40-GHz Optical Pulse Generation Using Strong External Light Injection of a Gain-Switched High-Speed DBR Laser Diode

Zhaoyang Hu, Hsu-Feng Chou, John E. Bowers, *Fellow, IEEE*, and Daniel J. Blumenthal, *Fellow, IEEE*

***Abstract*—We demonstrate a compact 40-GHz repetition rate optical pulse source using a gain-switched distributed Bragg reflector laser diode with strong external light injection. The 8-ps output pulses are nearly transform-limited and the timing jitter is dominated by the radio-frequency driving source. We experimentally demonstrate the dependence of the modulation efficiency and the chirp characteristic on the external injection power level.**

***Index Terms*—External injection, gain-switched lasers, optical pulse generation.**

I. Introduction

COMPACT and stable high-speed optical pulse sources are important for high-speed optical communications systems with transmission rates of 40 Gb/s and greater [1]. Mode-locked semiconductor lasers, electrically driven electroabsorption modulators (EAMs), and gain-switched laser diodes (LDs) are among techniques that have been previously demonstrated, but practical issues have limited their use in communications systems. Mode-locked lasers demonstrate high performance pulse generation, however, the repetition rate is difficult to adjust. Traveling-wave EAMs have been used to generate 40-GHz optical pulses [2], but EAMs introduce loss. The gain-switched laser is an attractive approach due to its potential for integration, power efficiency, relative long-term stability, and high output power. However, to date, the repetition rate of gain-switched pulses has been limited to less than 20 GHz [3], [4].

The theory for strong optical injection locking of LD predicts modulation bandwidth enhancement and chirp reduction [5]. This approach has been employed to extend the modulation bandwidth and reduce chirp for a strong injection-locked high-speed distributed Bragg reflector (DBR) LD [6], [7]. In this letter, we report the first experimental demonstration of 40-GHz optical pulse generation from a gain-switched high-speed DBR-LD using strong external light injection to enhance the modulation response of the DBR-LD. In this work, the output 40-GHz pulses are measured at 8-ps pulsewidth and are nearly transform-limited. The absolute root-mean square (rms) timing jitter of the 40-GHz pulses is dominated by the 40-GHz radio-frequency (RF) driving source. We also experimentally demonstrate the impact of the external light injection power level into the gain-switched DBR-LD on the modulation efficiency, the pulsewidth, and the spectrum bandwidth.

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The authors are with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, Santa Barbara, CA 93106-9560 USA (e-mail: huby@ece.ucsb.edu).

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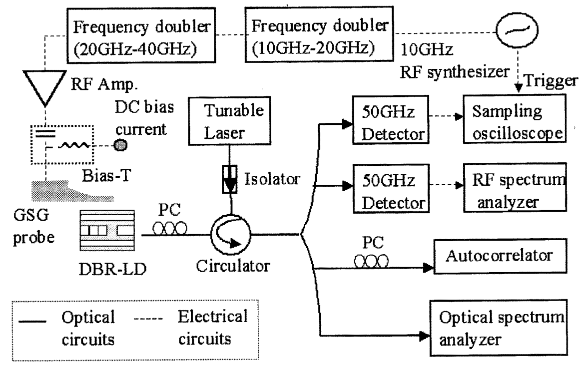

Fig. 1. Experimental setup.

II. Experimental Setup

The experimental setup is shown in Fig. 1. The DBR-LD was fabricated at the Royal Institute of Technology (KTH), Sweden [8], and has a threshold current of 12 mA. When the DBR-LD is operated at 60-mA bias current, the center wavelength of the emitted light is 1553.7 nm, the side-mode suppression ratio is above 40 dB, and the output power is 4 dBm into an antireflection-coated taper-lensed-fiber pigtail. Its 3-dB modulation bandwidth at 60-mA bias current is about 20 GHz. Two RF frequency doublers and a 40-GHz RF amplifier were used to obtain 40-GHz sinusoidal modulation signal from a 10-GHz RF synthesizer. A ground–signal–ground coplanar RF probe was used to apply the dc bias current and modulation signal to the DBR-LD. External light injection to the DBR-LD was realized by using a wavelength tunable laser via an isolator and an optical circulator. A polarization controller was used to optimize the light injection from the tunable laser. A 50-GHz sampling oscilloscope and an RF spectrum analyzer, in conjunction with a 50-GHz p-i-n photodetector, were used to measure the temporal and spectral behavior of the output pulses, respectively. An autocorrelator was employed to measure the pulsewidth.

