

Detailed Comparison of Injection-Seeded and Self-Seeded Performance of a 1060-nm Gain-Switched Fabry–Pérot Laser Diode

K. T. Vu, Andrew Malinowski, Michaël A. F. Roelens, and David J. Richardson

Abstract—We investigate and compare the performance of a gain-switched picosecond Fabry–Pérot laser diode operated at 1.06 μm under both injection- and self-seeded conditions. Our experiments show that comparable performance can be obtained for both modes of operation, with the self-seeding arrangement offering overall benefits in terms of reduced system complexity and cost, providing the associated quantization of available pulse repetition rate can be tolerated.

Index Terms—Fiber Bragg grating, optical pulse generation, semiconductor lasers.

I. INTRODUCTION

GAIN-SWITCHING of laser diodes has proved to be a convenient and practical method to generate picosecond pulses. Gain-switched distributed feedback (DFB) and Fabry–Pérot (FP) lasers were primarily developed for telecommunications applications [1]–[5] providing high repetition rate operation but relatively limited pulse powers. However, recently they have also been used as seed lasers for high-power cladding-pumped rare-earth doped fiber amplifiers emitting at 1.55 μm [6]–[10] and at 1.06 μm [11]–[14]. Such high repetition rate, high power systems have a variety of uses including applications in frequency conversion [15], [16] and materials processing [17], amongst others.

Interest in developing 1.06- μm -based master oscillator power amplifier (MOPA) systems is particularly intense at present, not least given that power-scaling of MOPA systems to the kilowatt regime can now be relatively straightforwardly and efficiently achieved. Interest in picosecond MOPA systems has also grown in particular due to the realization that picosecond pulses (typically 10–20 ps) offer most of the advantages associated with fs-pulses for precision micromachining applications (e.g., reduced heat-affected zones, high spatial resolutions etc) [17]. The reliability and cost advantages of being able to use a system

based on a compact, stable, diode-based seed oscillator versus the use of a solid-state femtosecond oscillator based system is self-evident. High-power FP laser diodes, developed from existing 980 nm pump laser technology, and capable of gain-switched operation have only just recently become available,¹ and understanding whether such systems are capable of providing pulses of suitable quality for micromachining applications, and how best to obtain the appropriate stability is thus an important technical and commercial issue.

In order to promote reliable and reproducible pulse build up within a gain-switched laser cavity some form of optical seeding is required [18]–[28]. In a FP cavity diode, this is essential in order to obtain good spectral quality output (i.e., lasing on a single longitudinal cavity mode [18], [21]), and provides timing jitter reduction in both DFB and FP gain-switched systems [6], [9].

In this paper we report a detailed comparison of the performance obtained for a FP laser operating at 1.06 μm using two methods of seeding: using an external narrow-linewidth continuous wave (CW) laser as the seed, and self-seeding by reflecting a portion of each pulse back into the laser diode. Compared to injection seeding, self seeding offers considerable advantages in terms of simplicity and reduced cost. For this reason, it is important to establish whether self seeding leads to any degradation of performance compared to injection seeding. Whilst previous studies have been made on either externally seeded systems [18]–[20], or on self-seeded systems [21]–[28], and the general conclusions have been that similar performance can be achieved from both seeding approaches, as far as we are aware, no systematic comparison of the relative performance of the two approaches using the same diode appears to have been previously published. Moreover, no detailed study of the pulse shapes obtained using a complete pulse characterization technique (providing both phase and amplitude profiles—in our case using a recently developed linear frequency resolved optical grating (FROG) technique [29]) has previously been provided.

II. EXPERIMENTAL SETUP

The commercial fiberized, single mode InGaAsP FP laser diode manufactured by Bookham (model LC92) operated at around 1060 nm, had a cavity length of ~ 0.8 mm and a front facet reflectivity of $\sim 1\%$. It was driven by a sinusoidal electrical signal to produce gain-switched pulses, similar to the seed laser in [14]. The device had a modulation bandwidth much greater

¹[Online]. Available: http://www.bookham.com/documents/datasheets_hpld/LC96A-10x0-20R_r4.0-00801.pdf

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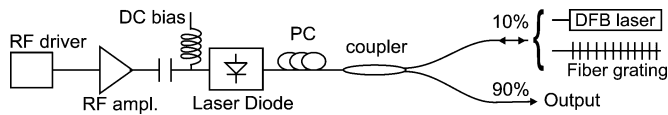


Fig. 1. Seeded gain-switched laser diode setup.

