Characteristics analysis and power amplification of 1.06 μm injection-locked gain-switching semiconductor laser

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Abstract: Detailed characteristics analysis and power amplification of gain switched Febry-Pérot cavity semiconductor laser at 1.06 μm were reported. The gain switched laser diode, which is modulated by high frequency sinusoid electrical signal, can generate stable pulse laser trains with pulse width around 100 ps, average power around 20 mW and repetition rate adjustable from 500 MHz to 2 GHz, while injection locking is employed effectively in improving the spectral performance of output pulse by suppressing the extra longitude modes. Besides, the effects of the variations of modulation frequency, modulation power, bias current magnitude, injection power and working temperature on the output performance of the laser diode were experimentally demonstrated in detail. Furthermore, the injection locked gain switching laser diode was amplified in power with a two-stage all fiber amplifier chain as a seed source, obtaining an output power of 82 W with a pump light of 108 W and light-to-light conversion rate of 76% while retaining good power to power linearity.

Key words: gain-switching; semiconductor laser; injection locking; fiber amplifier

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1.06 μm 注入锁定增益开关半导体激光器特性分析与功率放大研究

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摘 要: 报道了 1.06 μm 增益开关半导体激光器的详细特性分析和功率放大研究。用高频正弦信号调制中心波长 1.06 μm 的 F-P 腔半导体激光器得到脉宽约为 100 ps、平均功率约为 20 mW,重频从 500 MHz 到 2 GHz 连续可调的稳定短脉冲激光输出。采用注入锁定改善增益开关半导体激光器的输出特性。研究和分析了调制信号的频率、功率和偏置电流的大小以及注入锁定的功率、温度对激光器输出特性的影响。将该激光器作为种子,用 108 W 的抽运光进行两级全光纤功率放大得到了 82 W 的高功率输出,光光转换效率达到 76%。

关键词: 增益开关; 半导体激光器; 注入锁定; 光纤放大器

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0 Introduction

In recent years, high power picosecond pulsed fiber lasers around 1 μm have been widely reported[1-5]. Most of them adopted the architecture of master oscillation power amplification (MOPA), which is composed of a seed laser and a cascade power amplification chain. The building of seed laser is usually based on the techniques of mode-locking fiber laser[1], gain-switching of laser diode in the regime of picosecond [2,3,5,6]. Compared with mode locking, gain-switching laser diode has the advantages of superior temporal tunabilities, structural simplicity and performance stability. Because of these advantages, gain switching laser diode operating at 1.06 μm has been exploited as pulsed seed source in high power fiber laser amplification system, which has great prospects in a wide range of applications, including supercontinuum generation[7], pumping optical parametric oscillator[8], nonlinear frequency conversion[9-10], etc.

Detailed characteristics analysis of gain-switched Febry-Pérot cavity semiconductor laser at 1.06 μm was conducted, which has the capability of seeding a high power pulsed fiber MOPA system. The gain switched laser diode can generate stable pulse laser trains with pulse width around 100 ps, average power around 20 mW and repetition rate adjustable from 500 MHz to 2 GHz, while injection locking is employed effectively in improving the spectral performance of output pulse by suppressing the extra longitude modes. A side mode suppression ratio of 43.4 dB is obtained when raising injection power and the 3 dB spectrum bandwidth is narrowed down from 7 nm to 0.1 nm. Besides, the effects of the variations of modulation frequency, modulation power, bias current magnitude, injection power and working temperature on the output performance of the laser diode were experimentally demonstrated in detail. Furthermore, the injection locked gain switching laser diode is amplified in power with a two-stage all fiber amplifier chain as a seed source, obtaining an output power of 82 W with a pump light of 108 W and light-to-light conversion rate of 76% while retaining good power to power linearity. The pulse duration is around 95 ps and 3 dB spectrum bandwidth is 0.1 nm, and no nonlinearity effect is observed. Further power scaling is limited by the available pump power. It is believed this laser can find applications in many fields, including supercontinuum generation, pumping optical parametric oscillator, optical signal processing, etc.