III. Results and Discussion

We gain-switched the DBR-LD at a frequency of 40 GHz without external injection under 60-mA bias current. 40-GHz modulation RF power was fixed to the maximum available

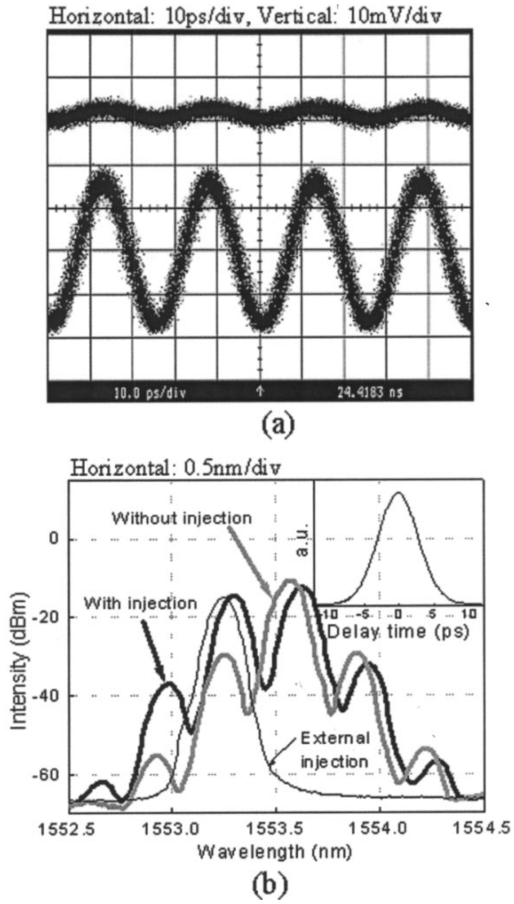

Fig. 2. (a) 40-GHz pulse outputs without injection (upper) and with injection (lower) at 60-mA bias current. (b) Corresponding optical spectra without and with injection, respectively. Inset waveform in (b): autocorrelation trace of 40-GHz pulses with injection.

output power of 20 dBm. The laser output was low and is shown in the upper waveform in Fig. 2(a) with the sampling oscilloscope persistence time set to 1 s. The corresponding optical spectrum is shown as the grey line in Fig. 2(b) and demonstrates 40-GHz pulses cannot be generated directly through strong modulation of the DBR-LD without optical injection due to the limited modulation response of the DBR-LD at 60-mA bias current. Although the DBR-LD cannot be effectively gain-switched at 40 GHz, its optical spectrum was broadened and generated multiple sideband components due to the strong modulation. When the wavelength of the strong external light injection is adjusted to overlap with either one of the sideband components, there is an increased coupling between the carriers and photons. Thus, an effectively higher differential gain is achieved with effective enhanced modulation efficiency. As a result, the DBR-LD can be gain-switched at higher speeds.

The tunable laser, with an output power of 9 dBm, was injected into the DBR-LD. We estimate the external optical injection power into the DBR-LD to be around 4 dBm assuming the insertion loss of the circulator and the coupling loss between the lensed fiber and the DBR-LD to be approximately 5 dB. The wavelength of the injected light was tuned to meet either one of the sideband peaks of the gain-switched DBR-LD. In the experiment, different modulation efficiency enhancements were observed under different injection wavelengths except when the injection wavelength coincides with the center wavelength of the DBR-LD due to competition between the comparable field amplitudes of the DBR-LD and the optical injection. The maximum modulation efficiency enhancement was obtained at an injection wavelength of 1553.3 nm. The corresponding pulse output is shown as the lower waveform of Fig. 2(a) and the average output power was about 2.8 dBm. The greatly enhanced pulse extinction ratio indicates that the DBR-LD has been gain-switched at 40 GHz. The excited optical field due to the external light injection also beats with the main mode when phase locked and further enhances the pulse extinction ratio. The dc level of the 40-GHz pulse stream cannot be judged directly from the sampling oscilloscope due to the limited photodetector bandwidth. A small dc offset was observed from the autocorrelation traces of the 40-GHz pulses. The optical spectrum of the 40-GHz pulses is shown as the dark line of Fig. 2(b). The insufficient separation of sideband components of the gain-switched DBR-LD were due to the insufficient wavelength resolution of the optical spectrum analyzer, whose wavelength resolution was 0.1 nm. The pulse trains in Fig. 2(a) appear to be sinusoidal due to the limited measurement bandwidth of the combined sampling oscilloscope and the photodetector. The actual pulsewidth was measured with a second-harmonic generation (SHG) autocorrelation method. The inset waveform of Fig. 2(b) shows the SHG autocorrelation trace for the 40-GHz pulses and it shows the pulsewidth is about 8 ps. Its 3-dB spectrum bandwidth was about 0.49 nm after fitting the optical spectrum into a Gaussian envelope. The resulting time bandwidth product is 0.49, which is close to 0.44 for transform-limited Gaussian pulses. The mode spacing was 0.32 nm ($\sim$40 GHz), which agrees well with the repetition rate of the optical pulses. We found that the lasing peak was about 0.2 nm red-shifted, which is partially due to heating and partially due to the reduced threshold carrier density.

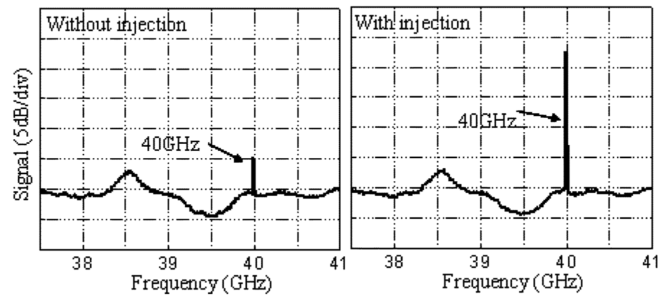

Fig. 3. 40-GHz pulse signal in the frequent domain. Top: without injection. Bottom: with injection.

