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Nonresonant Self-Injection Seeding of a Gain-Switched Diode Laser

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***Abstract*—We demonstrate step-tunable single-mode 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 bandwidth reduction from 11 nm to 0.05 nm and wavelength tunability has been achieved for picosecond (near-transform-limited) 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*—Gain-switching, laser diode, self-injection seeding.**

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 [1] and optical parametric oscillation [2] efficiencies. A number of semiconductor laser constructions have been developed specifically for the production of short optical pulses in practical configurations. A convenient way to obtain short-pulse generation with high average power is the direct modulation of a ridge-waveguide laser diode [3].

II. Experimental

With this objective in mind, we assessed the performance of commercial, 980 nm, InGaAs–GaAs single transverse mode ridge waveguide lasers under the condition of large-signal modulation. The laser has a stripe-width of 3 μm and a cavity length of 750 μm, with high-reflectivity (HR, $R > 95\%$) and low-reflectivity (AR, $R < 3\%$) coatings on the facets. The laser was mounted p-side up on a sapphire heatsink and maintained at a constant room temperature using a thermoelectric cooler.

The laser was operated with dc bias and supplementary RF-modulated injection currents. The RF signal was supplied by an Anritsu MG36933A synthesized signal generator, which had a frequency limit of 2.7 GHz. A electronic amplifier was incorporated to provide a RF power up to 35 dBm. The output optical pulses were detected using a fast InGaAs photodiode, which had a time response full-width at half-maximum (FWHM) of 12.5 ps, and displayed using a 50- GHz sampling oscilloscope.

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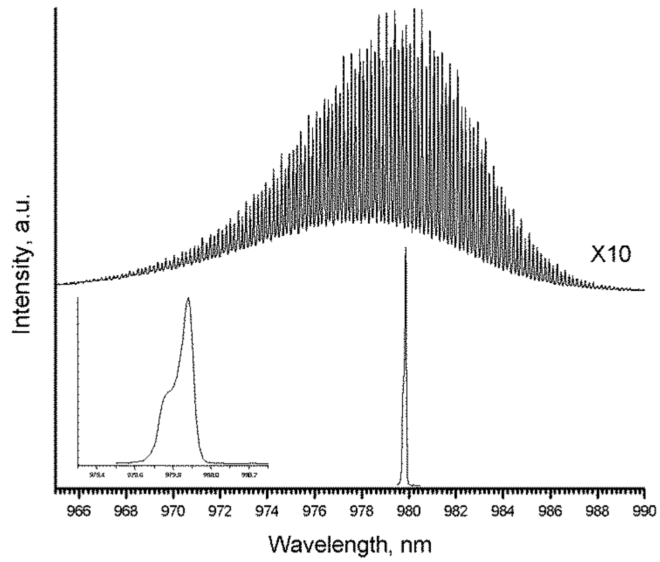

Fig. 1. Experimentally measured spectral characteristics for (a) no external cavity and (b) with nonresonant external cavity with a gain-switched laser ($L_{\mathrm{ext}} = 6.3$ cm, $F_{\mathrm{mod}} = 2$ GHz). Insert shows the high-resolution spectrum for (b).

For a given RF signal amplitude we adjusted the dc bias and the signal frequency to obtain the shortest output pulses. These were observed in the frequency range of 1.8–2.7 GHz and RF power of 35 dBm for a dc bias up to 100 mA, and the shortest durations was 27-ps FWHM. The average output power at this bias level was over 75 mW. The typical durations of the gain-switched pulses for a dc bias up to 150 mA were $\sim$30 ps at user-defined pulse repetition frequencies range. The average output power at this bias level was over 120 mW (corresponding to a peak power of $\sim$1.5 W) [the maximum RF signal amplitude was limited only by the RF power amplifier used in this work]. The spectral bandwidth of these pulses was $\sim$11 nm with a corresponding time-bandwidth product of 103.

