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Chaotic Self-Pulsation and Cross-Modulation in a Wavelength-Selective External-Cavity Laser Diode

E. C. Mos, G. W. 't Hooft, J. J. H. B. Schleipen, and H. de Waardt

Abstract—Chaotic self-pulsation in a single wavelength external-cavity laser diode is observed. It is shown that the self-pulsation is caused by interdependencies between the optical output power and the compound cavity losses through the refractive index of the laser diode material. Refractive index changes result in a detuning between the externally selected wavelength and the weak internal-mode structure of the anti-reflection coated laser diode. This detuning is directly related to the compound cavity losses. On the one hand, a change in optical output power results in a change of the refractive index via the carrier density. On the other hand, it results in a change of refractive index via temperature changes. Compared to the carrier induced refractive index change, the temperature induced refractive index change is opposite in sign, a factor of $\sim 10^2$ smaller and slower. The switch-on and switch-off time of the self-pulsation is governed by the carrier life time. The repetition rate of the self-pulsation is governed by the thermal time constant and is in the megahertz region. Cross-modulation resulting from the thermal induced refractive index change is demonstrated. In a two-wavelength double external-cavity laser diode, optical power at one wavelength effects the optical power at the other wavelength. This cross-modulation is shown to be related to previous experiments on a laser neural network. A novel technique is introduced to measure the thermal impedance of a laser diode that is based on the cross-modulation.

Index Terms—Chaos, cross modulation, laser thermal factors, optical pulses, semiconductor lasers.

I. INTRODUCTION

GRATING-TUNED external-cavity laser diodes are widely used as narrow-linewidth tunable sources for many applications. These sources consist of a laser diode that is coupled to an external wavelength-selective resonator. Although the facet of the laser diode facing the external resonator is usually anti-reflection coated, the reflectivity of the facet is finite and, thus, the laser should be treated as a compound cavity laser diode.

As a result, changes in the longitudinal cavity-mode spectrum of the laser diode will influence the behavior of the compound cavity laser diode. In Fig. 1, the longitudinal cavity-mode spectrum of a laser diode is plotted together with the externally selected wavelength (external-cavity-modes are spaced at a much smaller distance and are not shown). If, for some reason, the

Fig. 1. Internal longitudinal-mode spectrum and externally reflected wavelength of a compound cavity laser diode with wavelength-selective external optical feedback. Because of changes in the refractive index of the laser diode material, the internal-mode spectrum can shift. An increase in the refractive index will cause the spectrum to shift to longer wavelengths.

internal longitudinal-mode wavelengths shift, the externally selected wavelength will go in and out of resonance with one of the internal longitudinal cavity-modes. This will cause an increase in optical output power when a longitudinal-mode wavelength comes into resonance with the externally selected wavelength. When a longitudinal-mode shifts out of resonance, the output power of the compound cavity laser diode will decrease. These effects will be more pronounced when the laser diode is operated close to threshold and small changes in the laser characteristics have a large influence on the optical output power.

The shift of the longitudinal cavity-modes can be caused by a change in refractive index of the laser diode material. A change in refractive index changes the effective cavity length and, therefore, the longitudinal-mode wavelengths.

The index of refraction depends, among other things, on the carrier density of the active region [1], as well as on the device temperature [2]. The carrier density and the device temperature are related to the optical output power of the laser diode via the carrier rate equation and the thermal conductivity of the laser diode, respectively. This means that the refractive index depends on the optical output power of the laser diode and vice versa.

This can cause interesting phenomena in a single external-cavity setup. In particular, the carrier-induced refractive index change has received considerable attention [3]–[6]. Optical bistability [3]–[5] and self-pulsation at a repetition rate determined by the external-cavity length [6] have been reported. The effects of the optical power-induced thermal refractive index change, however, has not received much attention. Even in temperature-stabilized laser diodes, this effect will be present due to the finite thermal resistance between the

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laser active layer and the heatsink. The influence of the optical output power has often been neglected in the determination of the thermal properties of a laser diode [7], [8].

