Frequency Locking and Synchronization of Nanosecond Pulsed Broad-Area Lasers

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ABSTRACT

Pulsed lasers with pulse durations of nanosecond to millisecond are very important tools for free-space optical communication, LADAR, laser material processing, and optical sensing. Although Q-switched solid-state lasers or gas lasers are currently the most popular light sources for these purposes, pulsed semiconductor lasers have the potential for the above applications because of their compactness, accessibility of direct modulation, and inherently large electrical to optical conversion efficiency. The drawbacks with high-power semiconductor lasers are their poor beam quality and low coherence factors. This work addresses the above issues through experimental demonstration of frequency locking, wavelength tuning, and synchronization of nanosecond pulsed broad-area semiconductor lasers. Nanosecond optical pulses with the peak power of 25 W and the repetition rates of 4 KHz to 240 KHz are generated from a broad-area laser. An external cavity with a diffractive grating is used to reduce the linewidth of the laser from over 5 nm to less than 0.1 nm. The wavelength of the pulsed laser is tunable over more than 10 nm. We have conducted injection locking of a nanosecond pulsed broad-area laser with optical injection from a frequency-locked master laser. Successful injection locking strongly supports the feasibility of synchronization and beam combination of pulsed broad-area lasers.

Keywords: semiconductor laser, broad area laser, synchronization, nanosecond pulse, frequency locking, wavelength tunable, high power, external cavity, optical feedback

1. INTRODUCTION

Pulsed lasers with pulse durations over nanoseconds to milliseconds are very important tools for laser radar (LADAR)[1], free-space optical communication[2,3], laser material processing[4], and optical sensing[5]. Q-switched solid-state lasers or gas lasers are currently the most popular light sources for these purposes. For some applications such as LADAR or deep-space optical communication, in order to reduce the transmission attenuation and ensure the best signal-to-noise ratio (SNR), the light source requires high-altitude operation platforms such as aircrafts or satellites. The transmitter power levels are then limited by the size, weight, and on-board power allowed by the platform and, in turn, this limitation confines the operational range.

Pulsed semiconductor lasers meet the requirements of small size, weight, and on-board power due to their compactness and inherently large electrical to optical conversion efficiency. Nanosecond pulses in semiconductor lasers are usually generated via the pulse modulation of the drive current of the semiconductor lasers. A feature of the semiconductor laser that sets it apart from other lasers is that the cavity gain, and hence the output power, can be rapidly modulated by modulating the drive current. When a laser diode is subjected to a sharply rising current pulse from below the lasing threshold, the spectrum bandwidth is significantly broadened due to high speed turn-on and turn-off transients.[6] Reduction of the spectrum bandwidth of the pulsed laser is an important issue in free-space optical communication and/or optical remote sensing applications since low dispersion transmission as well as coherent optical pulses are extremely desirable in such applications.[7] Another drawback in considering pulsed semiconductor lasers for many applications is the relatively small emission power that can be obtained from semiconductor lasers. It is important to boost the output power and/or pulse energy from such light sources without degrading the beam quality and coherence factors.[8,9]

In this paper, we report experimental results of frequency locking and wavelength tuning of nanosecond pulsed broad-area semiconductor lasers. Using a commercial pulse driver, the broad-area laser with an emission area of $100\times1\ \mu m^2$ is capable of generating optical pulses with the peak power over 25 W and the variable repetition rates from 4 KHz to over 200 KHz. The spectrum bandwidth of the broad-area laser increased from ~1 nm in the CW operation mode to more than 5 nm in the pulse operation mode. An external cavity with a diffractive grating is used to reduce the spectrum bandwidth and tune the wavelength of the laser. Although external cavity with diffractive gratings have been used for locking CW lasers in previous work[10-12], frequency-locking of nanosecond pulsed high power broad-area lasers has not been demonstrated. In this work, we experimentally demonstrated that the pulsed broad-area laser is locked to a single frequency with a spectrum bandwidth less than 0.1 nm using the grating feedback. The wavelength of the pulsed laser is tunable within a range more than 10 nm. The linewidth of the pulsed laser strongly depends on the peak pulse power while shows no dependence on the pulse repetition rate or the pulse duration. We have not observed any significant change in either the peak pulse power or the pulse waveform due to the frequency locking. Upon the accomplishment of the frequency locking, we conduct the synchronization between two pulsed broad-area lasers by injecting a part of the frequency-locked laser output to another pulsed broad-area laser. Successful injection locking has been achieved with appropriate synchronization of driving current pulses and adjustment of time lag between the two lasers. The dependence of the injection locking performance on the time lag has been experimentally studied.