For the purposes of nonresonant self-injection seeding, the laser emission was collimated with an AR-coated X30 lens and an uncoated microscope glass slide was positioned at variable distances between 87–63 mm from the laser diode facet. This range which corresponds to an external cavity frequency (f_{ext}) from 1.72 to 2.38 GHz was chosen to be approximately centered around 2.00 GHz, the typical modulation frequency (f_{mod}). Once aligned, the small amount of feedback (less than 4%) from the glass slide was sufficient to reduce significantly the spectral bandwidth (Fig. 1). With this spectral narrowing the pulse duration increased from 30 to 39 ps (Fig. 2) but it had a negligible effect on the spatial characteristics and the output power of the laser. A time-bandwidth product of 0.60

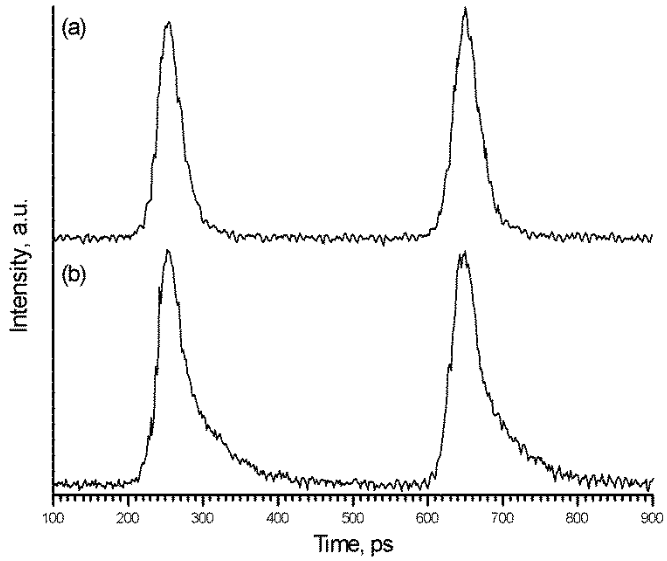

Fig. 2. Experimentally measured pulse duration for (a) no external cavity and (b) with nonresonant external cavity ($L_{\rm ext} = 6.3$ cm, $F_{\rm mod} = 2$ GHz).

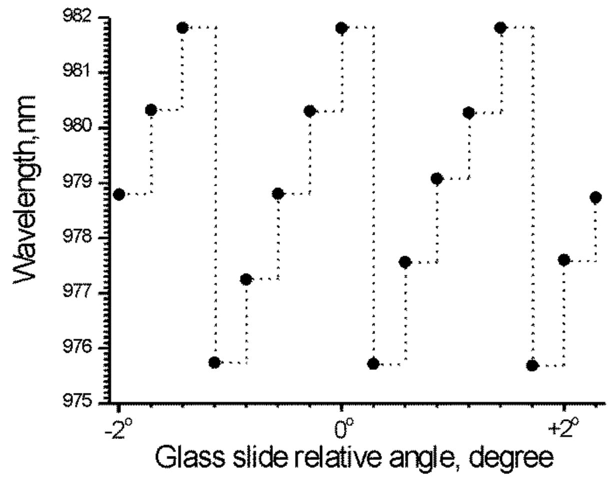

Fig. 3. Glass-slide angle tuning of a diode laser output operated under nonresonant injection optical feedback.

represented a reduction factor of 170, and corresponded to near-transform-limited pulses. Under optimum alignment the spectrum was reproducible and much more stable than that observed in CW operation.

Spectral narrowing was also observed with different external cavity lengths (20–170 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 $f_{\rm ext}$, which ensured that the range of $f_{\rm ext}$ did not coincide with any harmonics of $f_{\rm mod}$, thereby increasing the range of $f_{\rm mod}$ over which spectral narrowing could be observed.

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 *a periodic*. 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, the spectral range over which the output may be tuned is also 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 [4].