In a double external-cavity setup, where each cavity corresponds to one selected wavelength, modulation of the optical power at one wavelength can cause the longitudinal modes to shift. As a consequence, the optical output power at the second selected wavelength will vary. This cross-modulation can be either positive or negative, depending on the direction of the mode shift and the relative position of the second externally selected wavelength to the nearest internal longitudinal-mode wavelength.

In this work, self-pulsation at a megahertz repetition rate in a single external-cavity setup is reported. It is explained by the combined effect of carrier and temperature-induced refractive index changes. With a double external-cavity setup, operating at two wavelengths, we show cross-modulation that is caused by the thermal refractive index change that results from switching the external feedback for one of the selected wavelengths. The latter setup can be used in a novel technique to measure the thermal impedance of a laser diode.

In Section II, the mode shift caused by the refractive index changes that result from variations in optical output power is analyzed. The thermal- and carrier-induced refractive index change are compared. Section III describes experimental observations of self-pulsation in a single external-cavity setup, and cross-modulation in a double external-cavity setup. The results are discussed in Section IV, where we also relate this work to our previous publications on a laser neural network that consists of a laser diode coupled to a multiwavelength external-cavity setup. Our findings are summarized in Section V.

II. THEORY

In this section, we investigate the influence of the optical output power of a laser diode on the index of refraction. In Section II-A, the influence of the optical power P on the refractive index n via the carrier density N is analyzed. Section II-B is devoted to optical output power-induced changes in the refractive index via the device temperature T .

The change in refractive index caused by a change in optical power P can be written as

$$\frac{dn}{dP} = \frac{\partial n}{\partial N} \frac{\partial N}{\partial P} + \frac{\partial n}{\partial T} \frac{\partial T}{\partial P} = \left(\frac{\partial n}{\partial P} \right)_N + \left(\frac{\partial n}{\partial P} \right)_T \quad (1)$$

where $(\partial n)/(\partial P)_N$ and $(\partial n)/(\partial P)_T$ are the optical power-induced changes in the refractive index via the carrier density and the device temperature, respectively.

In the last part of this section, the longitudinal-mode shift and the resulting changes in effective mirror losses are analyzed. The carrier-induced refractive index change can lead to instabilities.

A. Influence of the Optical Power on the Refractive Index via the Carrier Density

For a fixed injection current, changes in optical output will cause changes in carrier density according to

$$\frac{\partial N}{\partial P} = -\frac{\tau_e}{\eta_d q V} \quad (2)$$

Fig. 2. Equivalent circuit diagram describing the thermal characteristics of a laser diode with electrically injected power P_{elec} and optical output power P_{opt} . The thermal capacity of the active layer is C_{act} . The active layer is thermally connected to the heatsink at temperature T_{sink} via a thermal impedance R_{th} .

where τ_e is the carrier lifetime, η_d is the differential quantum efficiency of the laser diode (in WA^{-1}), q is the elementary charge, and V is the volume of the active region. The value of the carrier-induced refractive index change $\partial n/\partial N$ can be found in the literature and lies in the range of $-(5-11) \times 10^{-21} \text{ cm}^3$ [1].

For the laser diode used in our experiment (Uniphase CQL806), we estimate $\tau_e \approx 1 \text{ ns}$, $\eta_d \approx 0.2 \text{ WA}^{-1}$, and $V \approx 2 \times 10^{-11} \text{ cm}^3$. This results in $(\partial n/\partial P)_N$ in the range of $8-17 \text{ W}^{-1}$. As we consider the influence on the spectral-mode structure of the laser diode, the effective refractive index change rather than the total refractive index change should be considered. The effective refractive index change for a mode is reduced by the optical confinement factor of the laser diode as only the carrier density in the active region changes [9]. The optical confinement factor for our MQW laser diode is estimated at $\Gamma \approx 0.02$. Thus, we find for the power-induced refractive index change via carrier density

$$\left(\frac{\partial n}{\partial P} \right)_{N, \text{eff}} = 0.16 - 0.34 \text{ W}^{-1}. \quad (3)$$

Changes in the carrier number can occur on a time scale equal to or greater than the carrier life time τ_e . This means that the carrier-induced change in refractive index occurs on a time scale larger than a nanosecond.