1 Experimental setup

The schematic diagram of the experimental setup is illustrated in Fig.1, a radio frequency signal generator(frequency range 200–40 GHz, model AV1463) was used to generate high frequency sinusoidal signal, and the signal was amplified by a radio frequency power amplifier (bandwidth 4.2 GHz, gain 37 dB). A bias tee circuit is employed to add DC bias current to

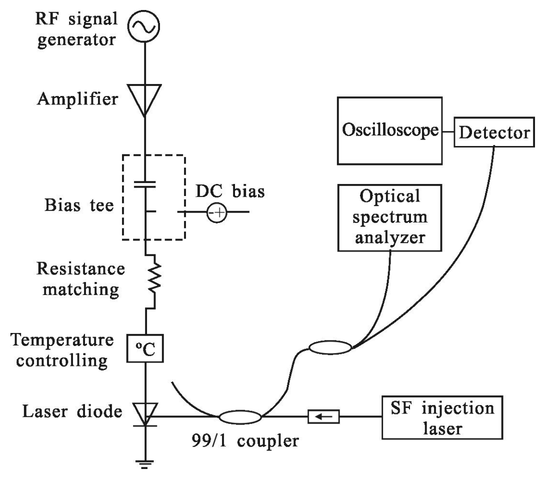
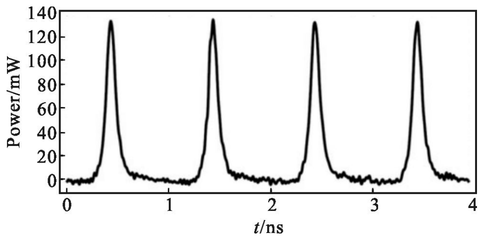


Fig.1 Schematic diagram of the experimental setup

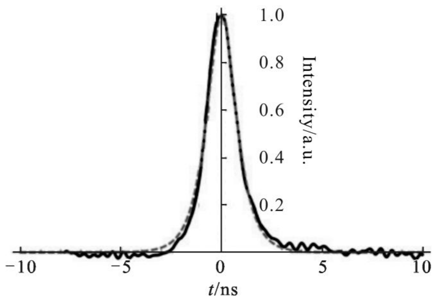
the amplified sinusoidal signal. The combined signal is applied to drive a commercial 1.06 μm Fabry–Perot laser diode through a resistance matching circuit, because the output resistance of signal generator (50) is different from the resistance of the laser diode(~3 Ω). A temperature controlling circuit is applied on the laser diode to control and maintain the working temperature. Injection locking is conducted through a single frequency fiber laser. The light from the single frequency laser is injected by an optical isolator and a 99/1 coupler. The output pulses are monitored by an optical spectrum(measurement scale of 600–1 700 nm, 0.02 nm minimum resolution), or converted to the electrical pulses by a high speed photodetector(25 GHz bandwidth) and then analyzed by a sampling oscilloscope (30 GHz bandwidth).

2 Experimental results and analysis

Figure 2 shows a typical output pulse train observed. In this case, the driving signal frequency and power from the signal generator are 1 GHz and 0 dBm respectively. The bias tee current is set 75 mA. Figure 2(a) shows the output pulse train observed in the oscilloscope. The repetition rate is 1 GHz and output power is 17 mW, the full width at half maximum (FWHM) of the pulse is measured to be 103 ps. A good fit is obtained by using a Gaussian pulse profile.



(a) Pulse waveform of gain-switched laser diode



(b) A single pulse waveform and a standard Gaussian pulse profile

Fig.2 Typical output pulse curve observed

Firstly, with fixed frequency and power of signal generator and no injecting light, the different pulse waveforms and optical powers of the laser diode under different bias current are recorded. The variation of output waveforms, pulse widths (the full width at 1/2 maximum and 1/10 maximum) and peak powers with respect to different bias current is illustrated in Fig.3 and Fig.4.