III. Theory and Discussion

There are two significant differences between our results and those reported earlier for the well-known technique of self-seeding in gain-switched lasers (see, e.g., [5]–[8] and references therein). First, we only observed the spectral narrowing under *nonresonant* operation, when the round-trip period of the external cavity was significantly detuned from the modulation period. The external cavity had no observed effect on the spectra for a $f_{\rm mod}$ of equal $f_{\rm ext} \pm 200$ MHz. This was also true within approximately the same frequency range around the second and fourth harmonics from both side of $f_{\rm ext}$. Secondly, the single-mode operation in our case was possible in a simple cavity *without any deliberate spectral selectivity* (Fabry–Pérot etalon 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 [7], by using a selective external reflector, or implicitly [8], by using a dispersive fiber in the external cavity and thus making the crucial timing of the seeding pulse spectrally dependent.

To explain these results, we note that the external cavity length $L_{\rm ext}$ in our case is several (at least 2–3) orders of magnitude smaller (and the external-cavity round-trip frequency $f_{\rm ext} = c/2L_{\rm ext}$ therefore greater by the same factor) than that typically used in the cavity configuration described in [5]–[8]. It has been shown [6], [7] that a timing detuning Δt between the seeding and lasing pulses, within a certain window of the order of several tens of picoseconds, is required for successful self-seeding. The frequency detuning Δf corresponding to this timing detuning may be estimated as

$$\Delta f = f_{\rm mod} - N f_{\rm ext} \approx f_{\rm mod} f_{\rm ext} \Delta t. \qquad (1)$$

Here, N is the modulation harmonic number (assuming $f_{\rm mod} > f_{\rm ext}$, $N = [f_{\rm mod}/f_{\rm ext}]$, $[x]$ standing for the integer part of x). For a given timing detuning Δt, the frequency detuning Δf increases linearly with $f_{\rm ext}$. With, say, $\Delta T = 50$ ps, $N = 1$ (i.e., $f_{\rm mod} \approx f_{\rm ext}$) and $f_{\rm ext} = 2$ GHz, we get $\Delta f = 200$ MHz, consistent with the nonresonant nature of operation in our short external cavity.

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. Indeed, the output loss of the kth (intrinsic)

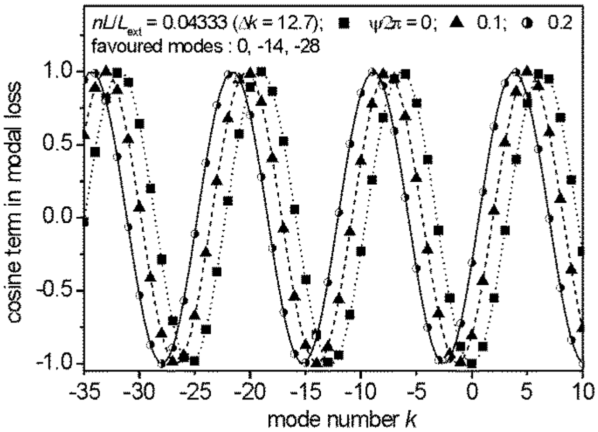

Fig. 4. Calculated spectral variation of the cavity output losses (a_c) in a weak external cavity.

laser cavity mode in the presence of the short external cavity terminated by a weak reflector (with an effective intensity reflectance $R_{\rm ext} \ll 1$) may be estimated as [9]:

$$a_{ck} \approx a_0 + \Delta a_{ck} \tag{2}$$

where

$$a_0 = \frac{1}{2L} \ln \frac{1}{R_1 R_2} + a_i$$

is the usual cavity loss without the external reflector. The first term here, as usual, is the outcoupling loss, with $R_{1,\,2}$ the higher and lower reflectances, respectively, L the intrinsic laser cavity length, and a_i is the dissipative loss. This intrinsic loss is of course independent on the mode number k. The spectral variation is introduced by the presence of the external reflector, described by the second term in (2):

$$\begin{aligned}\Delta a_{ck} &= -\frac{1-R_2}{L\sqrt{R_2}}\sqrt{R_{\rm ext}}\cos\left(\frac{2\pi k L_{\rm ext}}{nL} + \psi\right)\\ &= -\frac{1-R_2}{L\sqrt{R_2}}\sqrt{R_{\rm ext}}\cos\left(\frac{2\pi k}{\Delta k} + \psi\right).\end{aligned} \tag{3}$$