B. Influence of the Optical Power on the Refractive Index via the Device Temperature

The temperature of the active region of a laser diode depends on the amount of electrically injected power that is dissipated in the laser. This equals the injected electrical power minus the total optical power. With reference to the equivalent circuit diagram of Fig. 2, we can estimate the change in active region temperature that is caused by a change in optical output power.

For typical laser diodes, the thermal impedance $R_{\text{th}} = \partial T/\partial P$ is in the range of $30-140 \text{ kW}^{-1}$ [7], [10], [11]. This means that changes in optical output power of a few milliwatts can result in a temperature change of $0.1-1 \text{ K}$. Note that, with a fixed electrical current through the laser, an increase in optical output power will result in a decrease of device temperature.

A change in temperature will result in a change in refractive index via $\partial n/\partial T$. For GaAs, a value for $\partial \ln(n)/\partial T$ is reported to be $\sim 5.6 \times 10^{-5} \text{ K}^{-1}$ [2]. Using this value and the value for

Fig. 3. Compound cavity-model of laser diode with wavelength-selective external optical feedback. A laser diode with cavity length L has back facet power reflectivity R_0 . The front facet with anti-reflection coating of reflectivity R_{int} faces an external-cavity with reflectivity R_{ext} at frequency ω_0 .

$\partial T/\partial P$, a refractive index n of ~ 4 results in a value for the power-induced refractive index change via temperature

$$\left(\frac{\partial n}{\partial P}\right)_T = -(2.2 - 22) \times 10^{-3} \text{ W}^{-1}. \quad (4)$$

A typical time constant can be associated with changes in the temperature of the active region of the laser diode. This time constant is determined by the thermal capacity of the active region and the thermal impedance between the active region and the heatsink (see Fig. 2). For typical laser diodes, values on the order of $0.01\text{--}3 \mu\text{s}$ have been reported [8], [12], [13].

C. Stability Analysis

Comparing the results of the previous two subsections [(3) and (4)], we find that the thermal and carrier effects have an opposite sign. We also find that the carrier effect is much stronger than the thermal effect. Thus, neglecting the thermal effect, the carrier-induced refractive index change can cause instabilities via $\partial P \Rightarrow \partial N \Rightarrow \partial n \Rightarrow \partial \lambda \Rightarrow \partial \alpha \Rightarrow \partial P$ because the effective mirror losses α of the compound cavity depend on the detuning between the externally selected frequency.

To relate changes in the effective optical losses α of an external-cavity laser diode to changes in the refractive index n of the laser diode material, we consider the compound cavity-model of Fig. 3. The figure shows a laser diode with back facet reflectivity $R_0 = r_0^2$ and front facet reflectivity $R_{\text{int}} = r_{\text{int}}^2$. The oscillation frequency of the laser diode ω_0 is determined by the wavelength-selective external optical feedback with reflectivity $R_{\text{ext}} = r_{\text{ext}}^2$.

It is obvious that the effective amplitude reflectivity of the facet facing the external mirror reaches a maximum when the internal reflection is in phase with the optical wave reflected back from the external cavity end mirror. In other words, when a longitudinal cavity-mode wavelength is equal to the externally selected wavelength. Neglecting multiple reflections in the external cavity and considering an anti-reflection coated laser diode ($R_{\text{int}} \approx 0$) this maximum can be estimated at $r_{\text{eff}} = r_{\text{ext}} + r_{\text{int}}$. Accordingly, a minimum value of $r_{\text{ext}} - r_{\text{int}}$ can be calculated for the effective amplitude reflectivity of the laser diode front facet when the internally and externally reflected light is exactly 180° out of phase. In this case, the externally selected wavelength is exactly in the middle of two longitudinal cavity wavelengths. A more rigorous approach using a parametric solution of the phase and amplitude equations of a laser diode [3] yields the same result.

