Characterization of 1.55-μm Pulses from a Self-Seeded Gain-Switched Fabry–Perot Laser Diode Using Frequency-Resolved Optical Gating

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***Abstract*— The intensity and frequency chirp of picosecond pulses from a self-seeded gain-switched Fabry–Perot laser diode have been directly measured using the technique of frequency-resolved optical gating. Measurements over an output sidemode suppression ratio (SMSR) range of 15–35 dB show that higher SMSR's are associated with an increasingly linear frequency chirp across the output pulses. This complete pulse characterization allows the conditions for optimum pulse compression to be determined accurately, and indicates that transform-limited, pedestal free pulses can be obtained at an SMSR of 35 dB.**

***Index Terms*— Optical fiber communication, optical fiber dispersion, optical pulses, semiconductor lasers, ultrafast optics.**

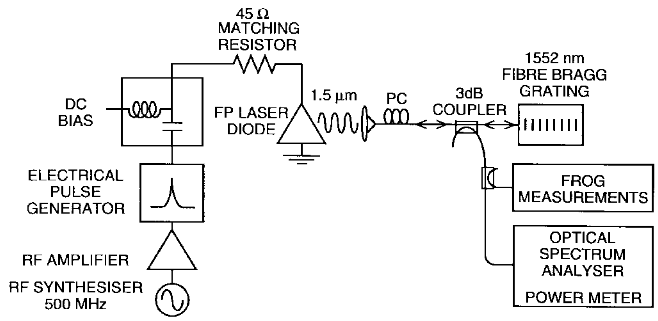

Fig. 1. Experimental setup used for pulse generation and measurement.

I. Introduction

The generation and measurement of picosecond pulses at wavelengths around 1.55 μm is very important for the development of high-capacity optical communications systems. A convenient technique for single-mode picosecond pulse generation is the self-seeding of gain-switched Fabry–Perot (FP) laser diodes, and many experimental schemes using this technique have been reported [1]–[6]. With self-seeding, an external cavity containing a wavelength-selective element reinjects a small fraction of the output light back into the gain-switched laser at only one longitudinal mode frequency. Provided that reinjection occurs during the pulse buildup time in the FP laser, gain is suppressed in all, but the reinjected mode, and the laser produces a stable train of single-mode pulses. This technique is an effective way to produce wavelength-tunable 10–100-ps pulses with low pulse-to-pulse timing jitter [3], and recent experiments have also demonstrated multiwavelength output [5] suitable for application in wavelength-division-multiplexed (WDM) networks.

An intrinsic problem associated with pulse generation using gain-switching is the presence of a large frequency chirp across the pulses. This arises from variations in carrier density in the gain region during pulse buildup [4], and is also present in self-seeded gain-switched lasers. For practical applications of gain-switched pulses, chirp compensation is usually employed, using dispersion-compensating fiber (DCF) [4], [7]–[9] or chirped fiber Bragg gratings (FBG's) [10]. In these experiments, however, the absence of *a priori* chirp characterization results in the conditions for optimum chirp compensation being obtained using an approximate pulse compression model assuming linearly chirped Gaussian pulses [4], [7], [8], or by trial and error using different lengths of DCF [9].

In this letter, we use the technique of frequency-resolved optical gating (FROG) [11] to measure the intensity and the frequency chirp of pulses from a self-seeded, gain-switched FP laser, and we study in particular the variation in the chirp as a function of the external cavity reinjection level. This complete pulse characterization allows the optimal conditions for pulse compression to be determined using numerical simulations without any assumptions about the pulse intensity or chirp characteristics. We use the simulations to determine the optimal laser operation conditions which result in transform-limited pulses after compression.

II. Experimental Setup

Fig. 1 shows our experimental setup. The FP laser was a temperature-controlled 1.5-μm p-side down InGaAsP device, with a longitudinal mode spacing of 1.1 nm, a threshold current of 27 mA, and a 10-GHz modulation bandwidth. With the laser biased below threshold at 5 mA, gain-switching was carried out around 500 MHz using a step-recovery diode to generate an electrical pulse train of 13-V amplitude and 80-ps full-width at half-maximum (FWHM) [2]. The external cavity for reinjection was all-fiber based [6], containing a polarization controller (PC), a 3-dB coupler, and a FBG with central reflection wavelength of 1552 nm and bandwidth of 0.3 nm. Gain-switching without reinjection resulted in the generation of 12-ps pulses (FWHM) with a multimode spectrum. Self-seeded gain-switched operation was achieved by first adjusting the FP laser temperature so that an oscillating longitudinal