2. FREQUENCY LOCKING OF NANOSECOND PULASED BROAD-AREA LASERS

Experiments have been conducted using a commercially available broad-area laser and a high peak current pulse driver. The broad-area laser used in the experiments is a single-stripe laser diode (Coherent Inc.). The 100 µm×1 µm aperture of the broad-area laser emits a far-field pattern subtended by 6°×35°. When the laser is driven with a CW current driver, the light output emits at the wavelength around 808 nm with the threshold of 350 mA. At the driving current of 1.2 A, the laser output measures about 1.2 W with a spectrum bandwidth about 2 nm. The laser is mounted in an H-package and the cap of the package is removed so that a collimation lens can be equipped at a very close distance of the laser facet. The front output facet of the laser is AR coated with the reflection ratio of about 10%. A commercial pulse driver (DEI PCO-7810/7120) is used to drive the laser. The driver provides electrical pulses at the pulse duration of 5 ~ 20 ns, the repetition rates up to 240 KHz, and the peak output current up to 40 A. This can generate the optical pulses with the peak power more than 40 W. The peak power of the optical pulse measures over 30 W at the pulse duration of 6 ns.

As schematically illustrated in Fig.1, the laser output is collimated by an AR-coated aspheric lens (*f*=4.5 mm, NA=0.55). A beam splitter and a diffraction grating (2000 l/mm, 5 cm) is put right after the collimation lens. The grating is aligned in a Littrow configuration (beam incidence angle is ~54° at 808 nm) with grooves parallel to the laser junction plane. Most of the light is reflected from the grating as the first order diffraction and is fed back to the laser cavity. It is important to put the external grating in a very close proximity to the laser front facet so that the external cavity round-trip time is much less than the pulse duration. In our experiment, we limit the distance between the grating and the laser facet within 6 cm for locking laser pulses

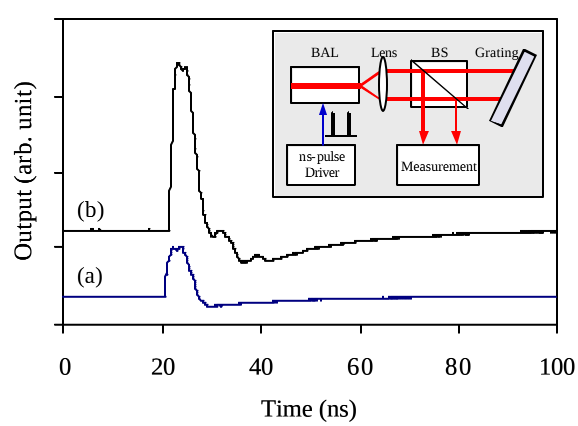

Figure 1 Temporal waveform of the nanosecond pulsed broad-area laser output at the peak pulse power of (a) 10 W and (b) 25 W. Inset box: schematic of nanosecond pulsed broad-area laser with external grating feedback.

above 6 ns. No telescope is used in the external cavity due to the space limitation. However, by carefully adjusting the distance between the grating and the laser front facet, the effect of the external reflection is optimized so that a complete locking of the pulsed laser output can be achieved. A part of the laser output is collimated into an optical fiber with a core size of 50 μm for spectral and temporal waveform measurements. We found that, when the laser is operated in a pulse mode, filamentation due to the thermal effect is much weakened compared to the CW operation mode and about 50% of the light output can be collimated into the optical fiber. Optical spectrum is measured using an Agilent Spectrum Analyzer (86140B) with a resolution of 0.07 nm. Pulse waveform is measured with a fast photo receiver (Newport 1580 with a bandwidth of 12 GHz) and a digital oscilloscope (Tektronix TDS6604 with a sampling rate of 20 Gps and a bandwidth of 6 GHz).