The optical losses of the compound cavity corresponding to the minimum and maximum effective reflectivity of the front facet can be evaluated using

$$\alpha = \alpha_{\text{int}} - \frac{1}{L} \ln(r_0/r_{\text{eff}}) \quad (5)$$

where α_{int} represents the optical losses of the laser diode material. By use of this equation we can estimate the minimum and maximum optical losses for the laser diode that is used in our experiments. The reflectivity of the anti-reflection coated front facet is $R_{\text{int}} \approx 5 \times 10^{-4}$, the internal losses for our MQW laser diode are estimated at $\alpha_{\text{int}} = 10 \text{ cm}^{-1}$ and the back facet reflectivity is typically $R_0 \approx 0.3$. The feedback efficiency of the external-cavity including coupling losses is estimated at $R_{\text{ext}} \approx 0.02$. The maximum value for the optical losses using these parameters is $\sim 65 \text{ cm}^{-1}$; the minimum value is $\sim 58 \text{ cm}^{-1}$.

To change the effective optical losses from a minimum to a maximum or vice versa, a mode shift of 0.5 spectral-mode distance is sufficient. The needed change in refractive index can be calculated using [14]

$$\frac{d\lambda}{\lambda} = \frac{dn}{n}. \quad (6)$$

For our laser diode operating around 675 nm with a cavity length of $500 \mu\text{m}$, which corresponds to a spectral-mode spacing of $\sim 0.1 \text{ nm}$, we find that the needed change in refractive index is $\Delta n \approx 3.4 \times 10^{-4}$.

Using this value of Δn and $\Delta \alpha$ from the preceding paragraph, we obtain a value of $|\partial \alpha / \partial n|$ on the order of 10^4 cm^{-1} . When the externally selected wavelength is on the short wavelength side of the nearest internal cavity-mode, the effective optical losses increase as a function of n . The nearest longitudinal-mode wavelength moves further away from the externally selected wavelength. Decreasing optical losses occur on the long-wavelength side. With this value of $\partial \alpha / \partial n$ and the value for $\partial n / \partial N$ from the literature [1], we can calculate $|\alpha'| = (0.5 - 1.1) \times 10^{-16} \text{ cm}^2$. Note that α' is positive on the long wavelength side whereas it is negative on the short wavelength side of an internal longitudinal mode.

As shown theoretically by Glas and Müller [5], instabilities can result on the longer wavelength side of an internal cavity-mode. Any detuning (or power fluctuation) causes a further detuning when the wavelength selected by the grating is on this side of an internal cavity-mode. As carrier density-induced refractive index changes are the cause of the effect, disturbances can grow with a typical time constant governed by the carrier lifetime.

III. EXPERIMENTAL

In this section, we present experimental observations that demonstrate the combined effect of carrier and temperature-induced refractive index changes in a compound cavity laser diode. Section III-A deals with a single external-cavity laser diode that exhibits self-pulsating behavior. In Section III-B, we present results of experiments using a double-cavity two-wavelength laser diode showing cross modulation between the two wavelengths.

Fig. 4. Single external-cavity laser diode setup. A temperature-controlled, anti-reflection-coated laser diode is coupled to a wavelength-selective external cavity consisting of grating G1 and mirror M1. The temperature can be controlled to shift the internal longitudinal-mode spectrum of the laser diode. The output light intensity and the output wavelength are monitored.

Fig. 5. Output light intensity as a function of diode temperature. Temperature values are calculated by use of calibration table of similar thermistor. Circles represent measurement points with stable operation, crosses represent measurement points with self-pulsation.