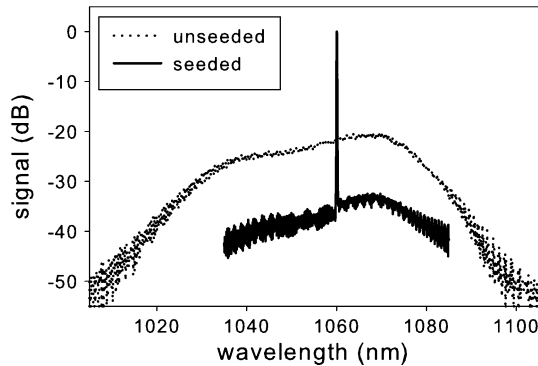


Fig. 2. Spectrum of the unseeded and seeded diode: DFB seeded with $19.4 \mu\text{W}$ power.

than 1.35 GHz. The diode is mounted in a butterfly mount on a home made printed circuit board (PCB) for impedance matching. Gain switching was realized by driving the laser with a modulated drive signal superimposed on a dc bias current (see Fig. 1). The diode was biased a little below threshold (~ 40 mA). The peak diode current was ~ 700 mA. Sinusoidal modulation was used in these experiments: it was found that sinusoidal and square pulse modulation produced very similar results as long as the square pulses were of suitable duration.

The diode output was spliced to a 90:10 coupler, allowing a small seed signal derived either from an external laser, or reflected diode output, to be fed back to the diode. A polarization controller was incorporated so that we could ensure that the seed signal had the same polarization as the diode.

Without seeding, the diode has a broad spectrum with a FWHM of approximately 20 nm. The spectrum consists of modes spaced at about 0.2 nm, corresponding to the cavity length of $\sim 800 \mu\text{m}$ (assuming a refractive index of InGaAs of ~ 3.5). The average output power was 3.3 mW and pulse duration was 61 ps. The spectral output of the diode with and without seeding (modulated at 1 GHz in both cases) is shown in Fig. 2.

In both the injection seeded and self-seeded cases, for the same drive current, the average output power increased slightly to about 5 mW, corresponding to ~ 5 pW pulse energy. The FWHM spectral bandwidth drops by a factor of ~ 100 compared to the unseeded case, to about 0.2 nm, consisting of a single longitudinal cavity mode, with all the other cavity modes strongly suppressed.

Pulse shapes were obtained using a 20-GHz oscilloscope, and pulse spectra were measured with a 0.01-nm resolution OSA.

III. DFB SEEDING

For injection seeding, the seed signal to the diode came from an optically isolated CW diode pumped DFB fiber laser operating at 1060.0 nm with a linewidth of less than 100 kHz and an output power adjustable in the range 0.2–1.4 mW, corre-

sponding to 20–140 μW being coupled to the diode. The pulse repetition rate, set by the driving electronics, was 1 GHz (the maximum frequency of the available RF amplifier).

Fig. 3 shows the pulse shape and corresponding spectra for DFB seeding at various powers. In these measurements, the seed laser wavelength was 0.02 nm shorter than the center wavelength of the gain-switched pulses. As we will see below, this gives the best side-mode suppression ratio (SMSR) for a given seed power. The pulse duration is 61 ps at low seeding powers, broadening progressively with increased power up to 78 ps at the highest seed power used. Note also that as the seed power is increased a small secondary peak appears at the leading edge of the pulse, approximately 80 ps from the main pulse peak. There is clearly a tradeoff between the SMSR and the size of this secondary feature. The spectral width is 0.18 nm at low seed powers, narrowing slightly to 0.15 nm at the highest seed power. This corresponds to a small decrease of the time-bandwidth product (TBWP) from 3.3 to 3.0. The strong pulse chirp associated with gain-switched diode laser pulses originating from the carrier density dynamics is well known [30]–[33].

