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Tunable Operation of a Gain-Switched Diode Laser by Nonresonant Self-Injection Seeding

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***Abstract*—In this letter, we report tunable operation of a gain-switched diode laser by nonresonant self-injection seeding from an uncoated glass slide used as an external cavity reflector. A spectral linewidth reduction from 11 to 0.05 nm has been achieved for picosecond pulses with little effect on other laser characteristics. Good agreement with numerical simulations based on a compound-cavity laser model is also reported.**

***Index Terms*—Optical feedback, optical modulation, semiconductor laser, tunable circuits and devices, ultrafast optics.**

I. Introduction

NARROWING the spectral bandwidth from a pulsed diode laser and broad spectral tuning of the output is of particular interest because of the potential for increasing second harmonic generation [1] and optical parametric oscillation [1] efficiencies. With this objective in mind, we assessed the performance of commercial 980-nm InGaAs–GaAs single transverse-mode ridge-waveguide lasers when under large-signal modulation. The typical durations of the gain-switched pulses were ~30 ps at user-defined pulse repetition frequencies in the range of 1.70–2.70 GHz, where average powers exceeded 100 mW [3]. The pulse spectral bandwidth was ~11 nm with a corresponding time-bandwidth product of 103.

II. Experimental Results and Modeling

To facilitate nonresonant self-injection seeding, the laser emission was collimated with an Ar-coated $\times 30$ lens, and an uncoated microscope glass slide was positioned at variable distances $(l_{\rm ext})$ between 87–63 mm from the laser diode facet (Fig. 1.) This range corresponds to an external cavity frequency $(f_{\rm ext})$ from 1.72 to 2.38 GHz, which was chosen to be approximately centred around 2.00 GHz, the typical applied modulation frequency $(f_{\rm mod})$. Once aligned, the small amount of feedback from the glass slide (less than 4%) was sufficient to reduce significantly the spectral bandwidth (Fig. 2) of the laser output. With this spectral narrowing, the pulse duration increased from 30 to 39 ps, but it had a negligible effect on the spatial characteristics and the output power of the laser. The measured time-bandwidth product of 0.60 represented a reduction factor of 170 and corresponded to the generation of near-transform-limited pulses. Under optimum alignment, the

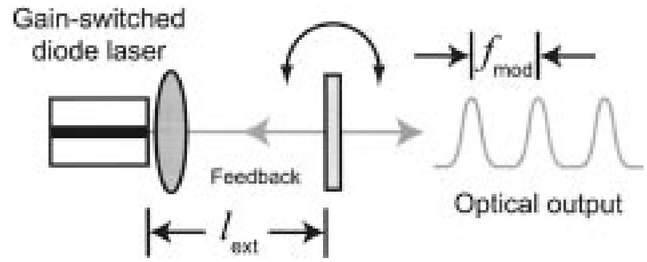

Fig. 1. Experimental scheme for the nonresonant self-injection seeding of a gain-switched diode laser utilizing a glass-slide as the feedback element.

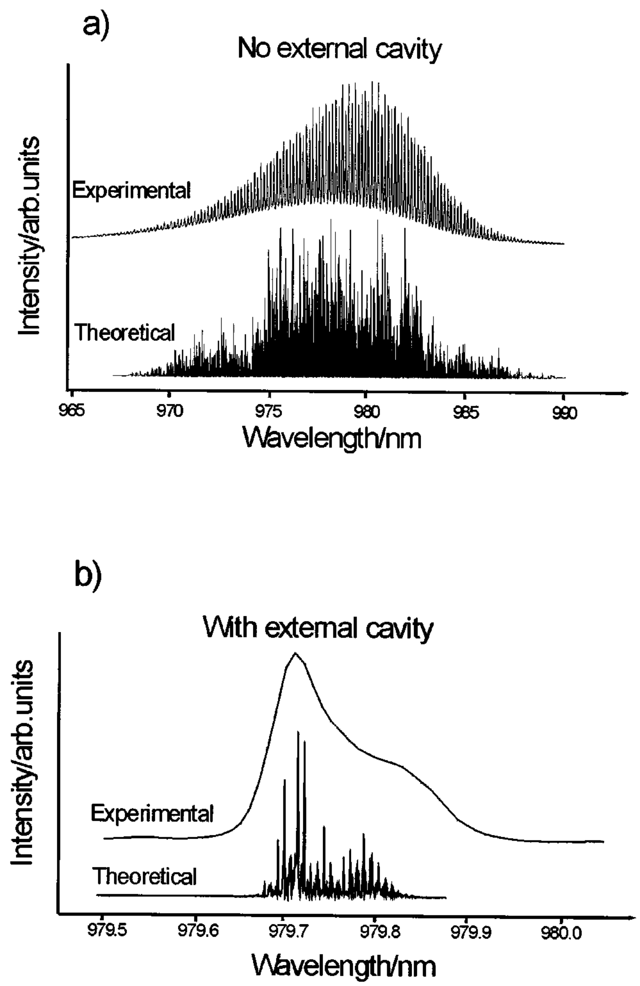

Fig. 2. Experimental and simulated spectral characteristics for a) no external cavity and b) with nonresonant external cavity.

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spectrum was reproducible, and much more stable than that observed in continuous-wave (CW) operation.