A. Single Cavity Setup

With the single external-cavity laser setup of Fig. 4 we measured the temperature dependent shift of the cavity resonance frequencies of a laser diode. The laser diode (Uniphase CQL 806 $\lambda \approx 680$ nm) is anti-reflection coated and operates below threshold without feedback. Wavelength-selective feedback is provided by use of grating G1 (2400 l/mm). The resulting wavelength selectivity is approximately 10^{-2} nm. The external-cavity length is ≈ 1 m. The amount of optical feedback is made such that the laser is still below threshold if the (fixed) wavelength selected in the external-cavity is between two internal longitudinal-mode wavelengths. The temperature of the laser diode chip is controlled and measured by use of a thermo-electric temperature controller and a thermistor. A part of the laser beam is coupled out and is used to measure the optical power and the spectrum of the external-cavity laser diode output.

In Fig. 5, the time-averaged output power of the laser diode is plotted as a function of temperature. The figure shows two peaks that occur when an internal longitudinal-mode wavelength coincides with the externally selected wavelength. In the figure,

Fig. 6. Various regimes of self-pulsation. Top curve: self pulsation when externally selected frequency is almost equal to an internal longitudinal-mode frequency. Bottom curve: external- and longitudinal-mode frequencies are far apart. Other curves show measurements with intermediate frequency differences.

circles indicate measurement points with stable, single external cavity-mode operation. Crosses indicate measurements with unstable, self-pulsating behavior. The self-pulsation occurs when the externally selected wavelength is on the long wavelength side of the nearest internal longitudinal-mode wavelength. The internal longitudinal-mode spacing is approximately 0.1 nm.

Various regimes of self-pulsation are shown in Fig. 6. The figure shows the light intensity of the laser diode as a function of time for various levels of detuning between the external feedback wavelength and the nearest internal longitudinal-mode wavelength. Chaotic transitions from a lasing to a nonlasing state and back can be observed. The top graph corresponds to a small difference between the externally selected wavelength and the nearest internal longitudinal mode, a cross somewhere near a peak in Fig. 5. The bottom graph is measured with a large wavelength difference, near a valley in Fig. 5. Other graphs show measurements with intermediate wavelength difference. With increasing wavelength difference, the laser tends to stay longer in the nonlasing state.

B. Double-Cavity Setup

To demonstrate cross-modulation, we have built a setup according to Fig. 7. The figure shows a laser diode that is coupled to two external cavities. In each external cavity, a different longitudinal mode is selected by use of gratings G1 and G2, and mirrors M1 and M2. A $\lambda/2$ -plate and a polarizing beam splitter enable us to direct a controllable portion of light to the two external cavities.

In one cavity, an electrooptical modulator is inserted to modulate the feedback for one selected wavelength λ_1 . When the modulator is open, the laser emits at wavelength λ_1 . When it is closed, the laser can emit at wavelength λ_2 , selected in the second external cavity, if the level of feedback provided by this cavity is sufficiently high.

Fig. 7. Double external-cavity setup to demonstrate cross-modulation. In each external cavity, a different wavelength is selected. A polarizing beam splitter (PBS) and a $\lambda/2$ -plate control the feedback levels for the two cavities. The feedback for one cavity is modulated with an electrooptical modulator.

Part of the intra-cavity optical power is coupled out and analyzed. Detectors (Opto Electronics Inc. PD 10) and a sampling oscilloscope (Tektronix 11 802 with SD-26 sampling heads) are used to monitor the optical power at the two selected wavelengths.

By tuning mirror M2, we are able to set the frequency mismatch between wavelength λ_2 and the nearest cavity resonance frequency. In a first experiment, λ_2 is tuned halfway between two internal longitudinal-mode wavelengths. The external optical feedback at this wavelength is controlled such that it is insufficient to make the laser lase. Now the feedback for λ_1 is modulated, and consequently, the laser emits at λ_1 when the modulator is open. The average output power of the laser diode measures 2.8 mW. When the modulator is closed, however, the laser starts lasing at λ_2 .