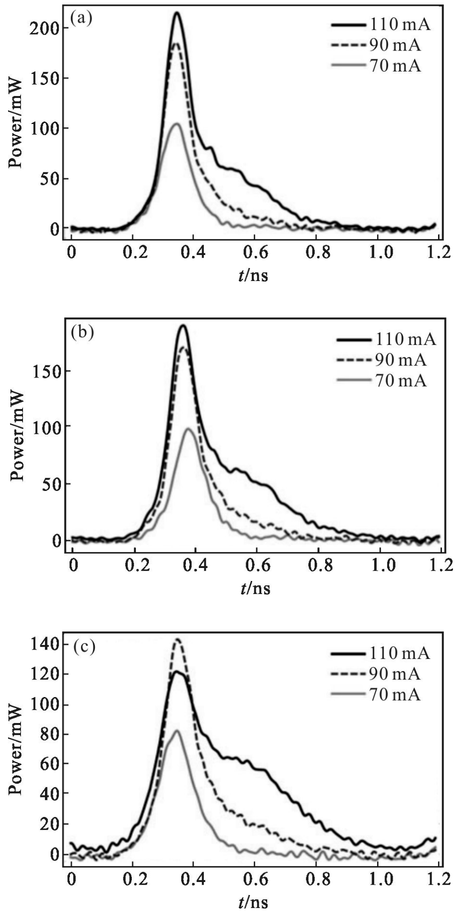
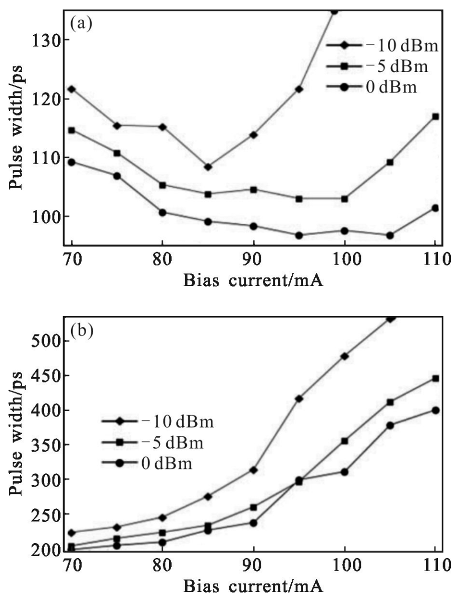


Fig.3 Output pulse shape variation with respect to different bias current: (a) modulation power 0 dBm; (b) modulation power −5 dBm; (c) modulation power −10 dBm



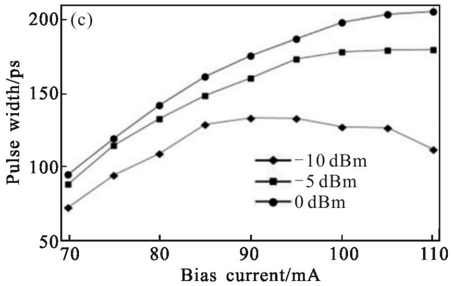


Fig.4 Variation of (a) 1/2 pulse width; (b) 1/10 pulse width; (c) peak power with respect to different bias current

Figure 3 shows the variations of waveforms under different bias currents, the varying process under signal power of 0 dBm, −5 dBm and −10 dBm are depicted in Fig.3 (a), Fig.3 (b) and Fig.3 (c) respectively. Figure 4 shows the variations of 1/2 pulse width, 1/10 pulse width and peak power under different bias currents with three different modulation signal power.

Then, we fix the frequency and bias current, and record different pulse waveforms and optical powers of the laser diode under different modulation power of signal generator. The variation of output waveforms, pulse widths (the full width at 1/2 maximum and 1/10 maximum) and peak powers with respect to different modulation signal power is illustrated in Fig.5 and Fig.6.

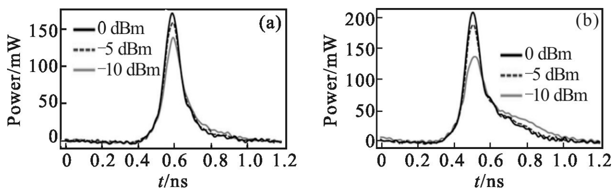
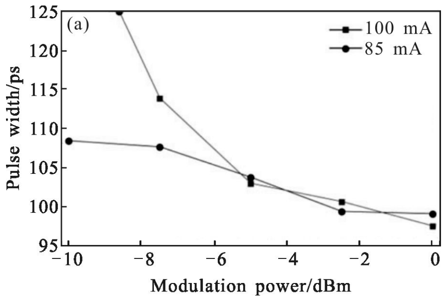


Fig.5 Output pulse shape variation with respect to different modulation power: (a) bias power 85 mA; (b) bias power 100 mA



