Analysis of Optical-Injected Distributed Feedback Lasers Using Complex Optical Low-Coherence Reflectometry

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***Abstract*—A theoretical and experimental investigation of reflectograms obtained for a distributed feedback (DFB) semiconductor laser using a phase-controlled high-resolution optical low-coherence reflectometer was carried out, yielding the effective group refractive index and its variation above threshold, the cavity internal loss, as well as the grating coupling factor of a multiquantum-well DFB laser. In addition, direct measurements of the injection-induced complex-modal index changes are presented for the first time.**

***Index Terms*—Distributed feedback (DFB) lasers, linewidth enhancement factor, optical injection, optical low-coherence reflectometry (OLCR).**

I. Introduction

OPTICAL low-coherence reflectometry (OLCR) has proven to be a successful technique to determine spatially and spectrally resolved parameters in passive optical devices [1]. More recently, OLCR simulations for active photonic devices have been proposed [2] and encouraging novel measurements have been reported [3]. The complex reflectivity of the device under test can be measured by precisely controlling the optical path difference between the two arms of the interferometer, thus, enabling exact determination of spatial phase shifts and spectral characteristics such as chromatic dispersion, group delay, and gain properties.

The OLCR technique is proposed here to fully characterize active devices under operation. External optical injection in these devices is important for new all-optical functions such as remote generation and control of RF signals using distributed feedback (DFB) lasers, 3R regeneration, multiwavelength conversion in semiconductor optical amplifiers, and high-speed dispersion compensation. It is interesting then to explore new and direct characterization techniques of optical injection effects. After a theoretical and experimental investigation of reflectograms obtained for a DFB semiconductor laser without injection, optically induced gain and index changes by injection locking are measured and discussed for the first time. Among other results, it is shown that the linewidth enhancement factor can be directly deduced from the OLCR measurements.

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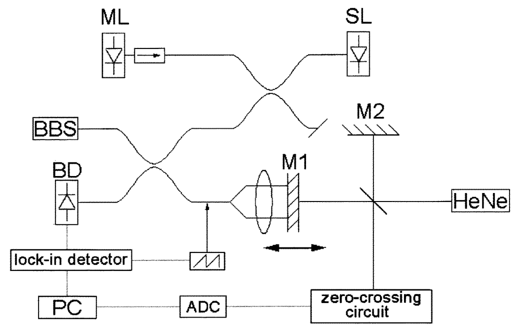

Fig. 1. Simplified scheme of the OLCR setup for measuring the reflectogram of a DFB laser [slave laser (SL)] optically injected by a master laser (ML).

II. Experimental Procedure

The experimental setup shown in Fig. 1 represents the OLCR used to measure an externally optical-injected DFB laser (SL). The OLCR is a scanning Michelson interferometer illuminated by a broad-band source (BBS) with the device under test at one arm. The spontaneous emission of an Er^{3+}-doped fiber amplifier is used as the BBS. The reflectometric signal detected at the low-noise p-i-n field-effect transistor balanced photodetector (BD) corresponds to the generated interference fringe pattern. Interferences only occur where this difference is less than the BBS coherence length. The corresponding spatial resolution is $\Delta l = 18$ μm in air. In order to track the reference mirror (M1) displacement, and hence, the scanning position, a coherent interferometer signal is used as a zero-crossing clock allowing to sample the OLCR data at uniform spatial intervals as it is recorded in a computer (PC). The 632.8-nm He–Ne laser wavelength of the coherent interferometer determines a 316.4-nm sampling period. All measurements were performed with a scanning distance slightly longer than the optical length of the laser cavity. To reduce noise in each reflectogram, four sets of measured data were averaged giving an excellent resolution due to the precise control of the motor position.