The transient behavior of the light emission at λ_2 is presented in Fig. 8. Before $t \approx 1 \mu\text{s}$, the modulator is open and the laser is lasing at λ_1 . Emission at λ_2 is suppressed. When the modulator closes, a sharp increase in the light intensity at λ_2 can be observed. Gradually the light intensity at λ_2 decreases to the spontaneous emission level until the modulator opens again at $t \approx 13 \mu\text{s}$ and lasing starts again at λ_1 .

The increase in light intensity at λ_2 after $t \approx 1 \mu\text{s}$ can be explained by the mode shift resulting from the emission of light at λ_1 . The mode shift results in a decrease of effective optical losses for λ_2 . The feedback for λ_1 , however, is much stronger and lasing action at λ_2 is suppressed. At $t \approx 1 \mu\text{s}$, the emission at λ_1 stops and the internal longitudinal-mode wavelengths relax to their original spectral positions.

The time scale at which the light intensity at λ_2 decreases is on the order of microseconds, the thermal time constant. This leads us to believe that the effect is caused by a temperature change due to the emission of optical power at λ_1 before $t \approx 1 \mu\text{s}$. To estimate the temperature change, the feedback path for λ_1 is blocked and the temperature of the laser diode is actively decreased by use of the temperature controller until the light intensity at λ_2 reaches the maximum level of Fig. 8. The temperature change amounts to $\sim 0.5 \text{ K}$.

The temperature trajectory corresponding to the measurement of Fig. 8 is indicated with arrow A in Fig. 5. Arrow A has a length corresponding to 0.5 K. The laser operates in a stable regime and the difference between the selected wavelength and

Fig. 8. Time-dependent light intensity at wavelength λ_2 showing cross-modulation. At $t \approx 1 \mu\text{s}$, the modulator closes and the laser stops lasing at λ_1 . From this point, the laser emits at λ_2 due to the decreased temperature. As the temperature increases to a steady state, the optical output power at λ_2 slowly decreases. The laser is in a stable state during the temperature relaxation. The corresponding temperature trajectory is indicated by arrow A in Fig. 5.

Fig. 9. Same as Fig. 8, but the laser goes from a stable to an unstable state. Temperature trajectory is indicated by arrow B in Fig. 5.

the nearest internal-mode wavelength increases as a function of time.

By rotating mirror M2, the wavelength difference between λ_2 and the nearest internal longitudinal-mode wavelength is changed. With the same output power at λ_1 as in the measurements of Fig. 8, the results of Figs. 9 and 10 were obtained. The corresponding temperature trajectories are indicated with arrows B and C in Fig. 5.

Fig. 9 shows an initially stable operation that turns into an unstable operation at $t \approx 3 \mu\text{s}$. After this point, the light inten-

Fig. 10. Same as Fig. 8, but the laser goes from an unstable ($1 \mu s < t < 2 \mu s$) to a stable ($t > 3 \mu s$) state. Temperature trajectory is indicated by arrow C in Fig. 5.

sity at λ_2 is similar to that of the bottom graph of Fig. 6 which is measured with an ordinary oscilloscope. The seemingly damped sinusoidal oscillation in Fig. 9 is an artifact of the measurement resulting from the random phase of the chaotic pulsation and the averaging mechanism of the sampling scope. A number of waveforms like the one of the bottom graph of Fig. 6 are averaged by the sampling scope. Due to the random phase of the chaotic pulsation, the pulsation averages out as a function of time.

In Fig. 10, laser operation at λ_2 starts in an unstable region near the resonance peak, but within a few microseconds, the temperature relaxes to a steady state and the laser operates in a stable regime from this point.

IV. DISCUSSION

A. Self-Pulsation

The results of Section III showed self-pulsation when the externally selected wavelength is on the long wavelength side of the nearest internal longitudinal mode. The self-pulsations can be explained by the instabilities resulting from the carrier-induced refractive index change in this wavelength region, that were discussed in Section II-C.

