

On the Various Time Constants of Wavelength Changes of a DFB Laser Under Direct Modulation

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Abstract—The temporal behavior of the optical frequency emitted by several DFB lasers under direct square wave modulation was measured using an all-fiber implementation of a Mach-Zehnder interferometer with an imbalance of 30 ps. The impulse response of the optical frequency to injection current modulation was found to contain a time constant as short as 10–20 ns, together with a few longer ones. The existence of such a short time constant is consistent with a thermal analysis of a laser structure with finite thermal impedance of the active region and should be taken into consideration in various wide bandwidth applications of direct modulated semiconductor lasers.

Index Terms—Distributed feedback lasers, optical communications, optical modulation/demodulation, thermal analysis.

I. INTRODUCTION

IT IS WELL KNOWN [1] that direct modulation of semiconductor lasers is accompanied by optical frequency modulation (chirp) of the output light. This chirp has two main non-transient [1] components. The first is an almost instantaneous adiabatic frequency change (the so-called adiabatic chirp), which follows the current and is associated with the effect of the injection current on the refractive index of the cavity. Here, the laser frequency increases with the injection current and would not change in time unless the injection current does. The second component is a slower thermal effect, where the temperature increase, induced by the injection current, lowers the laser frequency. Here, the laser frequency does not maintain a one-to-one correspondence with the current but rather with the junction temperature. Thus, following a sudden increase of the injection current, the continuously increasing temperature results in a continuous exponential-like decrease of the optical frequency (from a new higher value set by the adiabatic chirp) until thermal equilibrium is achieved. Under low-frequency sinusoidal modulation of the injection current, the resulting thermal chirp is stronger than the corresponding adiabatic one but the latter remains effective until very high

modulation frequencies approaching the AM modulation limits of the laser [2]. On the other hand, the slower thermal chirp rolls off at a modulation frequency of ≈ 10 MHz [1], which is equivalent to a time constant of about 100 ns. However, recent experimental studies of the sequence dependence of phase-induced intensity noise in optical networks that employ direct modulation [3] clearly indicate the existence of significant frequency chirp, with a time constant of the order of 20 ns.

These recent experiments studied the effect of interferometric noise, generated at the output of the optical square-law detector by mixing two or more delayed replicas of the data sequence [4]. This performance-reducing noise is centered around the beat frequency between the two interfering waves, and therefore may be reduced by RF filtering, whenever this beat frequency falls outside the system electrical bandwidth. This behavior has been previously demonstrated using high-frequency phase modulation of the laser output, or, equivalently, by adding a chirp-generating signal to the data-carrying injection current [5]. But in a recent publication [6] it was shown that the thermal-like chirp directly reduces the interferometric noise without the need for any additional modulation. However, for this effect to be significant, the change in frequency during each bit must be at least several hundreds of megahertz, requiring the relevant frequency chirp time constant to be on the order of the bit length [6]. This effect was successfully demonstrated [3] for frequencies as high as 622 Mb/s, implying the existence of time constants much shorter than 100 ns.

The thermal time constants of semiconductor lasers were previously measured using a variety of experimental techniques [1], [7]–[15]. However, a time constant of the order of 10–20 ns has never been previously reported. In some cases, the time scale of interest was relatively long, and the measurement resolution was too low to notice a short time constant [1], [7]–[9]. As mentioned above, studies of the FM response of semiconductor lasers illustrated thermal time constants longer than 100 ns [2]. Being interested in frequency tuning for WDM applications, Saavedra *et al.* [10] reported fast and slow time constants of 48 μ s and 1.34 ms, respectively. In other cases, the FM response measurements were limited to the 100-kHz range or less [11]–[13]. Ogita *et al.* [14] estimated the thermal time constant using time-resolved spectra of multimode lasers under step modulation,

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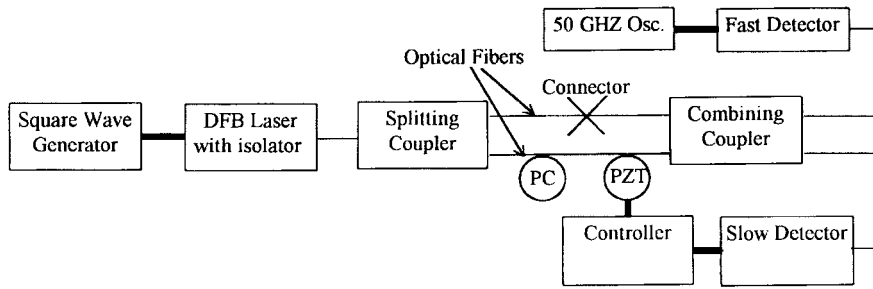


