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Longitudinal Mode-Switching Dynamics in a Dual External-Cavity Laser Diode

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Abstract—We study the potential speed of an optical neural network that uses the longitudinal cavity modes of an external-cavity laser diode as neurons. For this purpose, we used a laser diode coupled to two external cavities, each corresponding to one longitudinal cavity mode. The process of longitudinal mode switching is investigated for the case of intracavity optical modulation. In this experiment, the feedback for the mode in one cavity is modulated, and the length of the other cavity can be controlled. Three limitations are imposed on the switching speed. A number of external-cavity round trips are needed to switch from one mode to the other. It is observed that, depending on the amount of optical feedback in both cavities, between 7 and 21 round trips are needed. When the experimental results for varying cavity length are extrapolated to zero cavity length, a residual delay of a few nanoseconds remains. It is believed that this delay is due to a change in carrier density, needed to switch from one mode to another. Modified rate equations are used to model our experiments. The results of numerical simulations are in good agreement with the experimental results and predict the residual delay. The model also predicts a turn-on delay that is related to relaxation oscillations and imposes a third limitation on the operation speed of our optical neural network. Implications of our findings on the potential operation speed of the optical neural network are discussed and suggestions are made for optimization.

Index Terms—Laser modes, optical feedback, optical neural networks, semiconductor lasers, switching transients.

I. INTRODUCTION

EXTERNAL-CAVITY laser diodes have been the subject of many studies. A few examples of applications are narrow-linewidth tunable sources [1], remote sensing [2], blue-light generation by intracavity frequency doubling [3], and intracavity spectroscopy [4]. In our laser neural network (LNN), we employ an external-cavity laser diode to build an all-optical neural network [5]–[8].

To build a neural network, we need a set of simple computing elements, the neurons, that receive a weighted sum of inputs [9]. The computing elements should have an active output if the weighted sum is higher than a certain threshold level. If the neurons are combined to form a network, the resulting device can be used to compute an output vector from a vector of input elements. The computation in such a network is done in parallel

and is distributed over the neurons. The function implemented by the neural network is stored in the weights that connect the neurons with other neurons and the inputs.

In the LNN, each longitudinal cavity mode of the laser diode represents a neuron and the output vector corresponds to the power spectrum of the laser diode. A liquid crystal display (LCD), consisting of a matrix of transmission elements, is placed in an external cavity setup and enables us to control the amount of optical feedback for each longitudinal cavity mode individually. We use the LCD to implement the inputs and weights of the network by setting the transmission values of the pixels according to a sum of weighted neural inputs. In this way, the optical feedback is made proportional to the weighted sum of inputs for each longitudinal cavity mode of the laser individually. A longitudinal cavity mode starts lasing when the optical feedback exceeds a certain level. This means that the corresponding neuron becomes active when the weighted sum of inputs is above a certain threshold level. In this way, a neural network is formed with inputs in the optical transmission domain and outputs in the wavelength domain. In the current LNN [8], the number of inputs and outputs is limited by the LCD and the amount of optical feedback.

Applications of the LNN are envisioned in the area of pattern recognition and routing of data in high speed (>1 Gbit/s) optical telecommunication systems. For this type of application, it is desirable that the output state of the LNN changes within a nanosecond after the input vector is applied. Changing between output states in the LNN is equal to switching between longitudinal cavity modes of the laser diode. In this paper, we investigate the mode-switching transient behavior of an external-cavity laser diode subjected to a change in optical feedback.

To our knowledge, the transient response of a laser diode subjected to a change in external optical feedback has not yet been investigated. Reports have been made on directly modulated external-cavity laser diodes [10]–[13]. Olsson and Tsang [10] reported a transient time of a few external-cavity round trips when an external-cavity laser diode was driven with a step current excitation. A similar experiment was carried out by Kanjamala and Levi [11] for a laser diode that is coupled to a fiber grating external cavity.