Fig. 1 shows the measured temporal waveform of the pulsed broad-area laser at the repetition rate of 10 KHz. Two waveforms are plotted which correspond to peak pulse power levels of (a) 10 W and (b) 25 W. The pulse duration is measured to be ~ 6 ns. The overshot of the pulse waveform is considered due to the transient response of the detector circuit. When the peak pulse power is increased, we observe more overshot of the pulse. The pulse repetition rate is variable within the range of 4 KHz to over 200 KHz in the experiment using the present pulse driver. We did not observe any changes of pulse shape when the repetition rate is varied.

Large amplitude, nanosecond pulsed current modulations considerably increase the linewidth of the broad-area laser. Fig. 2 shows the optical spectra of the broad-area laser at three different operation situations: (a) free-running laser (without external cavity) at CW operation mode, (b) free-running laser at pulse operation mode, and (c) laser at pulse operation mode with the external grating. The average power of the laser at pulse operation mode measures 8 mW for a pulse repetition rate of 100 KHz and a pulse duration of 7 ns. To compare the CW and pulsed laser operations, the CW output (1 W at the drive current 900 mA) had been attenuated to match the average output power of the laser at pulse mode. The optical spectrum of the laser at CW and pulsed modes was then measured. It is found that the laser spectrum at the pulsed operation mode broadens dramatically from 1 nm to 5 nm.

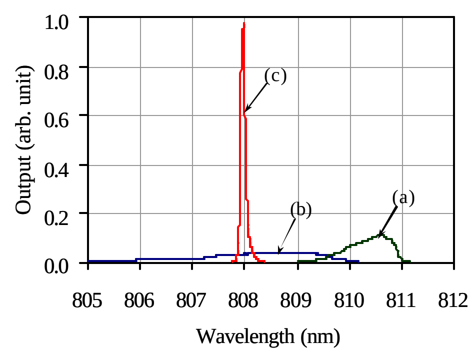

Figure 2 Optical spectra of the broad-area laser at different operation conditions. (a) CW operation mode (output ~ 1 W at 900 mA driving current) without external cavity, (b) and (c) pulsed operation mode (pulse duration: 7 ns @ 100 KHz) without and with the external feedback from grating.

In typical Fabry-Perot semiconductor lasers under the pulse modulation, the dynamic overshoot of the carrier concentration causes more longitudinal modes to be generated than in steady-state operation, even when the steady-state emission is at single-mode operation.[13] For a specific laser structure, the number of the excited modes, i.e., the overall linewidth of the laser, depends on the pulse currents and the modulation frequency. We observed that the spectrum broadening is proportional to the modulation amplitude. As a typical example, the linewidth increases more than 0.5 nm (~ 230 GHz) when the peak power increases from 10 W (Fig. 1(a)) to 25 W (Fig. 1(b)). On the other hand, when the pulse duration or the pulse repetition rate is changed, the spectrum distribution shows only a vertical shift without additional spectrum broadening. We believe that this is because the pulse duration (>6 ns) is larger than the laser relaxation time (measured to be about 0.5 ns) and the modulation frequency (<1 MHz) is too low to cause any noticeable change on the laser spectrum.

Such spectrum broadening was reduced to a single frequency with an external grating feedback. In Fig. 2 (c), one clearly observes a single frequency spectrum of the pulsed laser with the external grating. The 3 dB linewidth of the spectrum measured about 0.09 nm which corresponds to 40 GHz at the center wavelength of 808 nm. We measured both the temporal waveform of the pulse and the spatial pattern of the laser beam and observed no noticeable changes accompanying the frequency locking.