The factor at the cosine term describes the strength of coupling to the external cavity. If $L_{\rm ext}/nL > 1$ is not an integer, the expression (3) describes spectral selectivity with a characteristic period of

$$\Delta k = 1 \bigg/ \left\{\frac{L_{\rm ext}}{nL}\right\} \tag{4}$$

with $\{x\} = x - [x]$ being the fractional part of x. Depending on the precise values of optical lengths, Δk can span a range of values from several units to infinity, the latter case corresponding to the absence of selectivity for an integer ratio $L_{\rm ext}/nL$. However, the most typical value with L and $L_{\rm ext}$ of the order used in our experiments is $\Delta k N \sim 10$, as seen in Fig. 4. This is consistent with the experimentally observed mode hopping range (the vertical step magnitude in Fig. 3).

The phase ψ in (3) is

$$\psi = 2L_{\rm ext}\omega_0/c \tag{5}$$

(ω_0 being the reference optical frequency, usually taken to be close to the frequency of the mode with $k = 0$). The phase therefore changes strongly with subwavelength variations in the external reflector position—which can occur when the mirror is tilted. As seen from Fig. 4, these variations in phase may result in the global spectral minimum in threshold losses shifting from one local minimum to another, implying a possibility of step tuning.

The simple estimates (2)–(4) are only valid, first, for very small $R_{\rm ext}$ and, second, in the absence of modulation. Experimentally, spectrum narrowing and mode hopping due to external cavity adjustments are indeed observed during CW lasing—but are plagued by very poor stability and repeatability, in stark contrast to the very robust tuning of modulated lasers. This implies that the spectral selectivity mechanism is significantly modified by (and benefits from) modulation. We believe that qualitatively this modification may be understood as follows. Under the modulation conditions, gain (and refractive index, due to the SPM) of the solitary laser are modulated at the modulation frequency $f_{\rm mod}$. As the precise value of the refractive index is important for the selectivity mechanism (3), this would make the spectral selectivity dynamic, i.e., dependent on $f_{\rm mod}$ (and other modulation parameters).

Unfortunately, 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 frequency-domain analysis, of the type that led to closed-form analytical expressions (2)–(4) for spectral selectivity, very difficult in the case of the modulated laser. For this reason and also to perform more quantitative comparison with the experiments, we analyzed this situation numerically in time domain, using the distributed time-domain model (DTDM) adapted to compound cavities [12], [13]. The model calculates one-dimensional (1-D) propagation, along the longitudinal coordinate z, of slow amplitudes $E_{R,\,L}$ of right- (forward) and left- (reverse) travelling light:

$$\begin{aligned}&\mp\frac{\partial E_{L,\,R}}{\partial z} + \frac{1}{v_g}\frac{\partial E_{L,\,R}}{\partial t}\\ &\quad = \frac{v_g}{2}\left((\Gamma\hat{g} - a_1)E_{L,\,R} + i\Gamma\alpha(g - g_{th})E_{L,\,R}\right)\\ &\qquad + F_{\rm spont}(z,\,t).\end{aligned} \tag{6}$$

Here, v_g is the group velocity of light, Γ the carrier confinement factor, g and a_i stand for the optical gain and the internal dissipative loss ($g_{\rm th}$ being the threshold gain), α is the Henry linewidth enhancement factor, $g_{\rm th}$ is the threshold gain, and $F_{\rm spont}$ is the Langevin spontaneous source that ensures self-starting of the model and introduces noise. The operator nature of $\hat{g}$ represents gain dispersion; in the model version we used [12], [13], it simulates a Lorentzian curve using an integral relation

$$\hat{g}E_{R,\,L} = g(N,\,S)\Delta\Omega' \int_o^\infty E_{R,\,L}(z,\,t-\tau)\exp(-\Delta\Omega\tau)\,d\tau \tag{7}$$