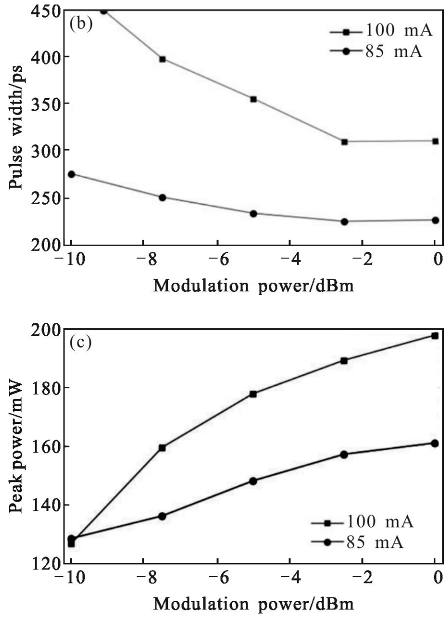


Fig.6 Variation of (a) 1/2 pulse width; (b) 1/10 pulse width; (c) peak power with respect to different modulation power

Figure 5 shows the variations of waveforms under different modulation power, the varying process under bias currents of 85 mA and 100 mA are depicted in Fig.5(a) and Fig.5(b) respectively. Figure 6 shows the variations of 1/2 pulse width, 1/10 pulse width and peak power under different modulation powers with two different bias currents.

Then, without injecting light, we fix the bias current of 85 mA and power of signal generator of −5 dBm, and then record the different pulse waveforms of the laser diode under different modulation frequencies. The variation of output waveforms with respect to different modulation frequencies (from 500 MHz to 2 GHz) is illustrated in Fig.7.

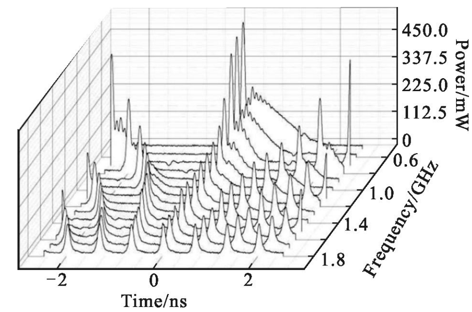


Fig.7 Output pulse shape variation with respect to different modulation frequency

With bias current at 85 mA, modulation power −5 dBm and modulation frequency 1 GHz, we changed optical power of injected single frequency fiber laser, the variations of output pulse waveform and optical spectrum is demonstrated in Fig.8. Figure 8(a) shows the variation of pulse shape with respect to injected power, pulse waveform distortion is observed when high power laser is injected. Figure 8(b) depicts the change of optical spectrum of injected laser diode with respect to different injected power. After injection, the 3 dB bandwidth of output spectrum is reduced from 7 nm to around 0.1 nm. The side mode suppression ratio (SMSR) increases from 29.06 dB to 43.4 dB, as the injecting power increase from 0.14 mW to 3.00 mW.

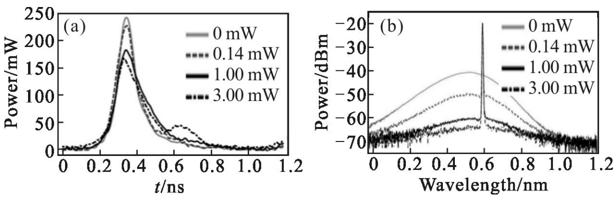


Fig.8 Output pulse shape (a) and output spectrum (b) variation with respect to injection power

Then, the injection power is fixed at 1.0 mW, and the working temperature is adjusted from 33.5 ℃ to 49.1 ℃. Figure 9 shows the optical spectrums and SMSRs at the working temperatures of 33.5 ℃, 39.5 ℃, 45.5 ℃, 49.1 ℃ respectively. At the temperature of 45.5 ℃, the highest SMSR(40.1 dB) is obtained.