The semiconductor lasers used on these experiments are 1550-nm Alcatel index-coupled multiquantum-well DFB (MQW-DFB) lasers. Their structure, shown in the insert of Fig. 2, consists of a straight section containing the Bragg grating and a tapered section that operates as a spot-size converter to improve the fiber–laser coupling [4]. The physical lengths of the laser sections measured with an atomic-force microscope are 345 and 135 μm, respectively. In the tapered section, the width of the active MQW layer linearly decreases as the passive waveguide underneath it increases. In this manner, the optical

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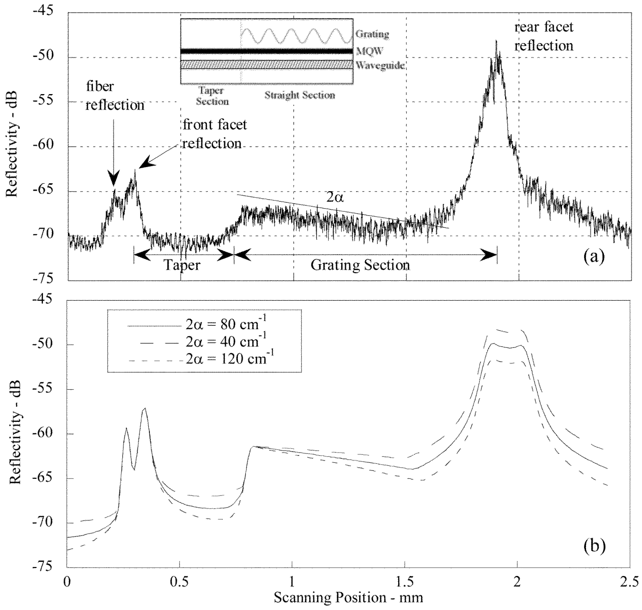

Fig. 2. (a) Measured and (b) calculated amplitude reflectogram of the free-running unbiased laser. Insert: structure used to calculate the reflectivity coefficient of the laser as seen from the fiber–air interface. α is the absorption coefficient of the device.

mode is transferred from the active MQW layer to the passive waveguide.

III. Results and Discussion

Using the coupled-mode theory of DFB lasers [5] and following the method in [6], the equivalent reflectivity $r_{\text{eqv}}(\omega)$ as viewed from the fiber–air interface was calculated including the facet and section reflectivities. The reflectivity $r_{\text{eqv}}(\omega)$ and the OLCR reflectogram $R_{\text{eqv}}(\tau)$ of the device form nearly a Fourier-transform pair given by $R_{\text{eqv}}(\tau) = \Re\{\int_{-\infty}^{+\infty} S(\omega) r_{\text{eqv}}(\omega) e^{jwr} d\omega\}$, where $S(\omega)$ is the power spectral density of the BBS and τ is the interferometer delay. This delay is associated to the scanning position $x_{\text{opt}} = \tau \cdot c$ used to obtain the spatially distributed reflectivity of the device $R_{\text{eqv}}(x_{\text{opt}})$. A Hilbert transform is applied to the measured OLCR data to obtain the complex envelope. This is possible because the OLCR data is sampled at constant spatial intervals, thus, providing exact localization of reflections inside the laser structure.

The reflectograms depicted in Fig. 2 represent the measured and calculated OLCR data for the free-running laser biased at 0 mA. The fiber and front facet reflection peaks can be clearly identified and are separated by 79 μm. The tapered and grating sections of the laser are distinguished and their optical length is measured to be 452.25 and 1155.75 μm, respectively. These values were corroborated on four sets of averaged data, thus, confirming the accuracy of the measurement. The effective group refractive index is obtained ($\sim$3.35) as the ratio of the total optical length L_{opt} of the device and the physical length L_{phy}. The slope 2α of the reflectogram in the grating section is due to absorption losses of the injected light in the unbiased active section. The corresponding reflectogram was calculated for several values of the cavity loss [Fig. 2(b)]. It was found that in the grating section, the loss is nearly equal to half the slope

