Generation of mode-locked optical pulses at 1035 nm from a fiber Bragg grating stabilized semiconductor laser diode

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Abstract: We report the generation of transform-limited, ~18 ps optical pulses from a fiber Bragg grating (FBG) stabilized semiconductor laser diode. Up to 7.2 pJ of pulse energy and a peak power of 400mW were achieved when operating at a repetition frequency of 832.6 MHz, a multiple of the cavity (diode + FBG) free spectral range (FSR). A small detuning in the repetition frequency resulted in broader optical pulses. We have shown experimentally the transition from a gain-switched regime of operation to mode-locked operation once the injection current modulation frequency is set to match a harmonic of the cavity FSR. The transition also results in a reduction in the timing jitter of the optical pulses.

OCIS codes: (140.4050) Mode-locked lasers; (140.5960) Semiconductor lasers.

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1. Introduction

The demand for high power fiber lasers producing picosecond optical pulses in the 1.0 μm wavelength region has grown significantly in recent years with such lasers widely used for applications such as laser machining and frequency conversion (e.g. frequency-doubling, the pumping of parametric oscillators and supercontinuum generation [1–3]). Semiconductor Laser Diode (SLD) seeded, fiber MOPA sources represent highly attractive sources for such applications, combining the compactness, stability and cost-effectiveness associated with semiconductor devices with the ready power-scaling possible using fiber amplifiers. Two primary techniques can be used to obtain picosecond pulses from an SLD: namely gain-switching and mode-locking.

Gain-switching provides a simple technique for the generation of picosecond optical pulses directly from an SLD with the added flexibility of generating a pulse on demand [5]. Optical pulses with a duration of tens of picoseconds have been demonstrated in the 1.06 μm wavelength region using this approach. However, there are a few issues associated with this technique that one needs to be mindful of. The minimum pulse duration is dictated by the device properties and parameters of the modulated current used to drive it and the optical pulses generated usually inherit a significant chirp due to the time-varying carrier density within the gain medium which leads to a large transient refractive index modulation. This results in chirped optical pulses with a corresponding time-bandwidth-product that can be many times the Fourier limit. Several techniques to compensate this chirp have been demonstrated in recent years but these all bring significant additional complexity to the setup. Approaches demonstrated include the use of a chirped fiber Bragg grating (CFBG) [6], a length of dispersive fiber [7], a nonlinear optical loop mirror [8] and spectral filtering using a Mach-Zehnder interferometer [9]. A further issue is that gain-switched optical pulses typically suffer from pulse-to-pulse timing jitter which is associated with the build-up of optical pulses from spontaneous emission which causes random fluctuation in the photon density [10].

Actively mode-locked SLD sources incorporating external cavity gratings have generated a lot of interest since first reported in 1991 in the search for high repetition rate pulsed sources for optical telecommunications at 1550nm [11]. Short picosecond optical pulses can be generated using this technique and the lasers can be operated at very high repetition frequencies. The optical pulses typically possess a low timing jitter and wide mode-locking bandwidth at a fixed operating wavelength [12]. Furthermore, mode-locked SLDs with a fiber Bragg grating (FBG) as an external cavity mirror have been demonstrated experimentally at 2.5 GHz [13] and 10 GHz [14] repetition frequencies. Unlike optical pulses generated through gain-switching, the mode-locked optical pulses are usually close to transform-limited and short pulse durations are possible depending on the gain bandwidth of the SLD and the spectral bandwidth of the grating used [14]. Therefore further pulse compression is generally not required making the seed configuration simple and more cost effective. To the best of our knowledge this particular approach has not previously been demonstrated with 1.0 μm SLDs.

Herein, we experimentally demonstrate a simple cavity configuration that allows the generation of transform-limited 18 ps optical pulses with an energy of 7.2 pJ, corresponding to a peak power of 400 mW in the 1.0 μm wavelength region. Our experimental results show that the mode-locking mechanism plays a key role in enabling short and stable optical pulses.