TABLE I
THE MAIN PARAMETERS USED IN THE CALCULATIONS

notation	meaning	value	units
L	Intrinsic laser cavity length	750	μm
R_1	Intensity reflectance, HR coated side	0.95	
R_2	Intensity reflectance, AR coated side	0.1	
d	Active layer thickness	0.01	μm
Γ	Confinement factor	0.02	
a_i	Internal (dissipative) loss	2.5	1/cm
$v_g=c/n_g$	Group velocity	$0.857\cdot10^{10}$	cm/s
N_0	Transparency carrier density	$1.2\cdot10^{18}$	cm^{-3}
A_0	Gain cross-section at transparency	$1.06\cdot10^{-15}$	cm^2
α	Linewidth enhancement factor	3	
ε	Gain compression coefficient	10^{-17}	cm^3
B	Bimolecular recombination coefficient	$2.5\cdot10^{-10}$	cm^6/s
τ_{nr}	Nonradiative recombination time	10	ns
$\Delta\Omega$	Gain spectrum width parameter	$5\cdot10^{13}$	1/s
Δz	simulation length step (time step $\Delta t=\Delta z/v_g$)	2	μm

with $\Delta\Omega$ being the gain curve width parameter and $g(N, S)$ the peak gain value, determined by the local carrier density $N(z, t)$ and photon density $S(z, t) = E_R^2(z, t) + E_L^2(z, t)$. We used the usual logarithmic approximation for QW lasers:

$$g(N, S) = \frac{AN_0}{1+\varepsilon S} \ln \frac{N}{N_0} \tag{8}$$

where N_0 and A are the carrier density and gain cross section at transparency, and ε the gain compression factor. In the passive part of the cavity, of course, $g = 0$.

At the laser facets and the external reflector, standard reflection/transmission boundary conditions are imposed on $E_{R,L}$; the reflectance of the external reflector was, in general, represented by a complex number whose phase could be adjusted to model subwavelength variation of the cavity length as in (5).

The field propagation equations are coupled with coordinate-dependent rate equations for the carrier density:

$$\frac{d}{dt} N(z, t) = \frac{J(z, t)}{ed} - N\left(BN + \frac{1}{\tau_{nr}}\right) - v_g \operatorname{Re}\left(E_L^* \hat{g} E_L + E_R^* \hat{g} E_R\right). \tag{9}$$

Here, J/ed is the pumping term, with J the current density (carrier capture dynamics is not taken into account in this version of the model, as we verified previously [3] that it is not important at the relatively slow modulation rates we use), e the elementary charge, d the active layer thickness, B the bimolecular recombination constant, and τ_{nr} the nonradiative recombination rate (Auger recombination can be neglected in the relatively broad gap materials used). The main parameter values used are summarized in Table I; the values were similar to those that were used previously to simulate similar lasers, in a simpler model, with good agreement with experiments [3].

Lasing spectra are calculated by fast Fourier transform of the resulting temporal profiles, after discarding the initial turn-on transient. The results are shown in Fig. 5–8.

Under CW operation, the simulated lasing spectra are narrow, as are the experimentally observed spectra, but reliable single-frequency operation is not obtained either with or without the external reflector. With large-signal modulation applied to a solitary laser to achieve gain-switching, the experimentally observed broad spectrum is reproduced theoretically (Fig. 5). Also in agreement with the experiment, no spectral narrowing is seen in the external-cavity configuration under the conditions of resonant modulation (Fig. 7).

