefore, for the coded TTL digital modulated signals besides PRBS, the Cs-DPAL can also output a coded laser based on acousto-optical modulation.

The above experimental results showed that the acousto-optically modulated Cs-DPAL could transmit a coded laser with a bit rate of the order of Mb/s. However, the bit rate is orders of magnitude lower than that of the state-of-art free-space laser communication. The speed of the coded Cs-DPAL should be improved furtherly to satisfy the requirement of the free-space laser communication.

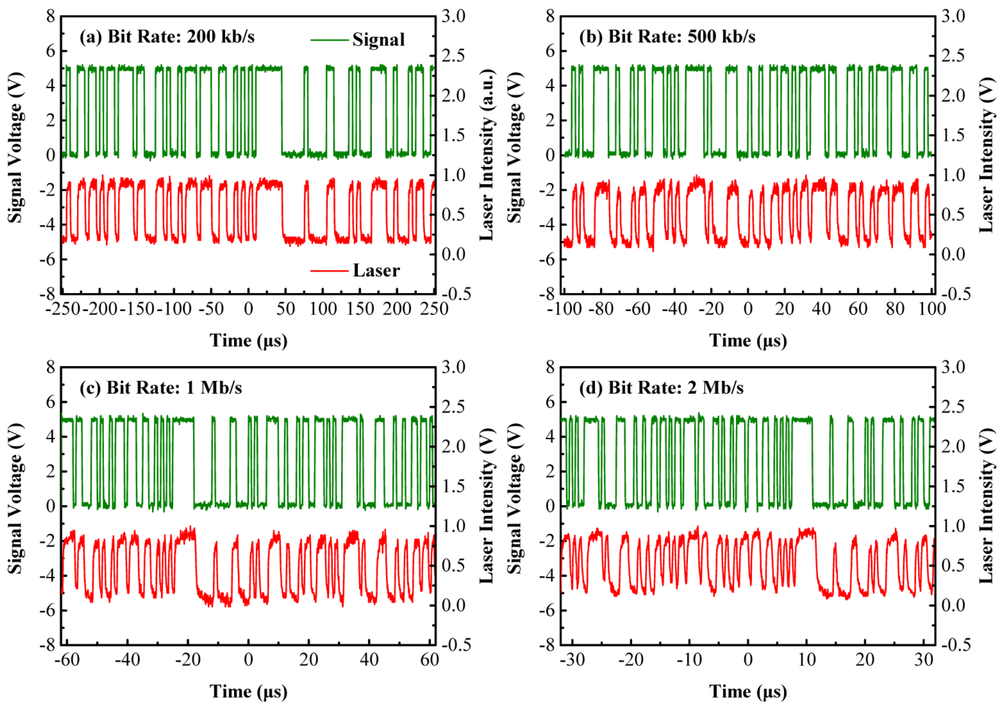


Fig. 7. Waveforms for the PRBS signals and output laser with bit rates of (a) 200 kb/s, (b) 500 kb/s, (c) 1 Mb/s, and (d) 2 Mb/s.

## 4. Conclusion

In our study, we presented an acousto-optically modulated linearly polarized Cs-DPAL for the first time. The pump source was a fiber-coupled CW LD operating at 852.25 nm. First, we studied the Cs-DPAL when the AOM was closed. A CW linearly polarized laser operating at a wavelength of 894.57 nm was obtained with a maximum output power of ~1.05 W. Subsequently, we investigated the high-repetition-rate pulse operation of the Cs-DPAL based on acousto-optical modulation. By controlling the switch mode of the AOM with a rectangular-modulated signal, the Cs-DPAL realized a pulse laser output with a high repetition rate of 1 MHz. To the best of our knowledge, this is the highest repetition rate reported in DPALs; the corresponding pulse duration was 238 ns. The maximum output power of the pulse laser reached ~0.20 W, and the corresponding $M_x^2$ and $M_y^2$ factors were 1.31 and 1.19, respectively. Finally, we demonstrated code modulation of the Cs-DPAL with a PRBS signal. A maximum bit rate of 2 Mb/s was achieved for the coded laser. With a

MOPA structure, the acousto-optically modulated Cs-DPAL is suitable for use as a seed laser source. We can attain a high-power pulse laser output by amplifying the seed laser with a tunable repetition rate and pulse duration over a wide range, which will promote the application of DPALs. In conclusion, we believe that our experimental results will contribute to the design of high-repetition-rate pulse and high-speed coded DPAL systems.

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