2. Experimental setup

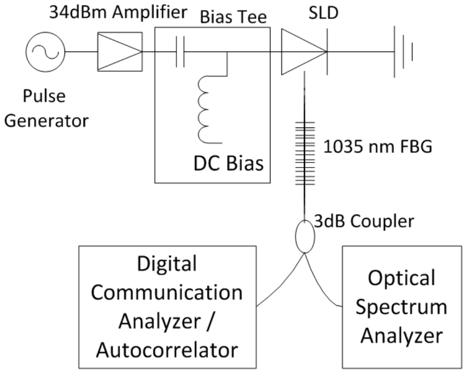

Fig. 1. Experimental setup.

Figure 1 shows schematic of the experimental setup. The semiconductor laser diode used in this experiment was a commercial Fabry-Perot SLD (OCLARO LC96A1030-20R) with a gain peak located at 1035 nm. The measured longitudinal mode spacing was 0.032 nm and the measured threshold current was 25 mA. The SLD was mounted on a modified printed circuit board (PCB) with resistors placed in series in order to match the impedance of the transmission line. The temperature of the SLD was stabilized by using a thermoelectric cooler (TEC) unit. A combination of a pulse generator and RF amplifier drove the SLD with a stable train of sinusoidal electrical pulses. The drive current had a peak-to-peak current of 632 mA which was superimposed on a DC bias current of 20 mA - slightly less than the threshold current to avoid a CW leakage signal. The pigtail of the SLD was spliced to a polarization maintaining 1035 nm FBG with a 3 dB bandwidth of 0.24 nm and a reflectivity of ~12%. The fiber length between the SLD and the FBG was ~2 m. The FSR of the cavity was ~52.04 MHz. For most of our experiments the system was operated at 832.6 MHz which corresponds to the 16th harmonic of the cavity FSR. A polarization maintaining 3-dB fused fiber coupler was spliced to the output end of the grating so that both temporal and spectral profiles could be measured simultaneously with a Digital Communication Analyzer (DCA) and an Optical Spectrum Analyzer (OSA) respectively.

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3. Results and discussion

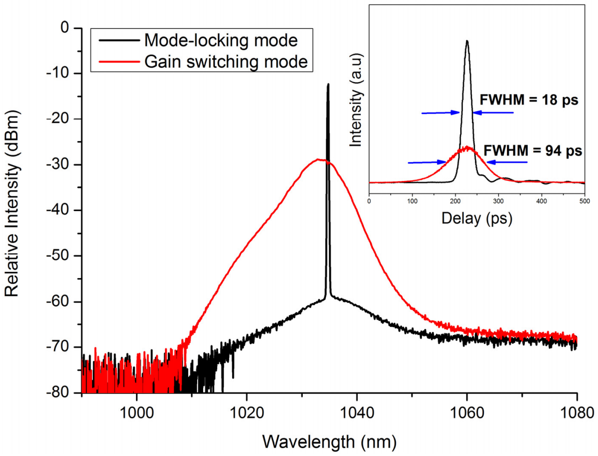

Fig. 2. Spectral profiles of the gain-switched laser diode with (black line) and without (red line) FBG. (Inset) Temporal profiles for the seeded (black line) and unseeded (red line) cases.

When the injection current modulation frequency (ICMF) was detuned relative to the harmonic of the cavity FSR, pulses with a broad optical spectrum with a full width at half maximum (FWHM) of approximately 6 nm and a pulse width of ~94 ps were measured, as illustrated by the red colored lines in Fig. 2. In such circumstances the SLD operated in a gain-switching (GS) mode as a result of the high drive current pulse of sub-ns duration. The broad spectrum generated consisted of a large number of longitudinal modes. The emitted optical pulses exhibited a strong red-shift in wavelength from the leading to trailing edge corresponding to a very significant chirp. The estimated time bandwidth product of the pulses is ~158. Moreover, the pulses exhibited significant intensity noise (~15%) and the RMS time jitter was measured to be 5 ps.

Once the ICMF was tuned to 832.6 MHz we observed substantial reductions in both the spectral bandwidth and the pulse width as shown by the black colored lines in Fig. 2. Furthermore, transform-limited optical pulses of 18 ps were measured with an intensity autocorrelator as shown in the inset of Fig. 3(a). This corresponds to an almost 5 times reduction in pulse width as compared to that of the GS case. A spectral Side-Mode Suppression Ratio (SMSR) of ~50 dB and a FWHM spectral bandwidth of 0.09 nm were measured corresponding to an almost 67 times compression in the spectral domain. Furthermore, the optical pulses were far more stable as compared to the GS case. The RMS timing jitter was estimated to be ~316 fs through the RF-spectra measurement method proposed by von der Linde [15]. The average optical power was measured to be ~6 mW corresponding to a pulse energy of 7.2 pJ. A highly stable train of optical pulses was measured with a fast photo-detector (Agilent 83440D) and a DCA as shown in Fig. 3(a).