If the externally selected wavelength is on the long wavelength side of an internal longitudinal mode, any disturbance will cause the internal-mode spectrum to shift until a stable region is reached. Depending on the sign of the disturbance, this can result either in a lasing or a nonlasing state.

The time the system needs to reach a stable state will depend on the rate at which initial disturbances grow and the way these disturbances affect the effective optical losses of the compound cavity. As disturbances will grow with a time constant on the order of the carrier lifetime (see Section II-A), the results of Fig. 6, where a steady state is reached at a time scale of $\sim 0.1 \mu s$, are in reasonable agreement with these considerations.

When the stable state is reached, the temperature of the active region will change as the output power of the laser diode is altered. Because the temperature-induced refractive index change has an effect opposite to that of the carrier-induced change, it will cause the internal-mode spectrum to shift back toward the unstable region. As discussed in Section II-B, the temperature-induced effect is much slower with a typical time scale on the order of microseconds.

The temperature of the active layer will oscillate around some average temperature as the laser switches on and off during the self-pulsation. This average temperature depends on the average optical output power of the laser diode and the heatsink temperature (see the equivalent circuit diagram of Fig. 2). At a given externally selected wavelength, the effective optical losses and thus the optical output power are related to the active layer temperature. This means that the average optical output power is a function of the heatsink temperature.

From the preceding, we can conclude that the laser diode switches on and off with a switch-on and switch-off time determined by the carrier effect. The repetition rate of the pulsation is governed by the thermal time constant of the laser. The average output power and, thus, the duty cycle of the pulses, depends on the heatsink temperature at a given externally selected wavelength.

B. Cross-Modulation

The fact that the temperature-induced change in refractive index plays a role in the behavior of the laser diode on a μs time-scale can also be seen from the results of Section III-B. This is in agreement with our explanation of the self-pulsation effect. Also the time scale at which the thermal effects influence our experimental results agrees with the explanation of the self-pulsation effect as well as with values of the characteristic thermal time constant reported in the literature [8], [12], [13].

The results of Section III-B show thermal cross-modulation. The optical output power at wavelength λ_2 is (temporarily) changed by the emission of optical power at λ_1 . The decrease in temperature resulting from the emission at λ_1 causes the internal longitudinal modes to shift. When λ_2 is on the long wavelength side of the nearest internal longitudinal mode, the shift caused by the decreased temperature will be toward λ_2 . On the other side of an internal mode, the shift will be away from λ_2 .

This means that the thermal cross-modulation effect between λ_1 and λ_2 is either positive or negative, depending on the position of λ_2 relative to an internal longitudinal mode. Thus, the effect shows a resemblance to asymmetric nonlinear gain [15] that is caused by the beating of two wavelengths in the active region, and also exhibits a wavelength asymmetry. The asymmetric nonlinear gain, however, only plays a role when the two wavelengths are less than a few internal longitudinal modes apart. The cross-modulation reported in this paper occurs throughout the whole spectrum of the laser diode.

The cross-modulation effect will be visible only if the light at one of the wavelengths exhibits pulsation. When it does not, the internal modes might be shifted but lasing action at the nonlasing wavelength will be suppressed by mode competition. Note that the carrier-induced refractive index change is much

larger than the thermally induced change and, hence, one would expect that this effect would play a dominant role in the cross-modulation. This, however, is not the case in our external-cavity setup as the cavity round-trip time (~ 10 ns) is much larger than the carrier life time. Therefore, changes in refractive index caused by variations in carrier density have disappeared before they have an effect on the optical output power.

In our laser neural network (LNN) that operates by applying controlled optical feedback for a number of wavelengths, anomalous behavior has been reported [16] that can be explained by cross-modulation as described in this paper. When increasing the level of optical feedback for one wavelength, the time-averaged optical output power for a second wavelength also increased. This increase can be due to a shift in the internal-mode spectrum that results from the increase in optical output power of the first wavelength. Although we did not measure the time development of the light intensity in the LNN, it is possible that self-pulsation occurred in the LNN as the setup of the LNN essentially is equal to that of Fig. 4.