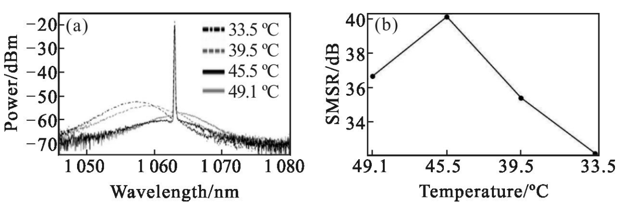


Fig.9 Output spectrum (a) and SMSR (b) variation with respect to temperature

3 Power amplification

The injected gain-switched laser diode is employed as seed laser in a fiber MOPA system to generate high power, high frequency pulsed laser. The experimental setup is illustrated in Fig.10, there are two stage amplification. The first stage is composed of a single mode pump source at 976 nm and a section of 1 m long single mode Yb-doped fiber as gain medium, the pump light is coupled into the gain fiber by a 976/1 063 WDM. With a pump light of 620 mW, the seed is amplified to 416 mW after the first stage amplification. There is a bandpass filter (centered in 1 064 nm) between the first and second amplifier, used to filter the ASE light. The second amplification stage, a total 108 W pump light from two multi-mode laser diode is coupled in a section of 2.5 m long double clad Yb-doped fiber laser(numerical aperture 0.08/0.46, absorption coefficient 33 dB/m at 976 nm, core/clad diameter is 15 μm/128 μm). The laser power is amplified to 82 W after the second stage amplification.

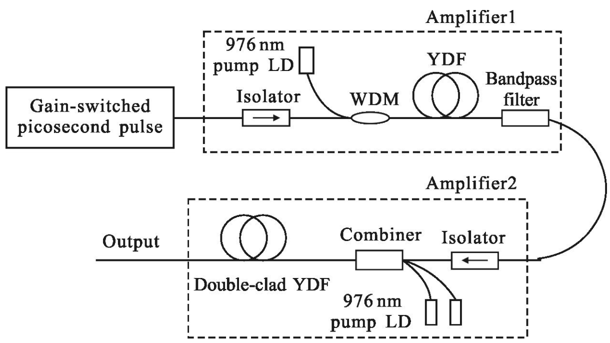
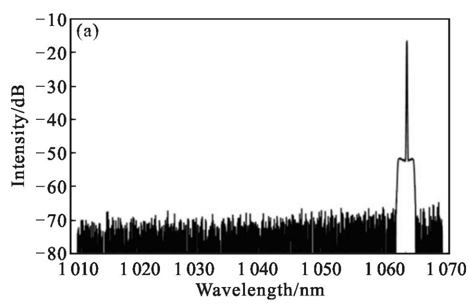


Fig.10 Experimental setup of pulse power amplification

Figure 11(a), (b) shows the optical spectrum and time domain waveform trace of the pulse laser after the second amplification. Figure 11 (c) depicts the linear increasing of output power with the increment of pump power. A power to power converting efficiency of 76% is achieved in the second amplification stage.



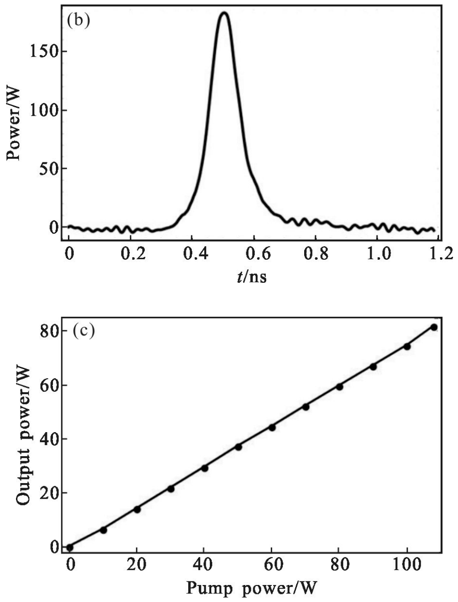


Fig.11 Optical spectrum (a) and time domain waveform trace (b) after the second amplification, and the output power vs pump power line(c)

4 Conclusion

We built an injection-locked gain-switched Febry-Pérot cavity semiconductor laser at 1.06 μm, which can generate stable pulse laser trains with pulse width around 100 ps, average power around 20 mW and repetition rate adjustable from 500 MHz to 2 GHz. The effects of the variations of modulation frequency, modulation power, bias current magnitude, injection power and working temperature on the output performance of the laser diode were experimentally demonstrated in detail. The injection locked gain switching laser diode is amplified in power with a two-stage all fiber amplifier chain as a seed source, obtaining an output power of 82 W with a pump light of 108 W and light-to-light conversion rate of 76% while retaining good power to power linearity.

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