The LNN setup described in previous papers [5]–[8] is unsuited to measure the transient response of the laser diode. The switching time of the LCD is of the order of milliseconds, while the round-trip time of our current LNN is of the order of microseconds. A dual external-cavity setup with an intracavity electrooptical modulator is built to emulate our LNN. The modulator is used to emulate the change in optical feedback for one longitudinal mode when the input vector is changed

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Fig. 1. Schematic drawing of the experimental setup. A laser diode is coupled to two wavelength-selective cavities, A and B via a polarizing beamsplitter (PBS). With gratings G1 and G2, the cavities are tuned to λ_1 and λ_2 . The time-varying optical output power at these two wavelengths is monitored via grating G3 with detectors (det. 1 and 2). The feedback for cavity A is modulated with an electrooptical modulator. The length of cavity B can be controlled by moving mirror M4. $\lambda/2$ -plates are inserted to control the power flow. The zeroth order of gratings G1 and G2 are used to monitor the temporal behavior of the electrooptical modulator (det. 3) and the spectral behavior of the laser diode.

from one state to another. With this setup, we measure the mode-switching transient behavior.

In Section II, we present our experimental setup. Section III describes the rate-equation model used to compare the measured results with laser theory and to estimate the speed of an LNN that is aimed at telecommunications applications. In Section IV, we present experimental results as well as results from numerical simulations that use the rate-equation model. We discuss the results and estimate the speed of a feasible, integrated optics device based on extrapolated experimental data and simulated results in Section V. We conclude the paper in Section VI, where we make recommendations for future work on the LNN.

II. EXPERIMENT

The longitudinal mode-switching behavior of an external-cavity laser diode was examined for variable feedback conditions and a range of external cavity lengths. The experimental setup is shown in Fig. 1. It consists of a 670-nm multiquantum-well (MQW) laser diode (Uniphase CQL806) coupled to two external cavities, A and B, via a polarizing beamsplitter, PBS. An antireflection coating with a residual reflectivity of approximately 5×10^{-4} is deposited on the front facet of the laser diode. The threshold current before the laser was antireflection-coated measured approximately 25 mA. With the applied coating, the threshold current was higher than 70 mA, the driving current in our experiments. The laser diode is temperature stabilized to prevent thermal drift of the internal longitudinal mode wavelengths.

In order to obtain wavelength-selective feedback, both external cavities are built according to the Littman configuration [14] that is formed by diffraction gratings G1 and G2 and mirrors M1 and M2. The wavelength selectivity of the two external cavities is approximately 10^{-2} nm. By rotating a mirror, the corresponding cavity can be tuned to an internal longitudinal cavity mode wavelength of the laser diode. The internal cavity modes are spaced at 0.1 nm. A $\lambda/2$ -plate is placed between the laser diode and the PBS to enable us to direct a controllable portion of light to the two cavities, thereby controlling the amount of op-

tical feedback for both cavities. By measuring the optical power at the end mirrors and the optical power emitted by the laser diode, we estimate the maximum feedback efficiency for both cavities to be approximately 10%. Using a ray-tracing program, we estimated the coupling efficiency between the laser and the cavities to be 20%. The resulting maximum feedback levels for modes A and B are approximately 2%.

An amplitude modulator, placed in cavity A, switches the feedback efficiency of this cavity between two levels. The modulator (Coherent model 20/317) has rise and fall times of approximately 8 ns. It was driven with a 50% duty-cycle square wave of approximately 3 MHz. The length of cavity A is approximately 1.05 m, corresponding to a round-trip time of 7 ns.

The length of cavity B can be controlled by changing the position of the retroreflecting mirror, M4. In this way, we are able to set the round-trip time of this cavity to any value between approximately 2 and 16 ns. The $\lambda/2$ -plate in cavity B is inserted to control the polarization state of the laser beam in this part of the setup for optimal reflection at grating G2.

We measured the temporal response of the laser diode with a number of high-speed detectors, det.1–3 (Opto electronics Inc. PD10). To measure the optical power of the two longitudinal cavity modes, a part of the intracavity optical power is coupled out by a beamsplitter and dispersed by a third grating, G3. The resulting spectrally resolved beams are imaged onto detectors 1 and 2. For timing calibration purposes, the zeroth-order reflection of grating G1 is used to monitor the optical response of the electrooptical modulator with detector 3. The electrical signals from detectors 1 and 2 are amplified and subsequently recorded with a sampling oscilloscope (Tektronix 11 802 with SD-26 sampling heads). The amplifiers (HP-8447) limit the detection bandwidth to a frequency range of 0.1–1300 MHz.