Fig. 1. Experimental setup for chirp measurements. PC: polarization controller; PZT: piezoelectric transducer. Optical and electronic connections are noted by thick and thin lines, respectively.

in which the power ratio of the first side modes is related to the active region temperature. However, this method could only be used after the first 50 ns of the response [14], resulting in a 160-ns estimate. Clark *et al.* [15], who measured the instantaneous optical frequency to a 1-ns resolution, were the first to point out that a single time constant could not describe the frequency chirp for the entire 1- μ s range, following a current step. Rather than introducing an additional time constant, Clark opted to model the heating process by a cylindrical heat wave generated from an active core of a finite diameter, spreading in a homogeneous medium. The resulting expression for the transient temperature as an integral of Bessel functions successfully explained the obtained experimental results [15], but may not hold for time scales beyond 10 μ s.

In this paper, the time-resolved optical frequency of DFB lasers under direct modulation was measured and the existence of a time constant in the range of 10–20 ns was directly verified for the first time. These measurements together with the experimental setup are described in Sections II and III. Section IV contains a numerical thermal analysis of a specific laser based on Nakwaski's formulation [16], predicting a thermal time constant of the order of 20 ns. This analysis indicates that the newly introduced short time constant could be of a thermal origin. In Section V, a semi-empirical approach that models the thermal chirp of a semiconductor laser as a sum of exponentials was proposed, having time constants ranging from tens of nanoseconds to many microseconds. The proposed approach uses a set of experimentally obtained chirp parameters to predict the exact optical frequency characteristics for any modulation sequence, from the nanosecond to the millisecond range. Using the suggested model and experimental technique, interferometric noise reduction capabilities of a specific laser can be calculated with no knowledge of its exact structural or thermal properties. Finally, Section VI discusses the effect of a short time constant on various applications.

II. EXPERIMENT

The temporal response of the optical frequency of five different DFB lasers under direct current modulation was measured using an all-fiber Mach-Zehnder interferometer, serving as a frequency discriminator (Fig. 1). While similar schemes have been built before [7], [17]–[19], this is the first all-fiber implementation having a temporal resolution of 30 ps [10], [20]–[21].

In order to understand the frequency discrimination of the setup, the electrical field of a DFB laser of intensity $I_0(t)$ and phase $\varphi(t)$ (derived from an instantaneous optical frequency $v(t)$) is expressed by

$$\begin{aligned} E(t) &= \sqrt{I_0(t)} \exp[j\varphi(t)] \\ &= \sqrt{I_0(t)} \exp \left[j2\pi \int_{-\infty}^t v(t') dt' \right]. \end{aligned} \quad (1)$$

When fed by the laser light $E(t)$, the interferometer output intensity is

$$\begin{aligned} I_{\text{out}}(t) &= |A_1 E(t) + A_2 E(t - \Delta\tau)|^2 \\ &= \left| A_1 \sqrt{I_0(t)} \exp \left[j2\pi \int_{-\infty}^t v(t') dt' \right] \right. \\ &\quad \left. + A_2 \sqrt{I_0(t - \Delta\tau)} \exp \left[j2\pi \int_{-\infty}^{t - \Delta\tau} v(t') dt' \right] \right|^2 \end{aligned} \quad (2)$$

where A_1 and A_2 depend on the coupling ratios of the two couplers and on losses along the two arms of the interferometer, and $\Delta\tau$ is the propagation time mismatch between the two arms. When $\Delta\tau$ is chosen to be short enough (28 ± 3 ps in our case), then for any modulation rate significantly shorter than 30 GHz ($\approx (\Delta\tau)^{-1}$), $I_0(t) \approx I_0(t - \Delta\tau)$ can be assumed, and (2) reduces to

$$\begin{aligned} I_{\text{out}}(t) &= S \cdot I_0(t) \left[1 + V \cdot \cos \left(2\pi \int_{t - \Delta\tau}^t v(t') dt' \right) \right] \\ &= S \cdot I_0(t) [1 + V \cdot \cos(2\pi \Delta\tau v_m(t))] \\ V_m(t) &= \frac{1}{\Delta\tau} \int_{t - \Delta\tau}^t v(t') dt' \end{aligned} \quad (3)$$