There are two significant differences between our results and those reported earlier for the well-known technique of self-seeding in gain-switched lasers [4]–[6]. First, we only observed the spectral narrowing under *nonresonant* operation, i.e., when the round-trip period of the external cavity was significantly detuned from the modulation period. The external cavity had no observable effect on the spectra for an f_{mod} of equal $f_{\mathrm{ext}} \pm 200$ MHz. (This was also true within approximately the same frequency range around the second and fourth harmonics of f_{ext}.) Spectral narrowing under nonresonant operation was observed for all other modulation frequencies within the typical operational range. Second, the single longitudinal mode operation, in our case, was possible in a simple cavity *without any deliberate spectral selectivity* (Fabry–Pérot *et al.* on properties of the glass slide may be ruled out because linewidth narrowing was also achieved with a thick uncoated glass wedge as an external reflector). With standard self-seeding, strong spectral selectivity is always introduced either explicitly [5] by using a selective external reflector, or implicitly [6] by using a dispersive fiber in the external cavity, and thus, making the timing of the seeding pulse spectrally dependent.

To explain these results, we note that the external cavity length, in our case, is smaller by a factor of several (at least 2–3) orders of magnitude than that typically used in the cavity configuration described in references [5], [6]. This implies that to achieve the timing detuning ΔT between the seeding and lasing pulses required for successful self-seeding [5], [6], the necessary frequency detuning $\Delta f = f_{\mathrm{mod}} - N f_{\mathrm{ext}} \approx f_{\mathrm{mod}} f_{\mathrm{ext}} \Delta T$ (N being the harmonic number) must, in our case, be larger by the same factor. Also, as the optical lengths of the laser and the external cavity become closer, this makes the spectral selectivity in the compound cavity formed by the external and intrinsic (facet) reflectors more important. The general physical mechanism of such spectral selectivity is well known; only modes supported by both the intrinsic laser resonator and the external cavity are excited in the laser spectrum. The usual formalism for analyzing compound-cavity lasers is frequency-domain analysis that can give closed-form analytical solutions for modal losses (see e.g., [7]). The difference in the case discussed here is that the nature of the experimental situation (large-signal modulation at a frequency commensurate with, but not equal to, the external cavity round-trip frequency) makes the compound-cavity effect *dynamic*. Indeed, the strong temporal variation of the carrier density in the modulated laser is translated, via self-phase modulation, into variation of the refractive index, and therefore, optical length of the laser cavity. This makes frequency-domain modal analysis prohibitively difficult. Therefore, we opted for numerical simulations using a distributed time–domain model adapted to compound cavities [7]. The simulations, overall, give good agreement with experimental results, predicting a broad lasing spectrum in a situation without an external cavity or with a resonant external cavity, but a possibility of the linewidth narrowing down to one intrinsic cavity mode under nonresonant conditions (Fig. 2). The conditions for single-mode operation in the simulations strongly depend on the linewidth enhancement factor α—with α set to zero, the line narrowing is not reproduced. The importance of self-phase modulation manifests itself also in the characteristic asymmetric shape of the spectrally narrowed line that is seen clearly both in experiments and in the theoretical modeling (Fig. 2).

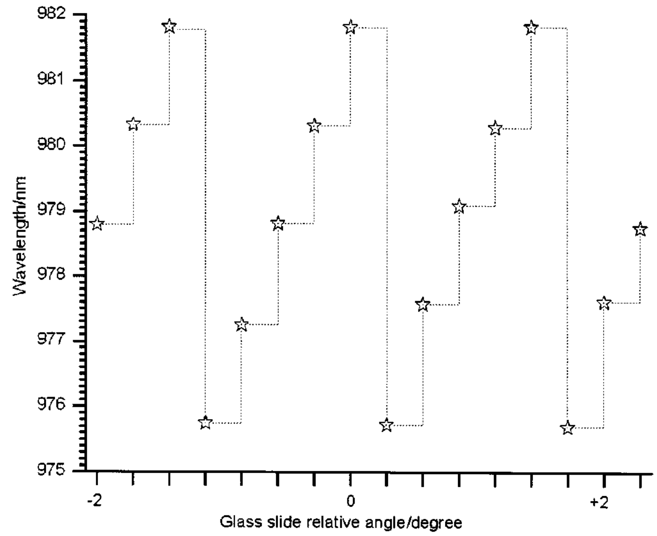

Fig. 3. Glass slide angle tuning of a diode laser output operated under nonresonant injection feedback.

Spectral narrowing was also observed with different external cavity lengths (20 to 170 mm), where the shorter cavities afforded superior spectral stability. We believe that the increased stability can be attributed mainly to the enhanced feedback caused by a decreased laser to glass slide distance. A reduction in the length of the external cavity increased f_{ext}, which ensured that the range of f_{ext} did not coincide with any harmonics of f_{mod}, thereby increasing the range of f_{mod} over which spectral narrowing could be observed. The external cavity length had no apparent influence on the emission wavelength of the nonresonant self-injection seeded diode laser output.

The output wavelength may be spectrally step tuned by varying the modulation frequency, though this tuning method had a disadvantage of the spectral jumps being aperiodic. More periodic step-tuning over 6 nm was achieved by a small variation of the angle of the glass slide in either direction. Illustrated in Fig. 3, is the center wavelength versus glass slide angle. Beyond the two extremes shown in Fig. 3, the glass slide angle was such that feedback was lost and the distinctive broad gain-switched spectrum was observed. Given that the bandwidth of the noninjection-locked laser increases with drive current, it is reasonable to conclude that the spectral range over which the output may be tuned would similarly be increased. We note that a similar tunable operation was previously reported in a more complex laser system using coherent photon seeding in actively mode-locked laser diodes [8].

III. Conclusion

We used the reflection from an uncoated glass slide to form an external cavity for self-injection seeding of a gain switched diode laser. Spectral narrowing from 11 to 0.05 nm, and periodic step tuning over 6 nm were observed. This represented a time-bandwidth product reduction of $\times 170$. We believe that due to its low cost and simplicity, the use of a glass slide is an attractive method for enhancing the average and peak powers of pulsed spectrally refined diode lasers. This technique of non-resonant injection seeding could easily be adopted for use with commercial diode lasers at all wavelengths.

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