Fig. 3 shows the measurement results in the frequency domain without and with external light injection. At around 40 GHz, strong optical injection leads to above 16-dB improvement in the electrical modulation frequency. Fig. 4 displays the RF spectra of the 40-GHz RF driving source and corresponding 40-GHz gain-switched pulses with injection. The RF spectrum of the 40-GHz driving source shown as the dark line in Fig. 4 is obtained by connecting the amplifier and synthesizer directly to the RF spectrum analyzer via a 20-dB RF attenuator. The RF spectrum of the 40-GHz gain-switched pulses is shown as

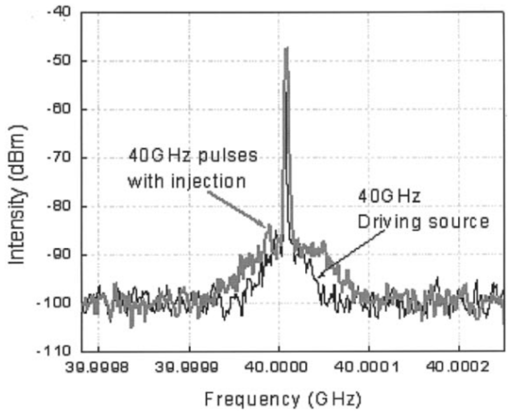

Fig. 4. RF spectra measured for 40-GHz RF driving source and 40-GHz pulses with injection. Span: 500 kHz. Resolution bandwidth: 1 kHz.

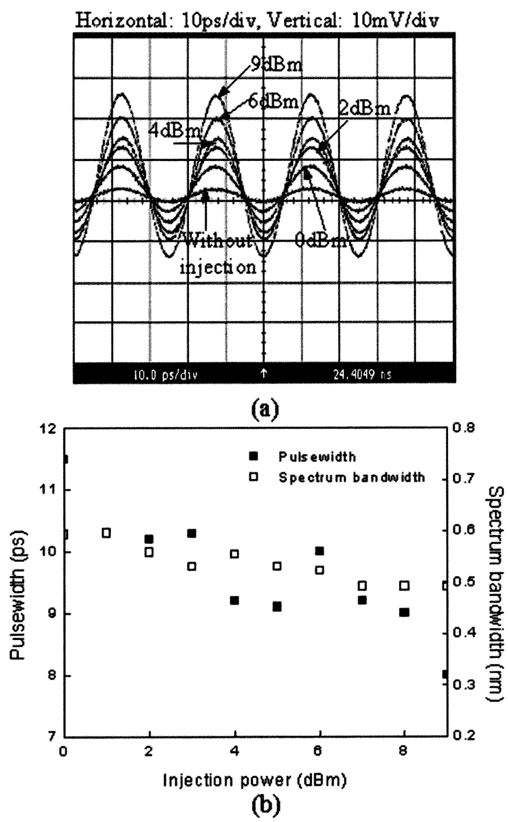

Fig. 5. Influences of the injection on (a) the modulation efficiency and (b) the pulsewidth and the spectrum bandwidth of 40-GHz pulses.

the gray line in Fig. 4. The absolute rms timing jitters of the 40-GHz driving source and the 40-GHz gain-switched pulses with injection were obtained by integrating the single sideband (SSB) noise [9] from the RF spectra in Fig. 4, which are 783 and 932 fs, respectively. This indicates the timing jitter is dominated by the driving source.

The influence of injection power on the modulation efficiency, the pulsewidth, and the optical spectrum bandwidth was studied by varying the injection power. Fig. 5(a) shows different modulation efficiency results corresponding to different injection power of 9, 6, 4, 2, 0 dBm and without injection, respectively. In order to compare the output pulses clearly, waveform average was used. The increase of the modulation response due to the increase of the injection power enhances the gain-switched pulses and consequentially reduces the pulsewidth [6]. Through calculating the time bandwidth product using the pulsewidth and the spectrum bandwidth, shown as Fig. 5(b), which was taken under optimum operation (minimum output pulsewidth), it indicates the reduction of the frequency chirping with the increase of the injection power. The spectrum bandwidth slightly decreased as the external light injection power increased. The reason is that external light injection reduced the threshold gain in the active region, and thus, the peak population inversion level could be reached during a short period of optical pulse generation. If higher external light injection is used, it could result in pulse degradation due to excessive heating.

IV. Conclusion

We have experimentally demonstrated 8-ps 40-GHz repetition rate direct pulse generation using a gain-switched DBR-LD. Strong external light injection is employed to enhance the effective modulation efficiency. The near transform-limited 40-GHz optical pulses show comparable timing jitter values to the RF driving source itself. We demonstrate that strong external light injection improves the modulation efficiency. This approach shows promise as a compact high-speed pulse source for 40-Gb/s applications using a relatively low modulation response LD.

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