Fig. 4(a) shows how the SMSR, the ratio between the peak mode and the next highest mode in the gain bandwidth, varies with seed power. It can be seen that, not surprisingly, the SMSR is higher for higher seed powers, rising from 32 dB at 20 μW seeding to 41 dB at 140 μW . The output power increased with seeding; 4.3 mW for the lowest seed power rising to 4.9 mW for the highest seed power. This corresponds to a maximum pulse energy of 4.9 pW.

Fig. 4(b) shows the SMSR as a function of detuning of the seed from the center wavelength of the diode, with the seed power fixed at 20 μW . Since the DFB laser was of fixed wavelength, tuning the wavelength difference between the cavity mode of the diode and the seed wavelength was achieved in practice by temperature tuning the wavelength of the diode. We found that the best SMSR was achieved when the peak output wavelength of the diode was tuned 0.02 nm longer than the DFB wavelength. This is as expected, since the change in refractive index of the active medium (due to changes in the carrier density) during gain-switching results in an intrinsic negatively chirped pulse (the blue shifted light is at the leading edge) [30]. Hence, seeding at a slightly shorter wavelength matches the wavelength of the leading edge of the gain-switched pulse.

It should be noted that the secondary feature in the pulse shape always appeared as the SMSR increased above ~ 30 dB, regardless of the particular combination of seed power and wavelength tuning used to achieve this.

We also made a crude estimate of the timing jitter reduction associated with the seed injection using the histogram feature on our digital sampling scope. The unseeded pulses had an amplitude jitter of $\sim 7\%$ and a root mean squared (RMS) timing jitter of ~ 4 ps. However, under DFB injection the amplitude jitter could readily be improved to $\sim 2\%$, and the timing jitter to ~ 3 ps. We believe this is dominated by the jitter correlated with the drive electronics, specified by the manufacturer of the pulse generator (Agilent 8133A) at 2.5 ps RMS. Hence, we estimate the uncorrelated jitter (due to the response of the diode itself) to be of order 1 ps, below our estimated timing jitter measurement accuracy of ~ 1.5 ps. This agrees with detailed jitter mea-

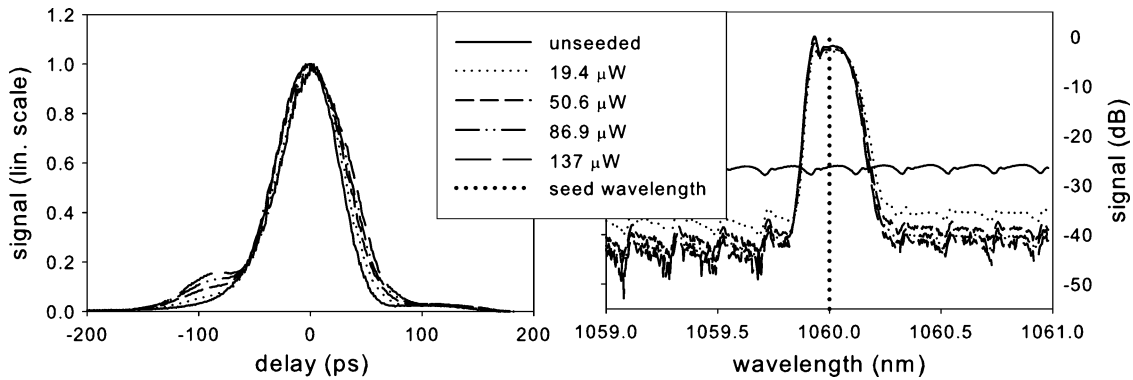


Fig. 3. (a) Pulse shape and (b) spectra with various DFB seed powers.