We monitored the internal mode power spectrum of the laser diode on the nanometer scale with an optical multichannel analyzer (EG&G OMA 1460) and the external-cavity mode power spectrum with a 1.5-GHz free spectral range Fabry–Perot spectrum analyzer (Tropel model 240), with a resolution of approximately 10 MHz, corresponding to $\sim 10^{-5}$ nm.

III. THEORY

In this section, we derive a theoretical description of our external-cavity laser diode to predict the time-dependent output power of the diode laser at the two wavelengths selected by the external cavities. The behavior of the laser diode will be dominated by the two external cavities because the reflectivity of the external mirrors is much higher than the residual reflectivity of the AR-coated front facet.

A theoretical description of the dynamic behavior of a laser diode subjected to weak external optical feedback has been introduced by Lang and Kobayashi [15]. Although the feedback in our setup can hardly be referred to as “weak,” the same method with a slight modification can be used to describe our experiments. In an analysis for weak feedback, a one-dimensional (1-D) model of a laser with external optical feedback as presented in Fig. 2 is used. In the figure, R_1 and R_2 denote the power reflectivity of the back and front facets of the laser diode. An external reflector with power reflection R_{ext} is placed at a

Fig. 2. One-dimensional model for an external-cavity laser diode. R_1 is the uncoated, back facet reflectivity. R_2 is the reflectivity of the AR-coated front facet and is approximately 5×10^{-4} . R_{ext} represents the reflectivity of an external mirror at a distance L_{ext} away from the laser diode. Multiple reflections can be ignored because of the AR coating.

distance L_{ext} . Since R_{ext} is assumed to be weak in the original model, multiple reflections in the external cavity can be neglected. In our case, the reflectivity of the coated front facet of the laser diode R_2 is small, which means that this is also a valid assumption for our experiment.

With this assumption, a set of rate equations [16], [17] can be formulated for the electromagnetic field of the compound cavity modes inside the external-cavity laser diode. For this purpose, an effective facet (amplitude) reflectivity $r_{\text{eff},m}$ can be introduced for each compound cavity mode to replace the reflectivity of the front facet in the expression for the distributed mirror losses. For a compound cavity mode m , we find

$$r_{\text{eff},m} = \sqrt{R_2} + \sqrt{R_{\text{ext},m}}(1 - R_2)e^{-i\omega_m\tau_m}. \quad (1)$$

In this equation, $e^{-i\omega_m\tau_m}$ represents the phase delay due to the external-cavity round-trip time τ_m of the reflected electromagnetic field of a compound cavity mode m with frequency ω_m , and $R_{\text{ext},m}$ is the external reflectivity for mode m . The real part of (1) is

$$|r_{\text{eff},m}| = \sqrt{R_2}(1 + \kappa_m \cos(\omega_m\tau_m)) \quad (2)$$

with κ_m the coupling coefficient for mode m according to

$$\kappa_m = \sqrt{\frac{R_{\text{ext},m}}{R_2}}(1 - R_2). \quad (3)$$

Using (2) in the rate equation for the modal electromagnetic field [16], [17], we find for the photon density $S_m(t)$ of compound cavity mode m

$$\dot{S}_m(t) = (G - \gamma_0)S_m(t) + R_{\text{sp}} + \Delta\gamma_m \sqrt{S_m(t)S_m(t - \tau_m)} \times \cos(\phi_m(t) - \phi_m(t - \tau_m)) \quad (4)$$

where G is the modal gain and R_{sp} the spontaneous emission as defined in Table I and a dot denotes a time derivative. In (4), $\phi_m(t)$ is the phase of the modal optical field. The optical losses of the diode laser without feedback, γ_0 , are given by

$$\gamma_0 = v_g \left(\alpha_{\text{int}} + \frac{1}{2L_D} \ln \left(\frac{1}{R_1 R_2} \right) \right) \quad (5)$$

with α_{int} the internal material losses, v_g the speed of light inside the laser diode, and L_D the length of the laser diode chip. Lang and Kobayashi used an approximate solution for the external mirror induced change in optical losses $\Delta\gamma_m$ based on the assumption that the external reflection adds a small disturbance on the front facet reflectivity R_2 . In our case, the external mirror