Wavelength tunability of the laser is useful in various applications where frequency matching is required. A precisely controlled wavelength and spectral width would result in more efficient and consistent operation in optical communication, spectroscopy, and medical applications.[2,3,7,15,16] In our experiment, the frequency of the pulsed laser can be tuned by adjusting the external grating. Fig. 3 records the optical spectra of the nanosecond pulsed broad-area laser locked to different wavelengths. A tuning range over 10 nm is achieved. The laser shows a stable frequency locking and pulse waveform over the whole tuning range. For each wavelength, we verified that the side mode suppression ratio of the spectrum is more than 20 dB.

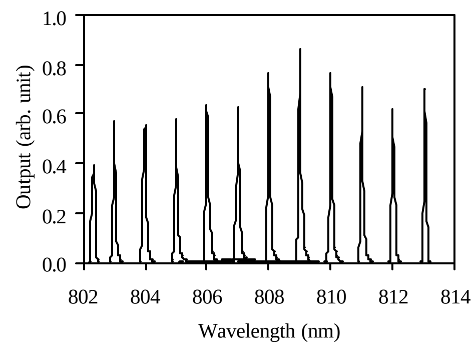

Figure 3 Wavelength tuning of the pulsed laser. Pulse rate is 10 KHz and pulse duration is 7 ns.

The dependencies of the frequency-locked laser linewidth on the pulse parameters have been experimentally investigated. Fig. 4 shows the change of the linewidth on (a) peak power, (b) pulse repetition rate, and (c) pulse duration. While the linewidth shows monotonic increase upon the growth of the peak pulse power, it does not show any evident dependence on the pulse repetition rate or the pulse duration. The peak-power-dependence of the linewidth can be explained based on the spectrum broadening due to the change of the pulse parameters. For semiconductor laser operating at continuous mode, the linewidth inversely depends on the photon density in the laser cavity, i.e., on the drive current level.[14] While for lasers under pulsed operation, amplitude modulation causes wavelength modulation and feedback through the linewidth enhancement factor.[6] As the carrier concentration experiences large variations during the pulse, the refractive index in the laser cavity also varies and the laser spectrum is 'chirped'. The wavelength shift is $\Delta l \sim (dm/dn)\cdot\Delta n$ where *n* is the carrier density in the laser cavity, *m* is the refractive index, *dm*/*dn* is the dependence of the refractive index variations on the carrier density variations, and *Dn* is the difference between the peak and minimum values of the carrier density due to the current modulation. As a result of chirp, pulse-modulated lasers have much larger linewidth than that under continuous operation. Therefore, larger modulation amplitudes (which produce larger average power) cause larger variation amplitude of the carrier concentration and consequently result in larger linewidth, as shown in Fig. 4(a). Meanwhile, since the pulse durations (> 6 ns) are well above the carrier relaxation time (< 1 ns) and the pulse repetition rates are far lower than the relaxation frequency, variations of either of them will not induce noticeable dynamical changes of lasers.