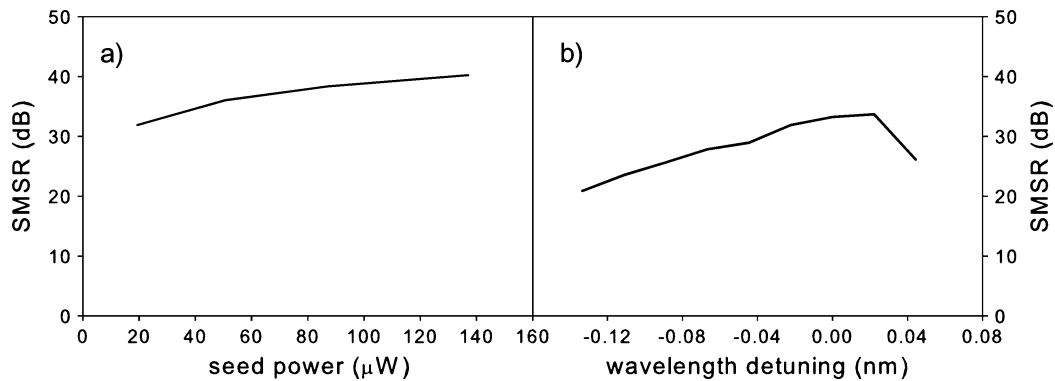


Fig. 4. SMSR with DFB seeding (a) as a function of seed power at a wavelength detuning of 0.02 nm and (b) as a function of wavelength detuning with for a fixed seed power of 20 μW .

measurements we previously performed on a similar diode using the same pulse generator which gave an uncorrelated jitter of less than 1.5 ps.

IV. SELF-SEEDING

For self-seeding, a portion of the pulse was reflected from a fiber grating. A set of fiber gratings manufactured in house, with reflectivities in the range 5%–99% were used, corresponding to 0.05%–1% of the diode output being fed back into the diode. This corresponds to average powers in the range 2.5–50 μW , and peak powers in the range 30–600 μW (given the $\sim 8\%$ duty cycle). Note that the seed pulse feedback needs to be properly synchronized with pulse emission i.e., the round-trip time between the diode and grating must be a multiple of the delay between pulses. In our experiment, the corresponding fundamental repetition rate associated with feedback from the external grating was ~ 9.1 MHz. The diode was driven with a sinusoidal electrical signal at 109 times this frequency (~ 992 MHz), with a superimposed dc bias current, with the same amplitudes as the DFB seeded case.

The reflection gratings varied considerably in spectral width. The 99% grating was broad enough to encompass four cavity modes of the diode, whilst the rest had a bandwidth comparable with the laser mode spacing (i.e. ~ 0.2 nm). In practice, the diode operated on a single mode with feedback from any of these gratings. The operating mode was the longest wavelength mode

available within the reflection window of the grating, presumably because we were always operating at wavelengths slightly below the gain peak.

Fig. 5 shows pulse shape and spectra for self-seeding at various powers. Because the different gratings had center wavelengths in the range 1060.3 to 1061.6 nm, the pulses had different center wavelengths at the different feedback levels. In Fig. 5(b) the center wavelengths have been normalized for convenience of viewing. As with DFB seeding, the pulse duration increases slightly with seed power, rising from 61 ps at low seeding powers to 81 ps at the highest seed power, and a secondary peak appears at the leading edge of the pulse as the seed power increases. The spectral width narrows from 0.18 nm at low seed powers to 0.13 nm at the highest seed power, corresponding to a decrease of TBWP from 3.2 to 2.8.

Fig. 6(a) shows the SMSR as a function of seed power. The SMSR rises from 27 dB with the lowest reflectivity grating to 42 dB with the highest. Again, the output power increased with seeding; 4.3 mW for the lowest seed power rising to 4.9 mW for the highest seed power, corresponding to a maximum pulse energy of 4.9 pW.

With self-seeding, the spectra of pulse and seed is essentially identical, so wavelength tuning is not an option. However, because of the pulsed nature of the seed, another degree of freedom is available. With a fixed cavity length, a small detuning of the drive frequency from the round-trip frequency corresponds to delaying the seed pulse with respect to the gain-switched pulse. Fig. 6(b) shows the SMSR as a function of the frequency, using