TABLE I
PARAMETERS USED IN THE
RATE-EQUATION MODEL WITH THE USED VALUES AND EXPLANATION

$G = a_0 v_g \Gamma (N - N_0)$	Modal gain
$a_0 = 4 \times 10^{-16} \text{ cm}^2$	Gain constant
$v_g = 0.75 \times 10^{-10} \text{ cm s}^{-1}$	Group speed inside laser diode
$\Gamma = 0.02$	Confinement factor
$N_0 = 2 \times 10^{18} \text{ cm}^{-3}$	Carrier density at transparency
$R_{\text{sp}} = \Gamma \beta_{\text{sp}} \gamma_e N$	Spontaneous emission per mode
$\beta_{\text{sp}} = 1 \times 10^{-3}$	Spontaneous emission factor
$\alpha_{\text{int}} = 10 \text{ cm}^{-1}$	Internal material losses
$R_1 = 0.32$	Back facet reflectivity
$R_2 = 5 \times 10^{-4}$	Coated, front facet reflectivity
$L_D = 500 \times 10^{-4} \text{ cm}$	Length,
$W = 1 \times 10^{-4} \text{ cm}$	Width and
$D = 0.04 \times 10^{-4} \text{ cm}$	Thickness of active region
$V = 2 \times 10^{-11} \text{ cm}^3$	Active volume

dominates the behavior of the laser diode and thus the influence of this mirror on the optical losses needs to be included without approximation. The change in optical losses caused by the external reflection for mode m is

$$\Delta\gamma_m = \frac{v_g}{L_D} \ln(1 + \kappa_m \cos(\omega_m\tau_m)). \quad (6)$$

In this equation, $\cos(\omega_m\tau_m)$ is a constant describing the phase matching between the internal and external optical fields. For a number of compound cavity modes with a frequency around an internal mode frequency of the laser diode, the phase-matching constant in (6) approximately equals unity.

To find the time-dependent optical output power at the two wavelengths selected in cavity A and B, the rate equation for the photon densities of all compound cavity modes selected in cavity A and B can be solved together with the corresponding phase equations. The resulting photon densities can be summed to find the output power at the two selected wavelengths. The selectivity of the gratings is such that, depending on the length of the cavity, a group of approximately 10 to 100 compound cavity modes will be selected in each cavity.

In this paper, we are not concerned with finding the power distribution of the compound cavity modes within the group of selected modes in each cavity. We are merely interested in the averaged photon density of the compound cavity modes in each group. Assuming the number of compound cavity modes is large enough, in each point in time a mode will exist for which $\phi_m(t) - \phi_m(t - \tau_m)$ is an integer multiple of 2π . This will be the lasing mode because the cosine in (4) is maximal for this mode.

Noise-induced changes in the phase of the compound cavity modes will result in mode hopping between the compound cavity modes. The total photon density contained in a group of compound cavity modes will only change if a mode hop occurs from a mode inside a group to a mode outside a group or vice versa. This means that the effect of the phase changes on the total photon number in a group disappears when the number of compound cavity modes in the group is large enough. Therefore, we neglect the influence of the phase term in (4).

Fig. 3. Measured transient response of the two selected modes. (a) Mode A. (b) Mode B. The modulator opens at $t = 0$, resulting in a switching-on of mode A. Mode B switches off due to mode competition. Neutral density filters are inserted into the mode A cavity to vary the external reflection for this mode. The value of the neutral density filter (ND) is inserted into the figure for each curve. The estimated external optical feedback is 2% ($ND = 0$), 1.3% ($ND = 0.1$), and 0.8% ($ND = 0.2$) in the open state of the modulator for mode A. The extinction ratio of the modulator measures approximately 10^4 . The feedback for mode B is estimated at 0.5%.

Including a rate equation for the carrier density inside the active region $N(t)$ results in

$$\dot{N}(t) = I/qV - \gamma_e N(t) - G(S_A(t) + S_B(t)) \quad (7a)$$

$$\dot{S}_A(t) = (G - \gamma_0)S_A(t) + R_{sp} + \Delta\gamma_A(t)\sqrt{S_A(t)S_A(t - \tau_A)} \quad (7b)$$

$$\dot{S}_B(t) = (G - \gamma_0)S_B(t) + R_{sp} + \Delta\gamma_B(t)\sqrt{S_B(t)S_B(t - \tau_B)} \quad (7c)$$

where $S_A(t)$ and $S_B(t)$ are the group averaged photon densities in cavity A and B, I is the electrical current, q is the elementary charge, V is the active volume of the laser diode, and γ_e is the carrier recombination rate.