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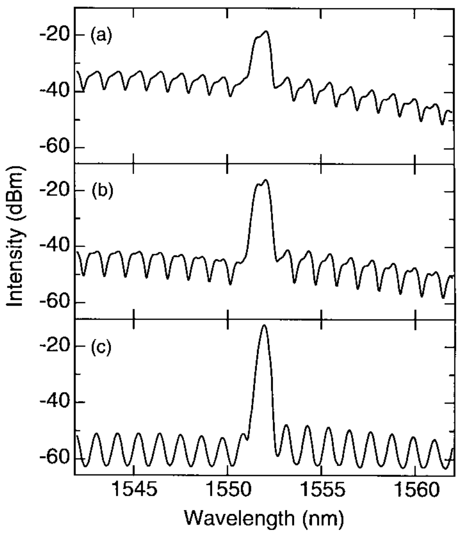

Fig. 2. Measured pulse spectra for gain-switched self-seeded laser operation corresponding to observed SMSR values of (a) 15 dB, (b) 25 dB, and (c) 35 dB.

laser mode coincided with the central reflection wavelength of the fiber grating. Then, the gain-switching frequency was tuned to 496.76 MHz, corresponding to the 26th harmonic of the external cavity. The amount of reinjection from the external cavity could be adjusted by varying the polarization of the reflected signal using the PC.

The laser output was taken from the 3-dB coupler shown in Fig. 1. Pulse characterization was carried out using an optical spectrum analyzer, a 25-GHz detector and digital oscilloscope, and a FROG measurement setup using second harmonic generation. The FROG measurement yields a two-dimensional (2-D) time-frequency spectrogram of the pulse from which the time-dependent intensity and phase can be obtained using phase-retrieval techniques [11]. Specifically, if the pulse electric field is written $E(t) = \sqrt{I(t)}\exp[i(\omega_0 t - \phi(t))]$, the FROG technique allows the recovery of $I(t)$ and $\phi(t)$. The instantaneous frequency chirp $\delta\nu(t)$ (in gigahertz) across the pulse is obtained from the phase $\phi(t)$ by $\delta\nu(t) = -(2\pi)^{-1}\ d\phi(t)/dt$. To obtain good signal-to-noise ratio in the FROG measurements, an erbium-doped fiber amplifier (EDFA) amplified the laser pulses to a peak power of around 1 W. At this power level, amplification was purely linear and introduced no intensity or chirp distortion.

III. Results and Discussion

The pulse characteristics from the self-seeded gain-switched laser were examined as a function of reinjection level. The highest sidemode suppression ratio (SMSR) in the output spectrum for stable pulse generation was 35 dB corresponding to an estimated reinjection level of 6%. With reduced reinjection, the SMSR decreased, and stable output pulses were obtained over a SMSR range of 35–15 dB. At 5-dB increments over this range, the pulses were characterized by monitoring the pulse spectra and by performing FROG measurements. Within experimental error, the average output power was measured at around 0.17 mW for all SMSR values. At estimated reinjection

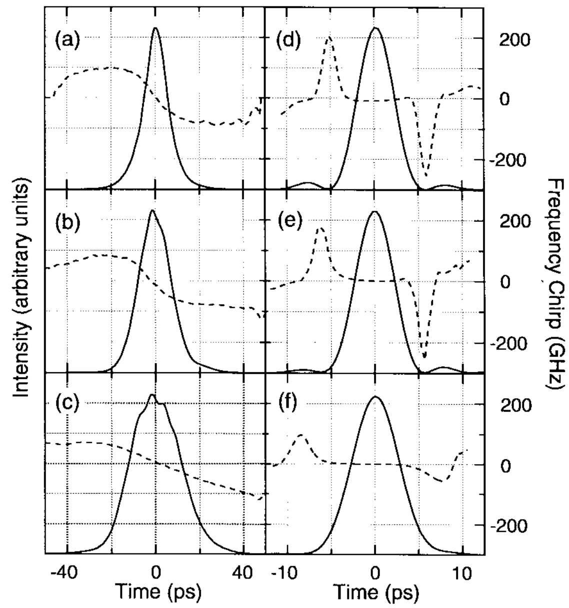

Fig. 3. Output pulse intensity (solid line, left axis) and frequency chirp (dashed line, right axis) for observed SMSR values of (a) 15 dB, (b) 25 dB, and (c) 35 dB. The corresponding simulation results after optimal compression are shown in (d), (e), and (f), respectively. Note the different timescales between (a)–(c) and (d)–(f).

levels greater than 6%, pulse deformation and instabilities were observed [12], although a comprehensive analysis of this operating regime was not carried out in our experiments.