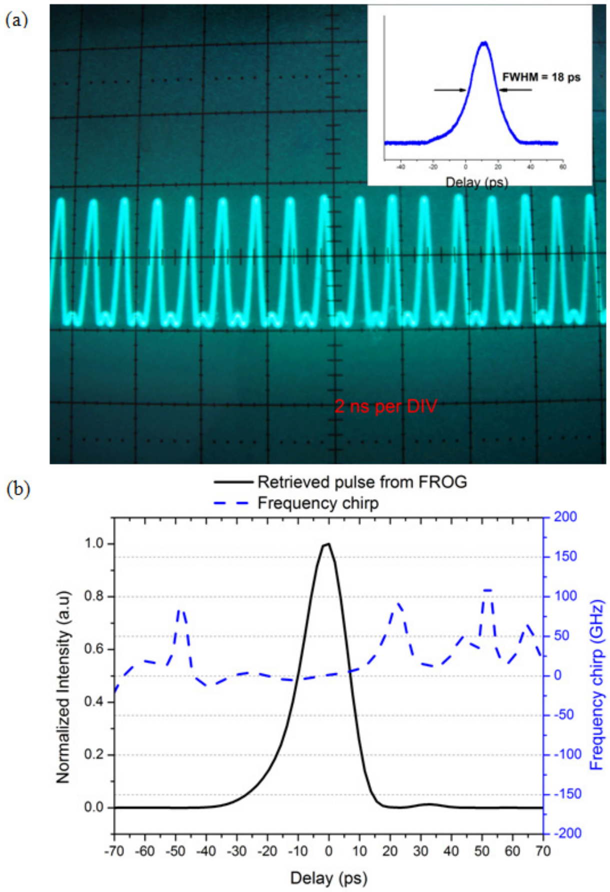

Fig. 3. (a) Pulse train measured at 16th harmonic (832.6 MHz). (Inset) Trace of intensity autocorrelator indicating ~18 ps optical pulses and (b) amplitude and frequency chirp as a function of delay obtained using a linear FROG technique.

The optical pulses were then characterized through the use of a linear frequency-resolved optical gating (FROG) technique. An electro-optic modulator (EOM) was used as a gate to temporally slice the pulses which were then spectrally resolved [16]. Information such as the temporal shape (black line) and chirp (blue dash line) across the optical pulses can be retrieved with this method as shown in Fig. 3(b). Figure 3(b) clearly illustrates that the measured chirp was constant across the central region of the optical pulse and increases linearly at the trailing edge due to the existence of a small secondary peak ~35 ps away from the main pulse. The estimated time bandwidth product (TBP) of 0.45 indicates that the output pulses were time-bandwidth limited (assuming a Gaussian shaped optical pulse).

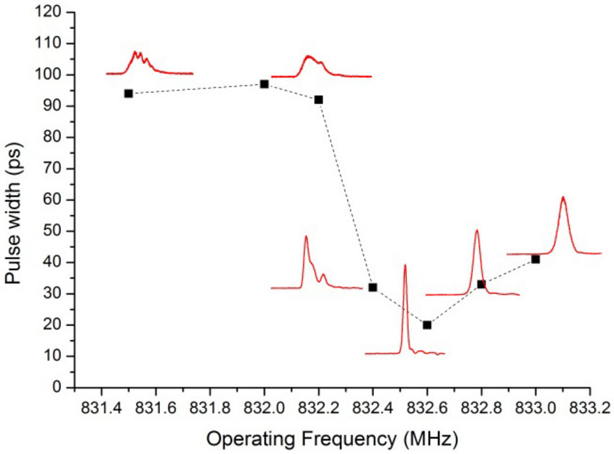

Fig. 4. Optical pulse width measured at different repetition frequencies and (color) the corresponding optical pulse shapes.