The parameter values in Table I are estimated for our MQW laser diode emitting in the red. In our estimate of the spontaneous emission factor β_{sp} , we took into account the enhancement factor for AR-coated laser diodes [18], [19].

IV. MEASURED AND SIMULATED TRANSIENT RESPONSES

With the experimental setup, the transient behavior of the external-cavity laser diode was studied under various conditions. We varied the amount of feedback for the mode selected in cavity A. For the mode selected in cavity B, we varied the cavity round-trip time. In this section, the measurement results are presented for the time-varying optical power of the two corresponding modes, modes A and B. The wavelength corresponding to these modes was 683 and 679 nm, respectively. These wavelengths were chosen around the gain maximum of the laser diode to make the modal gain for modes A and B approximately equal. When the feedback path for mode B is blocked and the modulator is continuously open, the laser operates in a single external cavity (A) mode, as measured with the etalon spectrum analyzer. The same holds if the feedback path for mode A is blocked. Thus, the external feedback is sufficiently high to dominate the behavior of the laser diode and the laser is operated in the strong feedback regime [20].

Also presented in this section are the results of computer simulations using the rate equations (7). These were numerically

Fig. 4. Simulation results corresponding to the experimental results presented in Fig. 3. (a) Mode A. (b) Mode B. In the simulations, the following external optical feedback levels were used: 2.0% ($ND = 0$), 1% ($ND = 0.1$), and 0.65% ($ND = 0.2$) in the open state of the modulator for mode A and 0.3% for mode B. In the closed state of the modulator, the feedback for mode A is a factor 10^4 lower than in the open state.

solved with a fourth-order Runge–Kutta routine with a 2-ps step size. In Table I, the used parameter values are listed. To match the simulation results to the experimental result, we used the reflectivity values for cavities A and B as fitting parameters.

A. Varying the Feedback Level for Cavity A

In a first measurement, we adjusted the $\lambda/2$ -plate in such a way that the estimated feedback for mode A is about 2% when the modulator is open. Considering the extinction ratio of the modulator, the feedback for this mode is about 2×10^{-6} when the modulator is closed. The maximum feedback level for mode A was varied by inserting neutral density filters in cavity A. The estimated feedback for mode B was about 0.5% for all measurements. The lengths of cavities A and B were fixed and corresponded to a round-trip time of 6 and 7 ns, respectively. In Fig. 3, the measured transient response of both modes is shown. At $t = 0$, the modulator opens; the transmission is then at 50% of its maximum value. In Fig. 3(a), the measured results are

plotted for mode A without a neutral density filter ($ND = 0$) and with neutral density filters ($ND = 0.1$ and $ND = 0.2$). The corresponding estimated feedback levels for mode A are 2%, 1.3%, and 0.8%, respectively. The transient response for mode B that switches off due to mode competition is presented in Fig. 3(b). Depending on the amount of feedback for mode A, it takes between 7 and 21 round-trip times of cavity A for the power to switch from mode B to mode A.

In Fig. 4, the simulation results for these experiments are presented. Again, the modal response of modes A and B are presented. The value for the external reflectivity of cavity A in the open state of the modulator was 2.0% ($ND = 0$). In order to match the simulation results to the experimental data, we had to assume an extra loss due to the insertion of the neutral density filters. This extra loss was estimated at 10% and can be due to misalignment and phase front distortion caused by the neutral density sheets. The resulting external reflection values are 1.0% for $ND = 0.1$ and 0.65% for $ND = 0.2$. In the closed state of

Fig. 5. Measured transient response of mode A and B for various values of the round-trip time, τ , of cavity B. The round-trip time in cavity A is about 7 ns, and the modulator closes at $t = 0$. The transient response of mode A does not depend on the cavity round-trip time of mode B. Steps are visible in the transient response of mode B. The duration of the steps is approximately equal to the round-trip time of cavity B. Also visible are relaxation oscillations that gradually build up and mark the beginning of each step.

the modulator, the external reflection for mode A was a factor 10^4 lower than in the open state. As with the modulator used in the experiment, the simulated modulator has a transient time of 8 ns; at $t = 0$, it reaches 50% of the maximum transmission value. For mode B, the external reflectivity was constantly 0.3% in all cases.