where S is a scaling factor and V is the interferometer visibility, which can be optimized through the use of the polarization controller. Again, for modulation rates much shorter than $(\Delta\tau)^{-1}$, $v_m(t) \approx v(t)$. When the induced frequency deviations are also much smaller than $(\Delta\tau)^{-1}$ and the interferometer is set at quadrature by the PZT phase modulator and its associated circuitry, the ac response of the interferometer under current modulation of the laser becomes

$$I_{\text{out}}(t) = S \cdot V \cdot I_0(t) \Delta\tau v_m(t) \rightarrow v_m(t) = \frac{1}{S \cdot V} \frac{I_{\text{out}}(t)}{I_0(t)}. \quad (4)$$

Once S , V , and $I_0(t)$ are experimentally determined, the frequency changes induced by $I_0(t)$ can be directly deduced

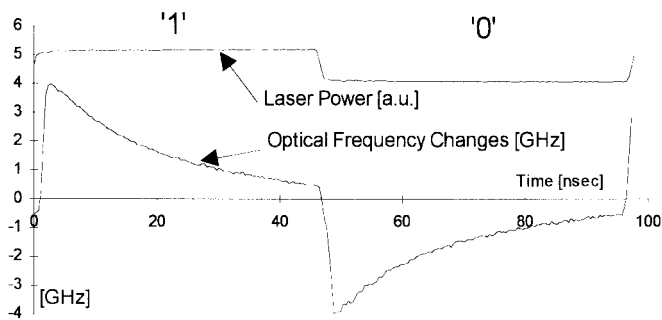


Fig. 2. Induced frequency changes in response to a 20 mA (p.t.p.) square wave modulation as a function of time for DFB laser #1. The optical power is also shown. Note that no transient chirp is observed for the given modulation.

from $I_{\text{out}}(t)$ using (4). The evaluation of (4) is much easier when square wave modulation is employed since only two values of $I_0(t)$ need to be measured.

III. EXPERIMENTAL RESULTS

A typical time evolution of the induced frequency changes in a 1.3- μm p-side-up buried heterostructure (BH) DFB laser in response to a square wave direct modulation is shown in Fig. 2, together with the optical power $I_0(t)$. The modulation index was smaller than unity so both the “1” and “0” bits represent nonzero optical powers. The frequency jumps at the rise and fall times of the square wave are due to the adiabatic chirp and a value of $C = 260$ MHz/mA was experimentally determined for the tested laser. At the power rise, the optical frequency jumps to a new value and then slowly decays as the junction heats up. Following the downward jump at the “1” \rightarrow “0” transition, the frequency rises as the junction cools.

The observed exponential-like behavior clearly indicates time constants of the order of 20 ns. Similar results were measured for four other 1.5- μm DFB lasers. All the experimental results will be presented in Section V in terms of our proposed model.

IV. THEORETICAL ANALYSIS

In this section it is shown that when the thermal properties of the active region itself are taken into consideration, a thermal analysis of a specific semiconductor laser structure qualitatively accounts for such a short thermal time constant as found in Section III. A modern semiconductor laser is a multilayered structure, sitting on a heat sink. The electrical current, which flows from the P-side to the N-side, creates population inversion in the central active layer, resulting in radiative (light) as well as in nonradiative (heat) recombinations of electrons and holes. This generated heat increases the temperature of the active layer, and the wavelength of the emitted light, being determined by both the physical size of the laser cavity and its refractive index, is thus altered. Quite often quoted is the detailed analytical study of Ito *et al.* [1] of the temperature step response of multilayered semiconductor lasers. Using a three-dimensional (3-D) analysis of heat flow in the chip, submount, and heat sink, as well as the full structural details and thermal properties of the various layers, the analysis predicts the thermal response of the active region

to a sudden (step) change of the injection current. The obtained temperature response for the specific GaAs laser studied in [1] is described in terms of three time constants: the fastest (600 ns) is that of the chip while the rest (20 μs , 2.3 ms) are those of the submount and heatsink, respectively. The model does not include time constants shorter than 600 ns. Experimentally, Ito *et al.* [1] measured the step response of the optical frequency, which is proportional to the temperature of the active layer. While the numerical results of [1] show, in general, excellent agreement with the experiment, some deviations exist at the first 200 ns of the pulse, where the experimental temperature increase is larger than predicted. These deviations can be corrected by introducing a short time constant. Note, though, that Ito *et al.* [1] have treated the active layer merely as a heat source, having no thermal capacitance.