A small detune in ICMF resulted in a substantial change in pulse widths and pulse shapes, similar to that reported in [17]. Figure 4 shows the variation in pulse width as the operating frequency was varied with the inclusion of the detailed pulse shapes observed.

At ICMFs below 832.0 MHz, broad, distorted and unstable optical pulses were observed similar to that of GS case. Increasing the ICMF to 832.2 MHz resulted in more stable but broad (90 ps) asymmetrical optical pulses with a long trailing edge. Furthermore, the pulses exhibited a double peak structure with the leading peak slightly broader than the trailing peak. The evolution of double peak optical pulses at frequencies just below the cavity resonance frequency can be explained as follows. For a fixed cavity length the time of flight of the pulses remains effectively constant irrespective of the operating frequency. Therefore at frequencies just below the harmonic cavity resonance frequency, the reflected pulses arrive back at the active region whilst the carrier density is still building up due to the ever so slightly longer time interval between the injected current pulses. Consequently a portion of the carrier density gets depleted through stimulated emission however the carrier density continues to build up in the presence of the current pulse. A second optical pulse evolves when the excess carrier density reaches the threshold condition.

An increase in ICMF to 832.4 MHz resulted in a reduction in the energy contained within the secondary peak due to insufficient recovery of the carrier density

When the ICMF was tuned to 832.6 MHz, a harmonic of the cavity FSR, short optical pulses with a width of ~18 ps were obtained. In this instance, the returning pulse arrives at the active region when the carrier density is at its maximum. This resulted in the highest peak power of 400mW that can be extracted cleanly from the mode locked laser diode, although a small secondary peak was still observable at the trailing edge of the main pulse. Note however that we managed to eliminate the secondary pulse completely by reducing the DC bias current down from 20 mA to 15 mA.

As the ICMF was further increased to 832.8 MHz and 833.0 MHz, the pulse width broadened to 30 ps and 40 ps respectively and both amplitude and timing jitter started to become significant with increasing frequency detuning. Beyond 833 MHz mode-locking was completely lost and the optical pulses returned to those characteristic of pure GS operation with a pulse width of ~94 ps.

The lasing wavelength of the output pulses was also affected when the ICMF was detuned. The optical spectra measured at various ICMF are plotted in Fig. 5. The central wavelength at different frequency detunings was compared relative to the FBG's peak reflectivity wavelength in order to quantify the accumulated shift in wavelength. We observed a red-shift of the central wavelength as the ICMF was increased to 832.0 MHz and 832.2 MHz. However, as soon as the ICMF was tuned to 832.6 MHz, a maximum wavelength shift of 0.1 nm was measured. We also observed that the spectrum exhibited an asymmetrical shape with a tail in the short wavelength region. Any further increase in repetition frequency resulted in a broader spectrum and a reduction in the wavelength shift. A similar red-shift in central wavelength was also observed in [13, 17, 18] suggesting that when the ICMF was changed, the device self-tuned its operating wavelength in order to maintain the correct effective cavity length needed to maintain resonance with the drive current signal.