B. Varying the Round-Trip Time of Cavity B

In the next experiment, the round-trip time of cavity B was set to ten different values between 2.1 ns and 15.4 ns. The round-trip time for cavity A was 7.0 ns in this experiment. The estimated reflectivity for cavity A in the open state of the modulator was 2%, and the reflectivity for mode B measured approximately 0.5%. The transient response of mode B to a closing of the modulator in cavity A was recorded for all ten cavity lengths. In Fig. 5, the transient behavior of mode B is shown for five of these external cavity lengths corresponding to $\tau = 2.1$ ns, $\tau = 4.3$ ns, $\tau = 7.0$ ns, $\tau = 12.3$ ns, and $\tau = 15.4$ ns. For clarity, the measured results for other cavity lengths are not included. Steps in the time evolution of the intensity for mode B can be clearly distinguished in the figure. The duration of these steps is approximately equal to the round-trip time. Also visible are relaxation oscillations that gradually build up during the transient and mark the beginning of each step. A steady state is reached after about ten round-trip times of cavity B.

The response of mode A was the same for all the measurements: the mode switches off within one round-trip time of cavity A after the modulator is fully closed. For a time reference, the transient response of this mode is included in the figure.

The simulation results corresponding to this experiment are shown in Fig. 6. In the model, the external reflectivity for mode A is switched from 2% to 2×10^{-6} at $t = 0$ in the same way as in the previous simulations. The external reflectivity for mode B is set to a constant value of 0.4% to obtain an optimal fit with the

experimental data. Just like in the experimental results, steps and a gradual build-up of relaxation oscillations are visible. Again, the steady state is reached after approximately ten round-trip times.

The operating current of the laser diode was 70 mA during the measurements presented in this section. The measurements were repeated with a driving current of 50 mA and 60 mA with similar results. Also the selected wavelengths of mode A and B were varied. Again similar results were obtained.

When the reflectivity for mode A is modulated, a multi-external-cavity mode spectrum is observed with the Fabry-Perot spectrum analyzer. This means that the laser is hopping between external-cavity modes during the transient. The simulations are in good agreement with the experimental results and thus we can deduce that the mode hopping only influences the distribution of optical power within the selected group of external cavity modes, as assumed in Section III.

V. DISCUSSION

In this section, we examine the implications of our measurements and simulation results on the operation speed of a current experimental LNN [8] and a proposed LNN using integrated optics devices [21]. The proposed LNN has an optical length of a few centimeters that corresponds to a cavity round-trip time of 0.1 ns. With the proposed integrated optics LNN, we aim, among other things, at increasing the operation speed of the neural network.

A. Round-Trip Delay

The experiments with varying external reflection show that, depending on the difference in external reflection between the two modes, up to 21 round trips are needed to switch the optical power from one mode to the other. The highest number of

Fig. 6. Simulated transient response of mode A and B for various values of the round-trip time τ of cavity B, and the modulator closes at $t = 0$. The simulated transient curves show the same features as the experimentally obtained curves presented in Fig. 5.

round trips were needed with the lowest difference in optical losses for modes A and B. This occurred when the feedback for modes A and B was about 0.8% and 0.5%, respectively. Olsson and Tsang measured the transient behavior of a single-mode external-cavity laser diode [10]. They reported that a steady state was reached in three round trips of the external cavity near the gain peak of the laser. When the gain was reduced by shifting the feedback from the gain peak, they reported 20 or more round trips before a steady state was reached. Although they modulated the driving current instead of the external optical losses, these findings are in agreement with our experimental results.

In our current LNN setup [8], the maximum feedback per mode measures approximately $R_{\text{ext}} = 0.08$. Each of the neurons receives six or more inputs. This means that, for each input, the external reflectivity for a mode can be changed by about $\Delta R_{\text{ext}} = 0.01$. To estimate the number of round trips needed to switch from one output state of the LNN to another output state, we assume that the change in output state is caused by switching only one input element. In this worst case, the amount of feedback for a mode will change by less than $\Delta R_{\text{ext}} = 0.01$ considering the weighting of inputs by a factor smaller than unity. This is approximately equal to the difference in feedback for the transient with ND = 0.1 reported above, where ~ 12 round trips were needed to reach a steady state. The number of round trips needed to reach a steady output state after a change of input state in our current experimental LNN will, therefore, be 12 or higher.