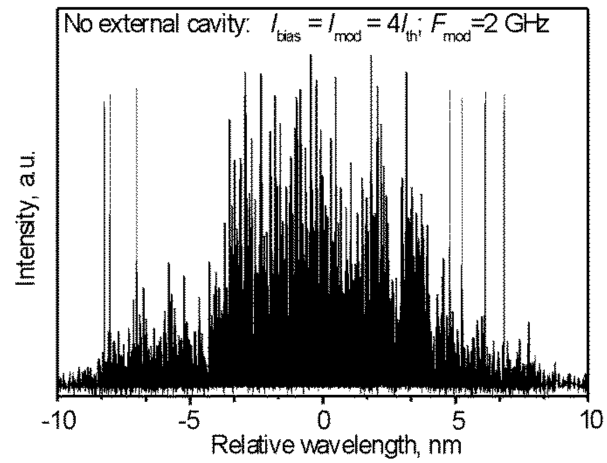

Fig. 5. Simulated spectral characteristics for a gain-switched laser without an external cavity. Geometrical parameters as in the experiment.

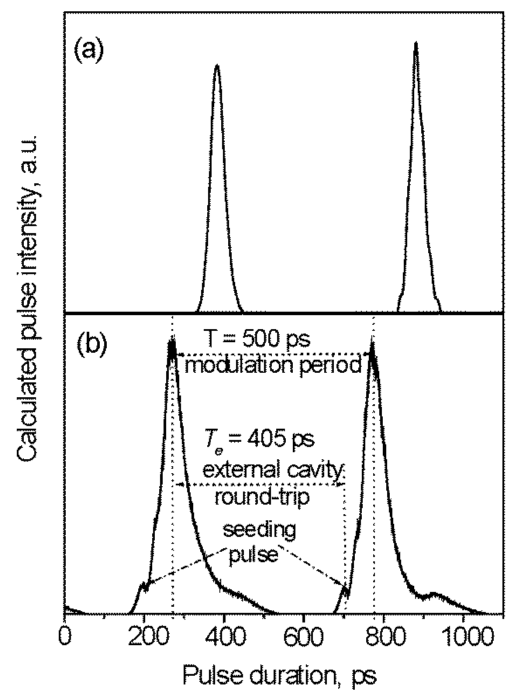

Fig. 6. Simulated optical pulses for a gain-switched laser diode (a) without external cavity (envelope intensity, with fast variations due to multimode lasing filtered out) and (b) with nonresonant external cavity ($L_{\rm ext} = 6.0592$ cm, $R_{\rm ext} = 0.002$).

However, under nonresonant modulation and with $R_{\rm ext} \sim 0.001$, consistent with the experimental conditions, simulations predict a dramatic spectral narrowing with only one intrinsic cavity mode remaining in the spectrum (Fig. 8). This is in good agreement with the experimentally observed behavior.

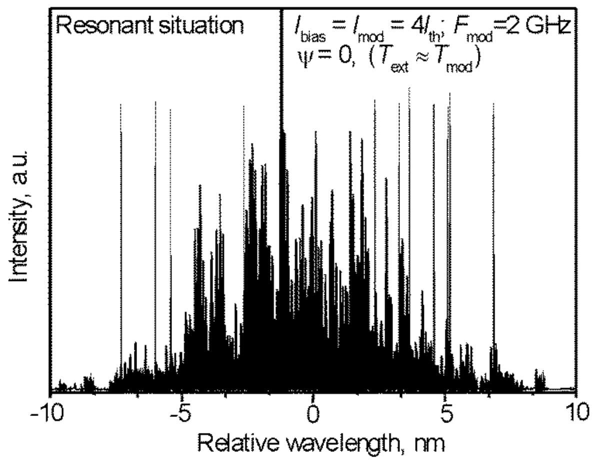

Fig. 7. Simulated spectral characteristics for the resonant external cavity ($L_{\rm ext} = 6.11$ cm) gain-switched laser.