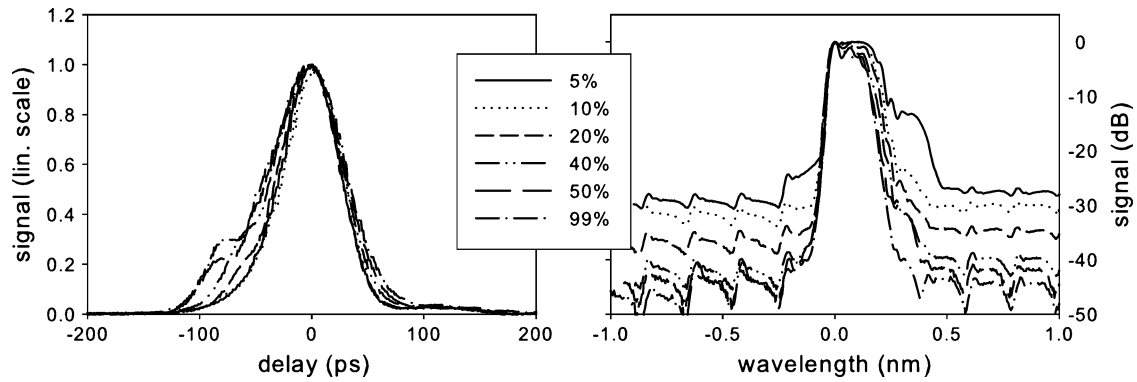


Fig. 5. (a) Pulse shapes and (b) spectra for gratings of various reflectivity being used for self-seeding. Multiply by $\times 0.01$ to get the actual fraction of pulse power injected as a seed. The center wavelengths of the spectra of pulses produced with different wavelength gratings have been normalized for convenience of viewing.

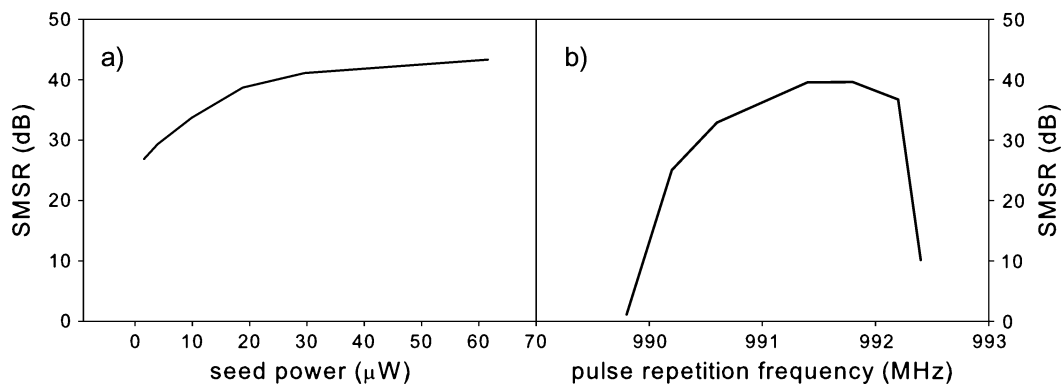


Fig. 6. SMSR with self-seeding (a) as a function of average seed power at a repetition frequency of 991.5 MHz (multiply by ~ 12.5 for peak power), (b) as a function of repetition frequency with 50% reflectivity grating ($30 \mu\text{W}$ average seed power).

the 50% reflective grating. Since we could not exactly measure the round-trip time, we cannot state precisely what frequency corresponds to zero delay for our system, however we can accurately determine that the scaling of the delay to the frequency is ~ 110 ps/MHz. Not surprisingly, the SMSR drops toward zero when the seed pulse no longer temporally overlaps the gain-switched pulse.

As with seeding with the DFB, the secondary feature in the pulse shape always appeared as the SMSR increased above ~ 30 dB.

In both the injection seeded and self-seeded cases, seeding increased the output power (to about 5 mW average power, corresponding to ~ 5 pW pulse energy). The achievable performance of the gain-switched diode differed very little depending on which type of seeding was used, with ≥ 40 dB SMSR achievable in either case, and with the pulse duration and quality being quite similar between the two approaches for any particular SMSR achieved. Fig. 7 directly compares the spectra and pulse shapes of DFB and self-seeded pulses at various seed powers. The tradeoff between SMSR and pulse quality, and the similar performance achieved by the two approaches (albeit at different values of seed power for the two approaches) is shown clearly. Pulse widths increase and spectral widths decrease slightly as seed power is increased. Side-mode suppression is slightly better at maximum power in the self-seeding case, and the spectrum is narrower and the pulse broader, all of which

is consistent with the higher peak seed power available in this case.

We also measured the timing jitter for the self seeded case and, as with the DFB injection, measured the amplitude jitter to be $\sim 2\%$, and the timing jitter to ~ 3 ps, dominated by the drive electronics. Thus, in jitter terms there seemed to be no difference in performance between the two approaches.