Fig. 2(a)–(c) shows measured output spectra for estimated reinjection levels of 0.1, 0.8, and 6% corresponding to SMSR's of 15, 25, and 35 dB respectively. It is clear that increased reinjection results in improved SMSR, reduced spectral width, and increased spectral symmetry. Additional physical insight is obtained from the FROG characterization, and Fig. 3(a)–(c) shows the corresponding retrieved pulse intensity $I(t)$ and frequency chirp $\delta\nu(t)$. As expected, the chirp blue-shifts the pulse leading edge and red-shifts the trailing edge [1]. It is also clear that an increased SMSR is associated with increased pulse duration and reduced chirp, consistent with the spectral data in Fig. 2. Significantly, the FROG measurements show that whilst the chirp is highly nonlinear at low SMSR, it becomes increasingly linear with increasing SMSR. The reduction in the chirp magnitude with increasing reinjection has been noted previously [12], [13] and arises since the presence of the reinjected signal reduces the peak inversion reached during the pulse emission process. To the best of our knowledge, the results presented here are the first direct measurements of the change in chirp across the pulse with reinjection level, and the first to demonstrate improved linearity with increased reinjection.

With the complete intensity and chirp characterization of the laser pulses in Fig. 3(a)–(f), the optimal conditions for pulse compression can be investigated by numerically simulating the propagation of the pulses in DCF [9]. By examining the intensity and chirp characteristics as a function of propagation distance, the required fiber length for optimum compression can be obtained accurately. In our simulations, we modeled pulse propagation neglecting nonlinear propagation effects at

TABLE I
SUMMARY OF RESULTS FROM EXPERIMENTS AND SIMULATIONS

SMSR (dB)	Spectral FWHM Δν (GHz)	Temporal FWHM Δτ (ps)	Average Chirp Slope - Δν/Δt (GHz/ps)	Compressed FWHM from Simulations Δτ (ps)	Compressed Pulse Δτ Δν from Simulations	Optimum Compression Length (m) From Simulations	Optimum Compression Length (m) Using Chirp Slope
15	142	12.1	8.4	4.7	0.67	1050	927
20	137	13.8	8.1	4.8	0.66	1150	961
25	123	17.0	6.7	5.0	0.62	1210	1162
30	103	20.8	4.9	5.3	0.55	1600	1589
35	75	26.1	3.0	5.9	0.44	2640	2595

the peak power levels in our experiments, and assuming a normal dispersion of $D = -16$ ps/nm $\cdot$ km in the DCF. Fig. 3(d)–(f) shows simulation results for the optimally compressed pulses corresponding to Fig. 3(a)–(c), respectively. In all cases, the chirp is close to zero across the pulse center, but the nonlinear chirp of the input pulses at the lower SMSR values shown in Fig. 3(a) and (b) results in imperfect compression and subsidiary pulses on the outputs shown in Fig. 3(d) and (e). At the highest SMSR $=$ 35 dB, however, the linear chirp of the input pulse in Fig. 3(c) results in the compressed output pulse in Fig. 3(f), which does not possess any significant substructure in the wings. Table I summarizes our results. For each SMSR value, we tabulate the pulse spectral and temporal FWHM, and the pulse chirp is characterized by its average slope $\Delta\nu/\Delta t$ across the pulse FWHM. We also tabulate the temporal FWHM and time-bandwidth product of the compressed pulses, and the required fiber length from the simulations. As expected, the linear chirp associated with higher SMSR's leads to improved time-bandwidth products after compression. Indeed, the most linearly chirped input pulse at an SMSR $=$ 35 dB is well-fitted by a Gaussian after compression, and is essentially transform-limited with $\Delta\tau\Delta\nu = 0.44$.

As well as using numerical simulations as described above, the direct retrieval of the pulse chirp slope $\Delta\nu/\Delta t$ from the FROG measurements allows the conditions for optimal compression to be obtained using the result $DL = c/\lambda^2(\Delta\nu/\Delta t)^{-1}$ [7], [8]. Here L is the optimal length of fiber with dispersion parameter D. Using $D = -16$ ps/nm·km as above, the required fiber lengths obtained using this technique are also summarized in Table I and we note that the results are in good agreement with simulations even for low SMSR's when there is appreciable nonlinear chirp and asymmetric pulse spectra.

IV. CONCLUSION

The FROG technique has been used to characterize the intensity and chirp of pulses from a gain-switched self-seeded FP laser. The pulse chirp has been found to decrease and to become increasingly linear with increasing SMSR. At the highest SMSR of 35 dB, simulations indicate that transform-limited pulses are obtained after compression. The optimum conditions for pulse compression can also be obtained accurately using the average chirp slope across the pulse FWHM. We anticipate that FROG measurements will allow further optimization and improved physical understanding of gain-switched laser diodes.

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