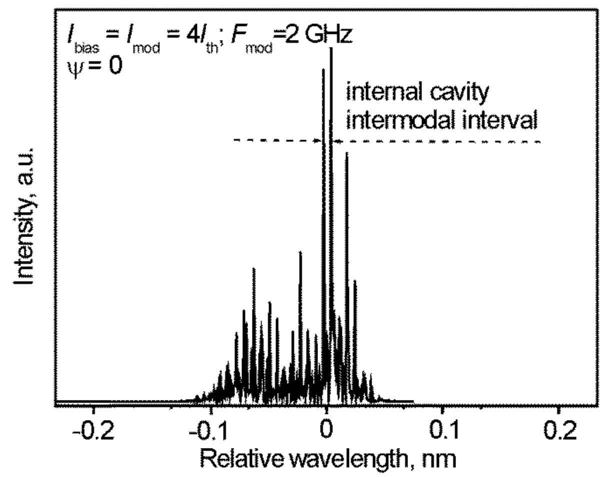

Fig. 9. Theoretical spectral characteristics for nonresonant external cavity ($L_{\rm ext} = 6.0592$ cm, $R_{\rm ext} = 0.002$) gain-switched laser.

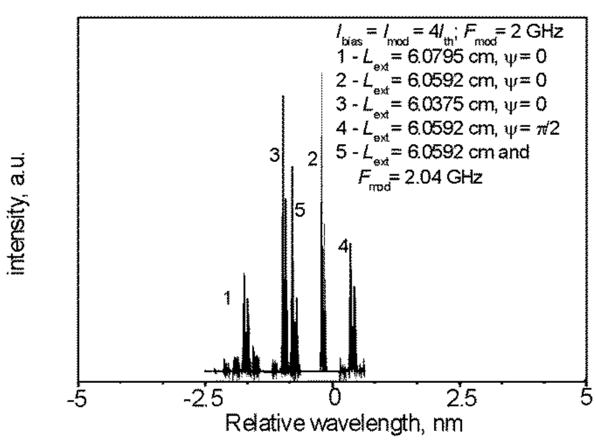

Fig. 8. Simulated spectral characteristics for nonresonant modulation under different operating conditions.

Spectral narrowing is accompanied by an increase of 30%–40% in the FWHM pulse duration, as seen experimentally. The seeding pulse forms a precursor for each of the lasing pulses in the simulated pulse sequence, and the expected position of the lasing pulse without seeding appears as a shoulder following the pulse maximum (Fig. 6).

On a logarithmic scale, additional peaks suppressed by 30–40 dB may be seen in the narrowed spectrum several intrinsic cavity modes away from the lasing mode. This is most probably due to the spectral selectivity characteristics of the compound cavity. Furthermore, the simulations show, in qualitative agreement with the experiment, that mode hopping by several (4 to 12) intrinsic cavity modes may occur with variations in either $f_{\rm mod}$, $L_{\rm ext}$ (of the order of 10–20 μm), or the phase of the external mirror reflectance (Fig. 8). The detailed shape of the step-tuning curve (Fig. 3) was, unfortunately, not reproduced in the simulations. This is possibly due to the numerical inaccuracy in modeling signals that are detuned significantly in frequency from the reference point, although the effects not taken into account by the model (such as thermal changes in refractive index and gain) may also play a part.

The conditions for single-mode operation in simulations strongly depend on the linewidth enhancement factor, supporting the dynamic compound cavity explanation. The importance of SPM manifests itself also in the characteristic asymmetric shape of the spectrally narrowed line which is seen clearly both in experiments (Fig. 1) and in the modeling (Fig. 9).

As regards the dynamics of the spectral narrowing, in a typical simulation it takes 25–40 ns, depending on the cavity length and external mirror reflectance, from the moment of the laser turn-on for the single-frequency spectrum to be established. This constitutes 50–80 external cavity round-trip periods as compared to several periods reported in [7]; the difference probably being due to the weaker spectral selectivity in our construction. In absolute units it may still be faster, as the round-trip period itself is much smaller in our case. In any case, for many applications such as those mentioned earlier, it is the steady-state operation that matters and the speed of spectral narrowing is therefore not critical.

IV. Conclusion

We used the reflection from a 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 represents a time-bandwidth product reduction of 170, and periodic step-tuning over 6 nm was observed. 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.

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