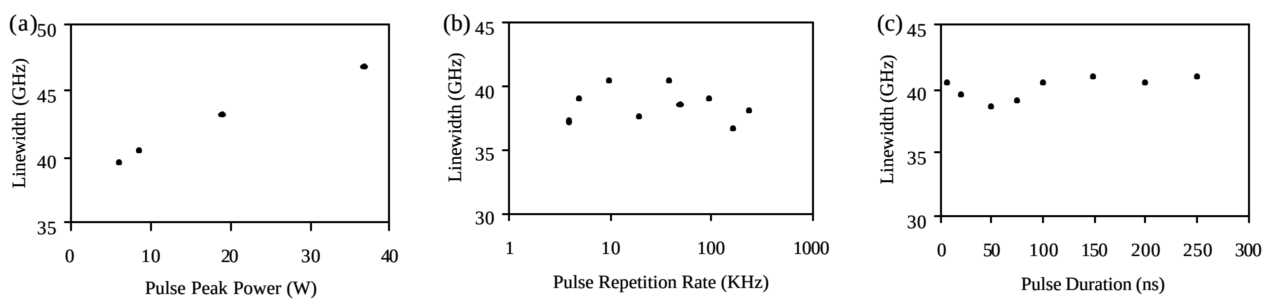

Figure 4 Dependence of the linewidth of the frequency-locked broad-area laser on (a) peak pulse power, (b) pulse repetition rate, and (c) pulse duration

3. SYNCHRONIZATION OF NANOSECOND PULASED BROAD-AREA LASERS

Although synchronization of CW broad-area lasers has been demonstrated using injection locking[17-19] or external cavity schemes[10-12,20,21], injection locking of nanosecond pulsed high power broad-area lasers has not been realized.

In order to investigate the feasibility of synchronizing multiple pulsed broad-area lasers, we conduct the injection locking of nanosecond pulsed broad-area lasers in a master-slave configuration. Experimental design is schematically shown in Fig. 5. Here, we use the frequency-locked pulsed laser as the master laser and another nanosecond pulsed broad-area laser as the slave laser. Two lasers are driven separately with two identical pulse drivers which are controlled by a multi-channel pulse/delay generator. In this way, two electrical pulses are phase synchronized and the time lag between two pulses is adjustable up to the pulse period. The slave laser output is collimated in the similar configuration as the master laser. A part of the master laser output is injected into the cavity of the slave laser. A telescope consisting of two cylindrical lenses (CL1 and CL2) in the slow-axis direction is employed in the injection path to adjust the beam size. The cylindrical lenses can also be shifted in vertical direction to optimize the beam incidence angle of the injection light.

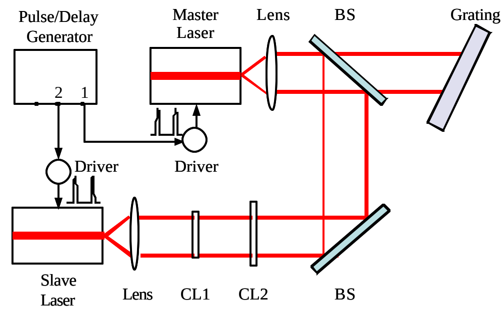

Figure 5 Schematic of injection locking of two nanosecond pulsed broad-area lasers. BS: beam splitter, CL: cylindrical lens.

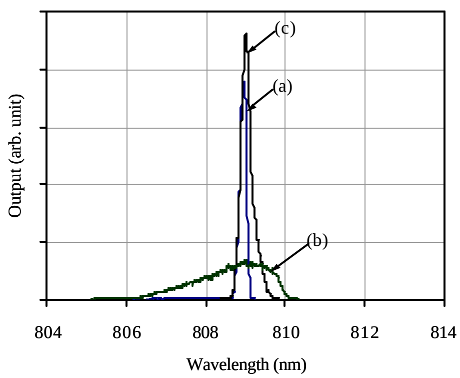

Figure 6 Optical spectrum of (a) master laser at frequency locking, (b) slave laser at free-running state, and (c) slave laser under optical injection.

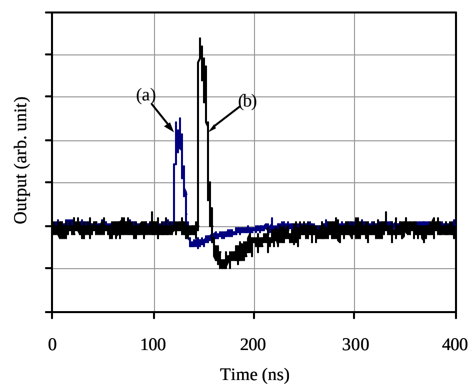

Figure 7 Temporal waveform of the nanosecond pulsed broad-area laser outputs of (a) master laser and (b) slave laser subject to optical injection.