V. FROG MEASUREMENTS AND PULSE COMPRESSION

We fully characterized the pulses using a linear FROG technique based on gating the pulses with a fast modulator [29]. Because no nonlinear interaction takes place, this technique is suitable for characterizing pulses with long durations and low peak powers. This allows us to completely retrieve the temporal and spectral pulses shapes including the chirp of the pulses. The use of this technique as a means of analysing chirped picosecond pulses in order to design optimal fiber compression gratings to minimize the compressed pulse duration will be the subject of another paper. In this paper, we will simply consider the results obtained.

As expected, the pulses were strongly chirped. FROG measurements of the pulses showed that in both the injection and self seeded cases the pulses had linear chirp (chirp slope ~ 0.0025 ps $^{-2}$ in both cases) across the central peak of the pulse (although there is a secondary feature at the leading edge of the pulse in the region where the chirp does not remain linear)

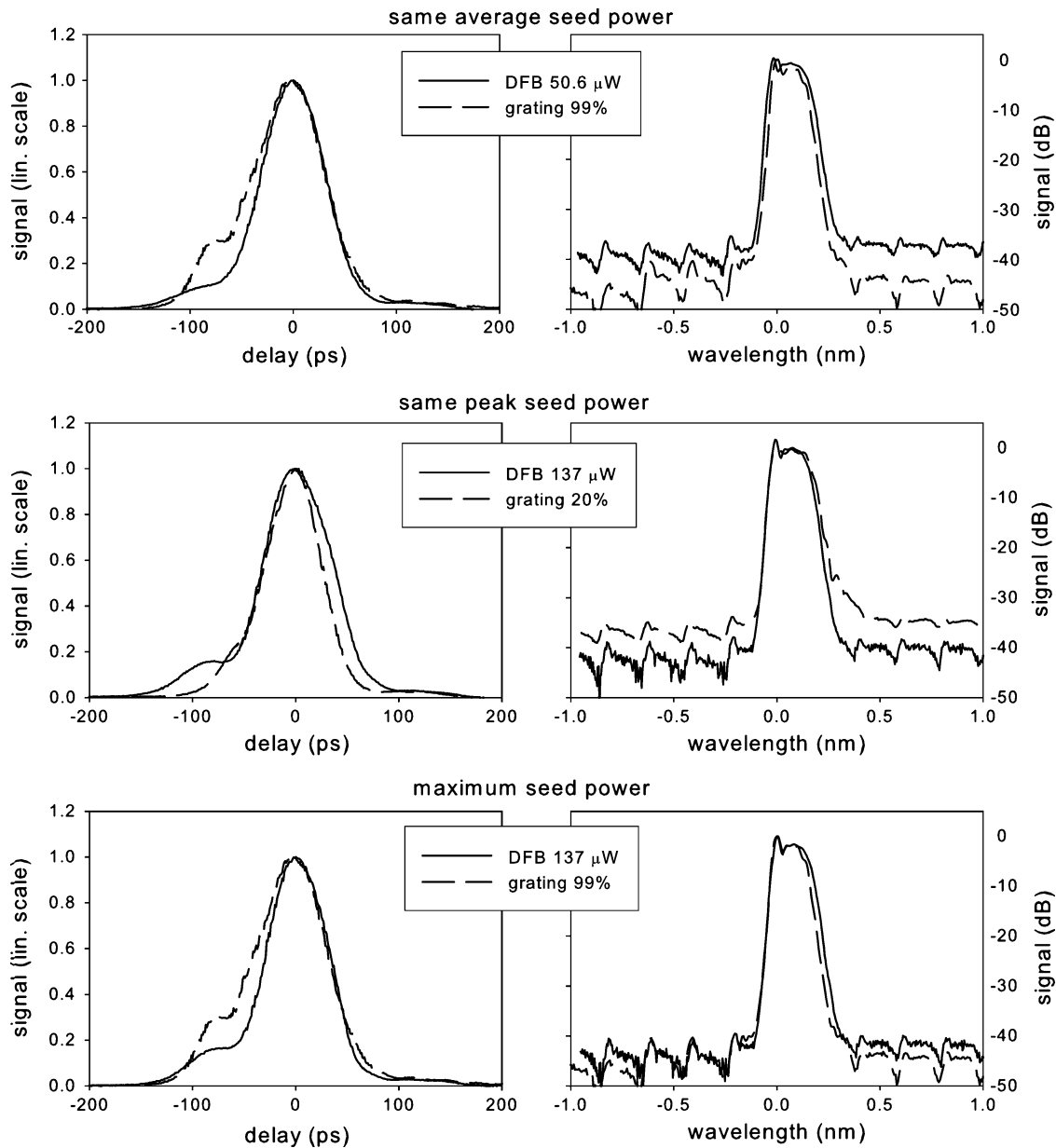


Fig. 7. Comparison of pulses obtained via DFB and self seeding (with equal *average* seed power, with equal *peak* seed power and with maximum available seed power in each case).

and hence should be cleanly compressible to near the transform limit. This was demonstrated by reflecting the pulses from a linearly chirped fiber grating fabricated at the ORC. FROG measurements showed that these compressed pulses had durations of 18 ps for the injection seeded pulses and 20 ps for the self-seeded pulses (TBWP = 0.7 in both cases), matching predictions based on the FROG retrievals of the uncompressed pulses well. In both cases, the FROG measurements revealed a small additional peak on the leading edge of the compressed pulse. However, the central peak contains more than 90% of the total pulse energy (see Fig. 8).

VI. CONCLUSION

While the advantages of self over external seeding in terms of simplicity and cost are obvious, this is the first detailed study to