Both the thermal capacitance and thermal conductivity of the active layer were taken into consideration in the analysis performed by Nakwaski, who presented [16] a simplified analytical expression for the two-dimensional (2-D) (parallel to the emitting surface) temperature transient of a stripe geometry double heterostructure laser. The author assumed a standard structure, with a GaAs active stripe in between N-(AlGa)As and P-(AlGa)As passive layers. Heat exchange through the side and top walls of the chip is considered negligible in comparison with the flow to the infinite heatsink. The main heat source in the laser chip is the nonradiative recombination and radiation reabsorption in the active region, which increases linearly with current density. For the considered structure, Joule heating of the various layers can also be neglected. When a current pulse is short enough, the temperature profile of the active region is not affected by the thermal properties of remote layers. For the structure considered in [16], this assumption holds for pulses shorter than 0.5 μs . The current density is assumed to be laterally confined to the stripe width.

The above assumptions were used in [16] to solve the 2-D heat conduction equation and analytically calculate the temperature step response of the active region. The equation is solved using a space transformation, replacing the heterostructure of the active stripe and the adjacent layers by a thermally equivalent (AlGa)As homostructure. The solution is further simplified by using the thermal conductivity of (AlGa)As for the entire structure. This substitution results in growing inaccuracies as we move away from the active region and for long current pulses. However, it has little effect on the temperature profile of the active region at the first 0.5 μs of the pulse.

Using [16, eq. (51)], the development of the temperature per unit heat power density as a function of time at the center of the active region following a current step was calculated. Results for a time span of 0–150 ns are presented in Fig. 3. The geometrical structure parameters and thermal conductivities of the various layers were taken from [16], and the value for the thermal diffusivity, not mentioned in [16], was taken from [1].

The results of Fig. 3 clearly indicate the existence of a time constant far shorter than 100 ns, thereby theoretically corroborating our experimental results of Section III. This general agreement with experiment, however, is by no means a proof of the thermal origin of the short time constant. In the

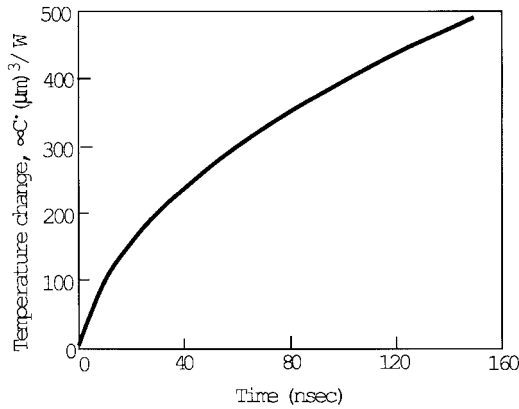


Fig. 3. Theoretical calculations of the active region temperature change of a stripe double heterostructure laser during a short current pulse.

next section, a semi-empirical model of the frequency chirp will be developed, in terms of a simplified one-dimensional (1-D) thermal analysis. The impulse response to be obtained from this model can be used to describe the optical frequency chirp, regardless of the specific mechanism producing the short time constant.

V. ANALYTICAL SEMI-EMPIRICAL MODEL

The exact magnitude of the thermal chirp of the laser can be obtained from a detailed calculation of the temperature distribution in the chip, taking into account all the relevant thermal constants of the various layers of the laser [1], [16], [22]. However, this formulation is too complicated to be used for the prediction of laser chirp or its noise reduction capabilities. Moreover, detailed knowledge, not normally available, of the exact different layer parameters is required. To alleviate these problems, a semi-empirical 1-D model, which expresses the step response of the thermal chirp of a DFB laser as a sum of a few exponentials, is developed here. Such an approach has been used before to describe the thermal step response of the active region in terms of several time constants [1], [7]–[14], [23], only one of which is associated with the chip itself. Innovatively, we claim that the thermal step response of the chip should be described by more than one time constant, with the shorter one of the order of 20 ns or less.