C. Determination of Thermal Parameters

The measurements of Section III can be used to determine some of the thermal parameters of our laser diode. The temperature change needed to shift the longitudinal-mode spectrum one mode spacing can be used to calculate $\partial n / \partial T$. With a mode spacing of ~ 0.1 nm and a corresponding temperature change of 2.4 K (see Fig. 5), we obtain $\partial \lambda / \partial T = 0.042$ nmK $^{-1}$. The relative change in wavelength $d\lambda / \lambda$ is equal to the relative change in optical cavity length $d(nL) / (nL)$. Thus, we can write

$$\frac{\partial(nL)}{\partial T} = \frac{\partial \lambda}{\partial T} \frac{nL}{\lambda}. \quad (7)$$

This leads to a normalized temperature-induced relative optical cavity length change $\partial \ln(nL) / \partial T$ of 6.2×10^{-5} K $^{-1}$. The cavity length also depends on the temperature with $\partial \ln(L) / \partial T = 5.7 \times 10^{-6}$ K $^{-1}$ [2]. This results in a temperature derivative of the refractive index of $\partial \ln(n) / \partial T = 5.6 \times 10^{-5}$ K $^{-1}$, which is in good agreement with the value for GaAs of 5.4 – 5.8×10^{-5} K $^{-1}$ reported in the literature [2].

The thermal impedance R_{th} can be calculated using the measurements of Section III-B. We measured a time-averaged optical output power of 2.8 mW. The duty cycle of the optical modulator was 50%. Thus, the optical output power at λ_1 in the open state of the modulator was ~ 5.6 mW. A change in active layer temperature of ~ 0.5 K was needed in a null method to adjust the optical power at λ_2 (see Section III-B). These values of dP and dT yield a thermal impedance R_{th} of 90 kW $^{-1}$. This value for R_{th} is within the range reported in literature [7], [10], [11].

Compared to other methods to measure the thermal impedance of a laser diode, the method proposed in this work uses the optical power instead of the electrical power [7], [10], [11]. These other methods measure the thermal impedance from the area where the electrical power is dissipated, to the heatsink. The method presented above can be used to measure the thermal impedance from the area where the optical power is generated, to the heatsink. The area where the electrical power is dissipated is, in general, extended beyond this region.

V. CONCLUSION

We have analyzed the influence of the optical output power on the refractive index-induced shift of the internal-mode spectrum of a compound cavity laser diode. The thermal- and carrier-induced changes in refractive index have been examined. The thermal-induced refractive index changes are expected to be of the order of 10^2 smaller than the carrier-induced refractive index changes and have an opposite sign. The time scale of the temperature effect is in the order of μ s. The carrier-induced refractive index changes will occur on the time scale of the carrier life time, which is ~ 1 ns.

In a single wavelength external-cavity setup, self-pulsation is observed. The self-pulsation is shown to be caused by the combined effect of the carrier and temperature-induced changes in refractive index. The carrier-induced refractive index causes unstable regions to occur in the tuning curve of the external-cavity laser. This effect determines the switch-on and switch-off time of the self-pulsation. The thermal refractive index change causes reentrance in the unstable area and determines the repetition rate.

In a double-wavelength external-cavity setup, cross-modulation is observed that is caused by the temperature-induced refractive index change. The effect will only be visible when the laser output power is modulated. In the experiments presented here, this modulation is caused by modulation of optical feedback for one wavelength. In our laser neural network, the self-pulsation effect can be responsible for the cross-modulation that was reported as an anomalous effect in the laser neural network experiments.

The measurements are used to determine the thermal impedance and the temperature-induced change in refractive index. The thermal impedance is measured using a novel technique that uses the optical output power of the laser diode. The results are in agreement with values found in literature.

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