If the feedback level of the proposed integrated optics LNN is the same as that for our current experimental LNN, the operation speed will be limited to about 0.5 Gbit/s. In order to reach a bit rate higher than 1 Gbit/s, the difference in the amount of external feedback between two input states needs to be increased. This can simply be achieved by reducing the number of inputs, which is undesirable from a functional point of view. A better solution would be to optimize the design of the integrated optics

Fig. 7. Extrapolated transient response curve for cavity B with a zero round-trip time using data of Fig. 5. The points are obtained by linear extrapolation of the time at which the intensity of mode B reaches a certain level for various round trip-times to a round-trip time of 0. Error bars indicate 95% confidence intervals of the linear fit. Measured response curves of mode A and B for a cavity round-trip time of 2.1 ns are included for comparison.

devices for maximum feedback efficiency. For this, it might be necessary to introduce extra gain regions into the design.

B. Residual Delay

The measurements with varying round-trip times were used to extrapolate the experimentally recorded transient curves for zero cavity length. For this purpose, the time t_x at which the optical power of mode B reaches a given amount x is extracted from the measurement data presented in Section IV-B as a function of cavity round-trip time. By use of a linear fit [22] on t_x , we extrapolated the time at which this amount of power would have been reached if the cavity length for mode B was zero. In this fit, we used the round-trip time of the cavity as an estimate on the uncertainty of the t_x values. The results are plotted

in Fig. 7 using the ten recorded transient curves discussed in Section IV-B. The horizontal error bars in these plots indicate the 95% confidence intervals of the extrapolated data. For reference, the intensity development of modes A and B with a cavity B round-trip time of 2.1 ns is included in the figures.

The extrapolated transient curves for a zero round-trip time of cavity B clearly show a residual delay between the switching off of mode A and the switching on of mode B. The delay is on the order of nanoseconds and will put an additional limit on the operation speed of the LNN on top of that imposed by the number of needed round trips. We believe that the residual delay is due to the fact that the total external reflectivity before and after the transient is different. As a result, the total emitted optical power will be different. Consequently, the number of charge carriers needs to change. Since the optical feedback for mode B is lower than that for mode A, the change in the number of charge carriers is also needed to reach the threshold condition for mode B.

To test our hypothesis on the origin of the residual delay and to estimate the operation speed of the proposed integrated optics LNN device [21], we carried out simulations with a cavity round-trip time of 0.1 ns for both cavities. As a transient time of the modulator, we choose 0.1 ns, a modest value for integrated optics modulators [23].

Although the rate-equation model (7) was derived for a large group of compound cavity modes, we will also use it for this cavity length with just one compound cavity mode per group. If the mode spacing is sufficiently large, changes in the modal phase are not expected to cause a mode hop to another compound cavity mode and, therefore, also in this case, the phase term in (4) can be neglected.

In a first simulation, we switched off the external reflectivity for mode A at $t = 0$ while keeping the external feedback for mode B constant. In a second simulation, the external reflectivity values for modes A and B were interchanged at $t = 0$. We used the same values for the external reflectivities as in the simulations of Section IV-B, so we expect a delay of approximately ten round-trip times.

The results of these simulations are presented in Fig. 8. Fig. 8(a) corresponds to the situation with a constant feedback level for mode B. In Fig. 8(b), results are shown for the simulated interchanging of the external reflectivity of modes A and B. The figures show the optical intensity of the modes, modes A and B, and the carrier density normalized to the transparency value N/N_0 . The steady state of the optical intensity of mode B is indicated with a dotted line. In Fig. 8(a), a difference in the carrier density before and after the transient is visible. The time delay between the complete extinction of mode A and the point at which the intensity of mode B first reaches the steady-state value is about 1.7 ns. This is more than ten round-trip times. In Fig. 8(b), this time delay is about 1.1 ns, approximately equal to the expected ten round trips. The carrier densities before and after the transient are equal in Fig. 8(b). Thus, we can conclude that the change in charge carrier density introduces a delay of about 0.6 ns. This value is in reasonable agreement with the measured residual delay.