The thermal model assumes that through nonradiative transitions, the injected current heats the active layer, which then feeds its heat to a constant temperature heatsink via a number of passive layers. The temporal behavior of this thermal model is governed by a linear differential equation of the N th order (where N is the number of layers excluding the heatsink); therefore, the temperature response of the active layer to a current impulse is a weighted sum of N exponents (T_A is the temperature of the active layer before the current impulse is applied, as well as after its effect has decayed)

$$h_T(t) = T_A(t) - T_A \Big|_{\text{current impulse}} = \sum_{n=1}^N a_n \cdot \exp\left(-\frac{t}{\tau_n}\right), \quad \tau_1 < \tau_2 < \dots < \tau_n. \quad (5)$$

Both a_n and τ_n can be determined if the laser structure and the thermal characteristics of its constituent layers are known in detail. Alternatively, they can be estimated from a set of measurements, to be described below. Once $\{a_n, \tau_n, n = 1, \dots, N\}$ are known, the effect of a given input current can then be calculated through a convolution of (5) with the input waveform. For very high bit-rate inputs, having a bit length much shorter than τ_1 [the shortest time constant in (5)], all terms with $n > 1$ can be ignored. As the bit rate slows down, more and more terms are required for an accurate estimation of the effect of the input current on the temperature of the active layer.

While the temperature of the active layer cannot be measured directly, its temporal behavior can be deduced from the dynamics of the laser optical frequency ν , composed of the adiabatic and thermal chirp contributions. While the adiabatic term is proportional to the temporal injected current, the thermal chirp follows the junction instantaneous temperature, which, in turn, could be given by a convolution of the modulating current sequence and the experimentally obtained impulse response. Therefore, an increase $\Delta i(t) \approx i(t) - i_0$ in the injection current will lead to a frequency change of the form

$$\begin{aligned} \nu(t) - \nu_0 &= B_A(t(t) - i_0) - B_T(T_A - T_0) \\ &= B_A(i(t) - i_0) \\ &\quad - B_T \cdot \text{convolution}[h_T(t), (i(t) - i_0)] \quad (6) \end{aligned}$$

where both B_A and B_T are positive constants, describing, respectively, the coefficients of adiabatic and thermal chirps.

To check the validity of this model, the frequency change along one bit when the laser is square wave modulated at different bit rates is highlighted. Such a measure of the chirp is not affected by the adiabatic contribution. The thermally induced optical frequency dynamics are obtained by a convolution of the impulse response of (5) with a modulating square wave, as expressed in (6). The resulting frequency change along a single bit would be

$$\begin{aligned} \Delta \nu_{\omega_1}(t_0) &= -\Delta \nu_{\omega_0}(t_0) \\ &= B_T \cdot I_0 \sum_{n=1}^N a_n \tau_n \cdot \tanh\left(-\frac{t_0}{2\tau_n}\right) \quad (7) \end{aligned}$$

where I_0 is the amplitude of the current modulation. By measuring and plotting $\Delta \nu_{\omega_1}(t_0)$ versus t_0 , one can determine the various τ_n and their corresponding coefficients $B_T \cdot a_n$. Experimental results for a wide range of bit lengths (5 ns to 50 μ s) are shown in Fig. 4 for the same DFB laser mentioned in Fig. 2. It should be noted that $\Delta \nu_{\omega_1}(t_0)$ was experimentally found to depend linearly on I_0 , thereby substantiating one of our basic assumptions.

Fitting the experimental results to (7) with $N = 4$ produces excellent results, as shown in Fig. 4, and proves the existence of four time constants: $\tau_1 = 16.8$ nS, $\tau_2 = 366$ nS, $\tau_3 =$

TABLE I
SUMMARY OF EXPERIMENTALLY FIT PARAMETERS FOR THE THERMAL RESPONSE OF FIVE
TESTED DFB LASERS: FIRST TWO TIME CONSTANTS AND RESPECTIVE COEFFICIENTS