be undertaken to investigate the differences in performance of a gain-switched diode depending on whether it is self or externally seeded.

In the injection seeded case, the side-mode suppression ratio is strongly dependent on the wavelength detuning of the seed laser from the center wavelength of the diode. With self-seeding, this adjustment is not available, but a similar dependence is observed by detuning the repetition rate of the diode from the cavity harmonic frequency (i.e., delaying the output pulse with respect to returning seed pulse). SMSRs in excess of 40 dB were achievable in both cases, with SMSR increasing with seed power. High SMSR was achieved at lower average seed powers in the case of self-seeding. However, bear in mind that since for self-seeding the seed is pulsed, then the peak power is $\sim \times 12$ the average power. In both cases, at SMSR values greater than

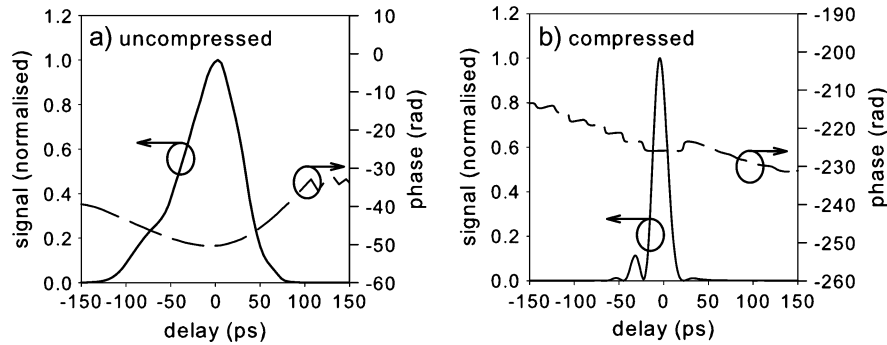


Fig. 8. Amplitude and phase as a function of delay retrieved by linear FROG on (a) uncompressed and (b) compressed pulses.

about 30 dB, a small secondary feature began to appear in the leading edge of the pulse. The timing and amplitude jitter of the pulses was identical for both injection schemes.

For both approaches a SMSR of greater than 40 dB is readily achievable, differences in pulse duration and shape are small, amplitude and timing stability is the same and, crucially for ultrafast applications, both approaches were shown to produce pulses with close to linear chirp across the center of the pulse, allowing compression using a simple linearly chirped fiber grating to a TBW product of ~ 0.7 , corresponding to pulse durations shorter than 20 ps.

Our results show that there is no loss of performance from self seeding rather than seeding with an external narrow-linewidth laser source, even though self seeding eliminates the degree of freedom given by the possibility to detune the seed from the center wavelength of the diode mode.

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