Fig. 6 shows the optical spectrum of (a) the master laser under frequency locking, (b) the slave laser at the free-running state, and (c) the slave laser under the optical injection. Pulse waveforms of master and slave lasers are plotted in Fig.7. The master laser outputs pulses with the peak power about 25 W, the pulse width around 10 ns and the pulse repetition rate of 10 KHz. The wavelength of the master laser is locked to 809 nm. About 10% of the master laser output is used as the injection light. The slave laser is injection locked to the master laser but the bandwidth is about twice of the master laser. We have tuned the wavelength of the master laser and found that the slave laser is locked to the injection beam in the wavelength range of 805-811 nm.

The injection locking performance depends on the time lag between pulses of the master and slave lasers. In fact, the injection direction can even be reversed by properly shifting the time lag. In our experiments, the pulse timing for each laser can be separately controlled with a multi-channel pulse/delay generator. The pulse timing of the slave laser is adjusted to match the arrival of the optical pulse from the master laser. The feedback from the slave laser to the master laser cavity will not affect the lasing property of the master laser as long as the propagation time between two lasers is longer than the pulse width. In the present experiment, the pulse width is less than 10 ns while the propagation time is set to be about 13 ns. Therefore, a unidirectional coupling between two lasers is guaranteed in our experimental design. Due to the asymmetric nature of the injection configuration, no optical isolator is necessary in the system. To further examine the influence of the time lag, we shift the time lag from 0 to 26 ns and measure the slave laser spectrum. Examples of experimental results are listed in Fig.8. These results show that time lags of 10~16 ns, i.e., ±3 ns around the propagation time (13 ns) of the injection beam, are required in order to achieve successful injection locking of two optical pulses with the pulse width of 10 ns. Fig. 8 also shows that the injection locking performance exhibits different bifurcation scenarios upon the increase and decrease of the time lag from the optimized value.

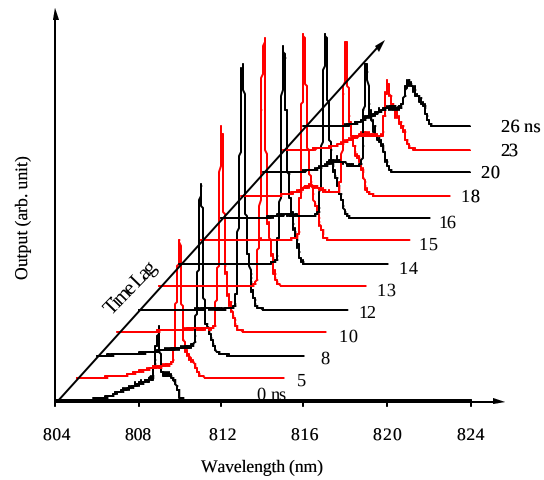

Figure 8 Optical spectrum of the slave laser under optical injection at different time lags. The slave laser pulse matches the arrival of the injection pulse at the time lag of 13 ns.

4. SUMMARY

In summary, we have demonstrated frequency locking of a broad-area laser at the nanosecond pulsed driving. The single broad-area laser emitter is capable of generating peak pulse power of up to 30 W at the repetition rates of 4 ~ 240 KHz and the pulse duration of ~ 6 ns. With an external cavity, the laser spectrum is locked to a single longitudinal mode with the linewidth reduced from 5 nm to less than 0.1 nm. The wavelength can be tuned in a range over more than 10 nm without noticeable changes of either temporal waveforms or the optical spectrum. We have investigated the dependence of the laser linewidth on the pulse parameters. Experiments on synchronization of pulsed broad-area lasers have been conducted and successful injection locking has been achieved. The results strongly indicate the feasibility of synchronization and beam combination of nanosecond pulsed broad-area laser arrays.

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