Laser	Lowest modulation frequency [Mb/s]	Wavelength [nm]	τ_1 [ns]	τ_2 [ns]	$V_{\max}(\tau_1) \frac{\text{GHz}}{10 \text{ mA}}$	$V_{\max}(\tau_2) \frac{\text{GHz}}{10 \text{ mA}}$
#1 p-up BH	0.05	1300	$16.8 \pm 10\%$	$366 \pm 10\%$	$2.5 \pm 6\%$	$3.4 \pm 6\%$
#2 p-up BH	2	1550	$20 \pm 15\%$	$> 100 \pm 25\%$	$1.8 \pm 15\%$	$> 4.8 \pm 20\%$
#3 MQW	2	1547	$11 \pm 15\%$	$> 110 \pm 25\%$	$1.4 \pm 15\%$	$> 4 \pm 20\%$
#4 p-down BH	4	1558	$19 \pm 15\%$	$> 220 \pm 25\%$	$1.2 \pm 15\%$	$> 1.1 \pm 20\%$
#5 p-up BH	1	1537	$18 \pm 15\%$	$> 190 \pm 25\%$	$3 \pm 15\%$	$> 1 \pm 20\%$

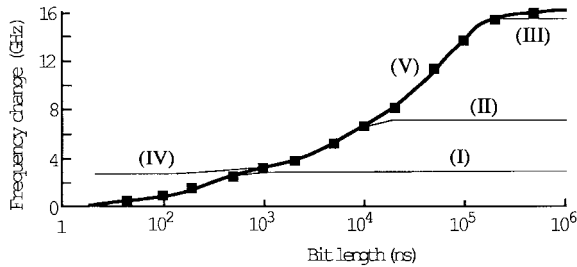


Fig. 4. Thermal frequency changes along one bit $|\Delta v_{-1}|$ of laser #1 under square wave direct modulation as a function of bit length. (■) represents experimental results and the different curves are the result of an exponential fit using various combinations of the time constants $\tau_1 - \tau_4$. (I): τ_1 only; (II): τ_1 and τ_2 ; (III): τ_1, τ_2 and τ_3 ; (IV): τ_2, τ_3 and τ_4 ; (V): $\tau_1 - \tau_4$. Peak to peak current amplitude was 10 mA.

4.1 μS , $\tau_4 = 20 \mu\text{S}$ and an expression for $\Delta v_{-1}(t_0)$

$$\begin{aligned} \Delta v_{-1}(t_0) \left[\frac{\text{GHz}}{10 \text{ mA}} \right]_{\text{thermal}} &= 2.5 \cdot \tanh \left(-\frac{t_0}{2 \times 16.8 \text{ nS}} \right) \\ &+ 3.4 \cdot \tanh \left(-\frac{t_0}{2 \times 366 \text{ nS}} \right) \\ &+ 9 \cdot \tanh \left(-\frac{t_0}{2 \times 4100 \text{ nS}} \right) \\ &+ 0.9 \cdot \tanh \left(-\frac{t_0}{2 \times 20000 \text{ nS}} \right). \end{aligned} \quad (8)$$

Fig. 4 also shows the predicted dependence of $\Delta v_{-1}(t_0)$ on t_0 when only partial sums of (8) are used. Evidently, if only very high bit rates ($t_0 < \tau_1$) are of interest, approximating the impulse response by its first term may prove sufficient (as in [3]). As t_0 increases, more and more terms are required for an accurate description of the thermal chirp of the laser. On the other hand, the 16.8-nS time constant is of no importance if attention is limited for $t_0 > 100$ ns (as in [1]). Also, the 20- μs time constant most probably describes the thermal role of the submount [1].

Similar results were obtained when the same model was applied to four additional lasers in the 1.5- μm range. The time constants that were found are summarized in Table I along with the respective frequency changes. One of the lasers, having relatively low power output, required the use of an optical amplifier before the interferometer. Another laser was tested with and without an amplifier, in order to make sure the amplifier does not affect the obtained results. The modulation rates used in the last four lasers were limited at the lower

cutoff by the highpass nature of the electronic driver circuitry of the laser. The lowest modulation rates applied were 2 Mb/s (laser #2), 2 Mb/s (laser #3), 4 Mb/s (laser #4), and 1 Mb/s (laser #5). Thus, no information about time constants above 200 ns could be obtained and the accuracy of the longer time constant was not as high as for laser #1.

The same approach was also used to characterize the theoretical curve of Fig. 3. Using only two time constants, we obtain

$$\begin{aligned} T \left[\frac{\text{deg}}{\text{W/cm}^3} \right] &= 92 \left[1 - \exp \left(-\frac{t[\text{ns}]}{8.5} \right) \right] \\ &+ 670 \left[1 - \exp \left(-\frac{t[\text{nsec}]}{170} \right) \right] \end{aligned} \quad (9)$$

with an average error of only 1%. Curve-fitting with a time constant longer than 50 ns results in errors exceeding 10%. These results further substantiate the claim that the observed short time constant in the measured optical chirp is of thermal origin.