The simulations of Fig. 8(b) show that the delay can be avoided by controlling the total external reflectivity in such a

Fig. 8. Results of simulation of the time development of optical power for both modes with a cavity round-trip time of 0.1 ns. The light intensity of modes A and B are plotted, together with the normalized carrier density, N/N_0 . The steady state of mode B is indicated with a dotted line. (a) At $t = 0$, the modulator closes with a transient time of 0.1 ns. Relaxation oscillations and a delay of about 1.7 ns can be observed in the transient response of mode B. The carrier density is different before and after the transient. (b) At $t = 0$, the optical feedback levels of modes A and B are interchanged. The carrier density is the same before and after the transient. The delay is reduced to 1.1 ns or approximately ten round-trip times of the external cavities.

way that it is equal before and after the transient. To avoid the residual delay, the total amount of external reflectivity should be the same for each state of the LNN. Although this should be possible, it will considerably complicate implementations of the LNN. The resulting constraint on the input vectors will reduce the functional capabilities of the LNN.

C. Relaxation Oscillations

In Figs. 8(a) and (b), relaxation oscillations can be observed. These relaxation oscillations originate from the change in charge carrier density during the transient which, in turn, is caused by the temporary change in total emitted light intensity. Compared to the oscillations that are visible in the measurements and simulations with longer cavity round-trip times, the oscillations are more pronounced in these simulations with a round-trip time of 0.1 ns. With still lower round-trip times, the relaxation oscillations will dominate the behavior during the transient. This is illustrated in Fig. 9, where we show simulation results for a zero cavity length.

The relaxation oscillation frequency is proportional to the square root of the optical output power of the laser and has a typical value of ~ 5 GHz [16], [17] for laser diodes operated well above threshold. The frequency of the relaxation oscillations in Fig. 9 is about $f_r = 1.7$ GHz. This relatively low value

Fig. 9. Simulated time evolution of the intensity of mode B for a zero cavity length of both cavities. The steady state is indicated by a dotted line. Relaxation oscillations in the intensity of mode B can be observed. The oscillation frequency is about 1.7 GHz. A switch-on time of approximately 0.3 ns can be observed.

is caused by the fact that the laser diode in our LNN is operated close to threshold.

A switch-on time, t_{on} , can be associated with the relaxation oscillation frequency according to [16]

$$t_{\text{on}} = \frac{\sqrt{2}}{\omega_r} \left[\ln \left(\frac{S_{\text{on}}}{S_{\text{off}}} \right) \right]^{1/2} \quad (8)$$

with $S_{\text{on}}/S_{\text{off}}$ the intensity ratio of the considered mode in the “on” and “off” states and ω_r the angular relaxation oscillation frequency. The value of t_{on} resulting from (8) is about 0.35 ns and is in agreement with the simulation results of Fig. 9. The bandwidth of the system will essentially be limited by the relaxation oscillation frequency [16], [17]; hence, the current LNN will be bandwidth-limited to about 1.7 GHz even if the round-trip delay is zero.

VI. CONCLUSIONS

We have studied the mode-switching behavior of an external-cavity laser diode under optical modulation conditions to estimate the feasible operation speed of an LNN implemented with integrated optics. In our experiments, the feedback level for one mode of the external-cavity laser diode was kept at a constant value, while the feedback level for another mode was switched by means of an optical modulator. The round-trip delay for one of the modes was varied.

It was found, both experimentally and theoretically, that, depending on the amount of external optical feedback, between 7 and 21 round trips of an external cavity are needed to reach a steady state. Switching between two states in our LNN is expected to take more than 12 round trips considering the feedback level of our current setup. To obtain switching times < 1 ns in an integrated optics LNN with a cavity length of a few centimeters, the amount of optical losses needs to be reduced or extra optical gain should be introduced.

For a zero cavity length, a residual delay of a few nanoseconds is identified by extrapolation of experimentally obtained transient curves for various cavity lengths. Simulations indicate that this delay is due to a change in charge carrier density, needed

to reach the threshold condition for the initially nonlasing mode. Simulations indicate that this delay can be avoided by ensuring an equal feedback level in each state of the LNN.

A third limitation on the operation speed of the LNN is imposed by the occurrence of relaxation oscillations. This limits the bandwidth of the current LNN to about 1.7 GHz. To increase the relaxation oscillation frequency of the laser diode, the feedback efficiency can be increased to operate the laser diode further above threshold in the on state.

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