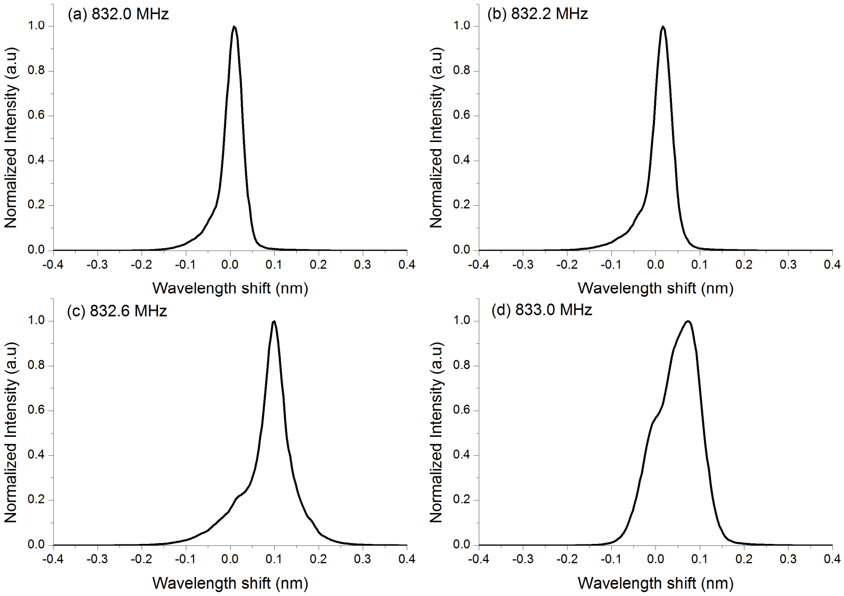

Fig. 5. Optical spectra measured for a range of injection current modulation frequencies showing the observed wavelength shift with respect to the central wavelength of the FBG.

The stability of the mode-locking mechanism depends on the reflectivity of the FBG. In this work, we examined three uniform pitch FBGs of different reflectivity, namely 4%, 8% and 12%. We observed that mode-locking was unstable when a 4% reflectivity grating was used. The stability and shape of the optical pulse varied randomly over a period of time. Much better mode-locking was achieved with a 7% reflectivity FBG. However, environmental conditions such as changes in temperature of the air surrounding the FBG affected the stability of the optical pulses over a longer time scale and fine adjustment of the TEC was necessary from time to time to recover the optimum stable mode-locking condition. On the other hand, when a 12% reflectivity FBG was used stable mode-locked operation was accomplished without the need for periodic tweaking of the temperature controller highlighting the fact that the strength of the external cavity feedback is important in sustaining uninterrupted mode locked operation - mode competition between the SLD modes and that of the external cavity is less well controlled with a weaker grating resulting in unstable mode locked operation.

Since the constituent longitudinal modes of a mode-locked optical pulse will have a defined phase relationship, an interference measurement based on a fiber based Mach-Zehnder interferometer that enabled the interference between one pulse and that emitted 9 pulse periods later was carried out to confirm that the mode-locking mechanism is indeed responsible for the generation of the short optical pulses observed. Interference patterns are clearly visible in the spectral domains as shown in Fig. 6 for ICMF of 832.6 MHz and 833 MHz. The interference pattern was lost completely above 833 MHz and at or below 832.0 MHz, indicating that the mode-locking mechanisms no longer exist in these operating regimes. Instead, injection seeding dominates the pulse generation process.

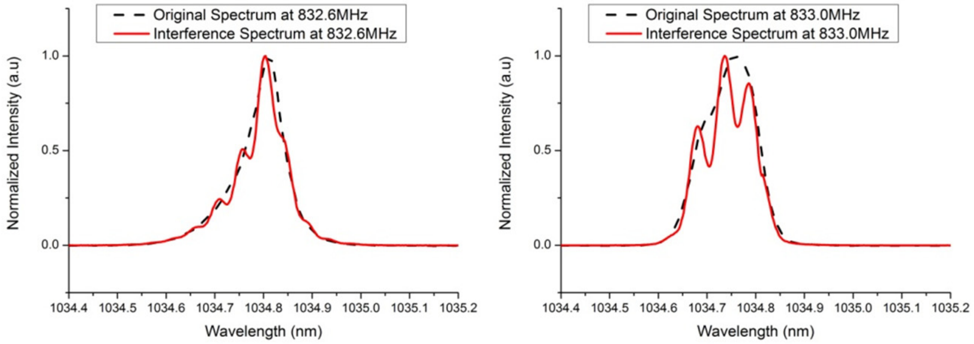

Fig. 6. Interference patterns between the 1st and the 10th optical pulses for two different operating frequencies corresponding to different operating regimes. The separation between peaks corresponds to the temporal separation between the two interfered optical pulses.

4. Conclusion

We have demonstrated a simple cavity configuration incorporating a gain switched SLD and an external FBG capable of generating transform-limited 18 ps optical pulses with a pulse energy of 7.2 pJ and peak power of 400 mW. We have shown that the mode-locking mechanism is responsible for the generation of the shortest picosecond optical pulses observed. We have also investigated the impact of injection current modulation frequency on the spectral and temporal evolution of the pulses. The combination of the excellent stability of the optical pulse produced and simplicity of this seed configuration make this SLD based system an attractive seed source for picosecond MOPA systems.

Acknowledgments

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