VI. DISCUSSION

As previously mentioned, the short time constant reported here could be due to the nonzero thermal capacitance and finite conductivity of the active region of the laser [15], heated by the nonradiative processes. Since laser FM is controlled by quite a few physical mechanisms, it may well be the case that some other mechanism such as diffusion of carriers away from the active region could also contribute to the gradual decrease of the optical frequency following the rise time of the current pulse [24]. While the diffusion of carriers must also introduce optical intensity changes with similar time constants, so far undetected, one should note that the observed frequency changes are of the order of 10^{-4} of the central frequency. Intensity changes of the same order would be very difficult to determine experimentally.

As can be seen from Table I, the value of the shortest time constant obtained for the MQW laser is considerably shorter than those of the four tested BH devices, which display very little diversity. These results suggest that the value of the shortest time constant apparently depends on the detailed structure of the diode in the vicinity of the active region. Assuming a thermal mechanism, the time constant would be related to the thermal capacitance of the active region and the conduction of heat to the adjacent layers, where a shorter time constant corresponds to a smaller capacitance and a higher conductivity. On the other hand, all the experimentally

measured short constants are of the same order of magnitude, and therefore, a complete physical understanding of the effect and its dependence on the laser fine structure requires further research.

The practical importance of the short time constants is application-dependent, as proposed by Fig. 4. Following are some examples.

- 1) *Unwanted FM in direct communication systems*: Here the FM broadens the linewidth. Looking back at (8) and Fig. 4, we see that thermal FM is mainly contributed by those terms with relatively long time constants. Indeed, the thermal contribution to the FM response above 10 MHz, i.e., the first term in (8), is overshadowed by the adiabatic contribution and would hardly be detected. Thus, the time constants of importance for these applications are of the order of a few hundred nanoseconds.
- 2) *FM of directly modulated lasers in coherent communication systems*: This FM is beneficial in frequency-shift-keying systems, where efforts were made to flatten the FM response [1]–[2], [19], [25]–[27]. Again, significant contributions to thermal chirp are characterized by relatively long time constants of the same order of magnitude as above.
- 3) *Optical frequency-domain reflectometer (OFDR) [8], [28]*: A ramp waveform drives the laser to ideally produce a linear sweep of the optical frequency. The unavoidable thermal chirp introduces nonlinearities, which have to be compensated for. The related literature quotes time constants in the microsecond range.
- 4) In wavelength switching of DFB and DBR lasers for WDM systems [10], [29], the reported time constants exceed a few hundred nanoseconds.
- 5) *Laser frequency stabilization [12]*: When locking lasers to reference frequencies, dynamic control of the laser frequency can be achieved via thermal frequency modulation of the laser. Time constants of 3 μ s were reported [12] and when modulating the injection current at low frequency, the thermal chirp may introduce a phase shift in the control circuitry.
- 6) In combating interferometric noise in communication systems, having an RF bandwidth of a few gigahertz, the first term in (8) is important enough to significantly reduce the overall system noise [6]. Nevertheless, short time constants should be taken into considerations in all applications when the time resolution is in the nsec range and frequency deviations of a few GHz are important.

VII. CONCLUSIONS

The optical frequency chirp of DFB lasers and other semiconductor narrow-linewidth emitters can be described by a multitude of time constants. For the DFB lasers tested here, the shortest time constant was 11 ns and is possibly due the thermal response of the very thin active region to nonradiate heating processes. The complete dynamic behavior of these lasers can be modeled by an impulse response, which is the sum of several exponents, each having a different time constant. The values of these time constants depend on the

exact structure of the laser and range from tens of nanoseconds to many microseconds. The number of time constants needed for a particular application depend on the time range and resolution of the measurements. A model comprising four time constants produced an excellent fit to the measured optical frequency deviations of a directly modulated DFB laser along the modulating bit, for bits ranging in length from a few nanoseconds and up to 100 μ s. Only two time constants are required when the range of bit lengths is limited to 1 μ s. The existence of such a short time constant should be important in various wide bandwidth applications of semiconductor lasers, especially in the suppression of interferometric noise in modern fiber optic networks.

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