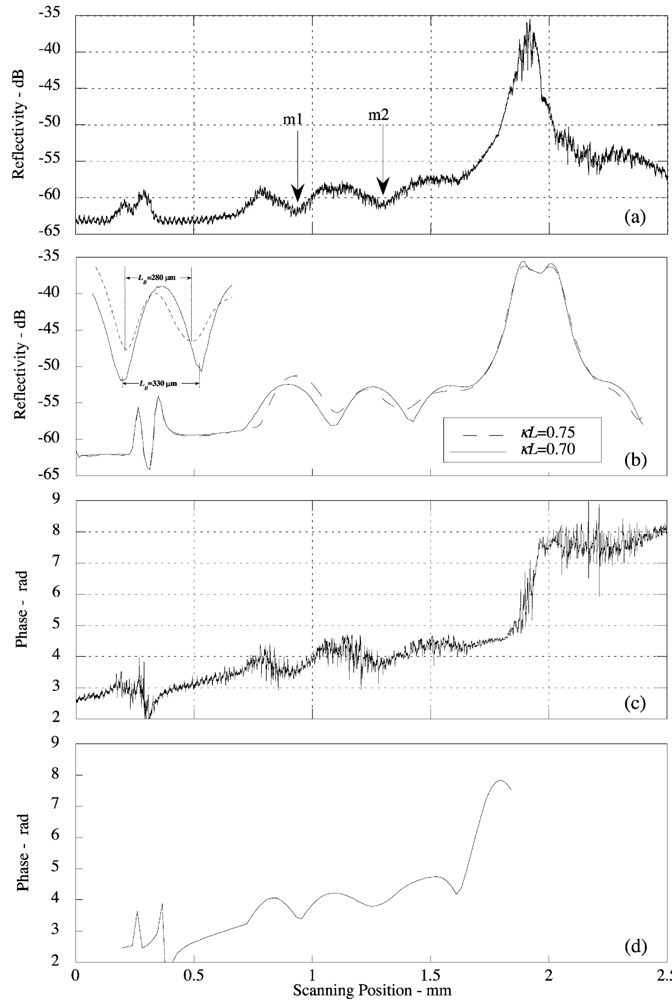

Fig. 3. (a) Measured and (b) calculated amplitude reflectograms of the free-running laser biased above threshold and their corresponding (c) measured and (d) calculated phase reflectograms.

observed and it is measured to be 6 dB/mm for a biasing current of 0 mA. This corresponds to a loss coefficient of 40 cm^{-1}.

The amplitude and phase reflectograms obtained for a free-running laser biased just above threshold are shown in Fig. 3. The difference between two consecutive minima (m1 and m2) is known as the beat length (L_B) and can be used to calculate the refractive index modulation of the grating $\Delta n_{p-p} = \lambda_0/2L_B$ [7], where Δn_{p-p} is the peak to peak value and λ_0 is the emission wavelength. The origin of the beat length is the existence of counterpropagating waves in a medium with an index difference. This was confirmed by numerically investigating the beat length obtained for different values of the grating coupling factor $\kappa = \pi \Delta n_{p-p}/2\lambda_0$ [Fig. 3(b)]. A beat length of 365 μm was measured from the OLCR data [Fig. 3(a)], yielding a coupling factor $\kappa = 21$ cm^{-1} very closely to the $\kappa = 20$ cm^{-1} value provided by the stopband width measurement. The phase reflectograms, shown in Fig. 3(c) and (d), may be used to obtain the complex coupling factor $\tilde{\kappa}$ in the case of gain-coupled lasers.

When an external optical injection is applied to a semiconductor laser, the complex refractive index undergoes a change inducing a variation of the emission frequency [8]. The imaginary part variation $\Delta n'' = (\lambda_0/2\pi) \cdot \Delta g$ is described by

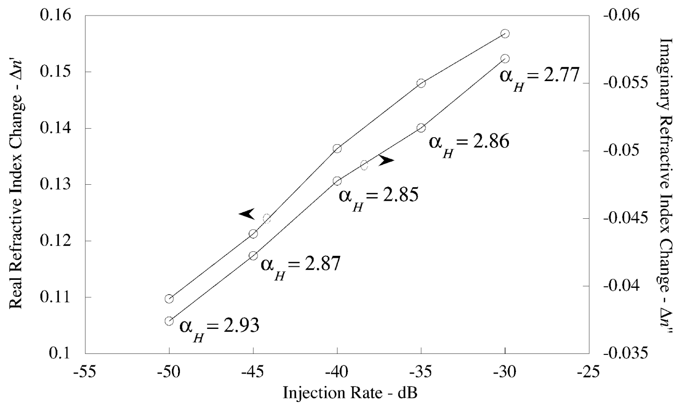

Fig. 4. Complex index changes due to optical injection for different injection rates.

a net gain change Δg that is different from the cavity losses. The linewidth enhancement factor α_H, describing the coupling between the real and imaginary parts of the carrier-dependent refractive index changes, is simply defined by the ratio of their partial derivatives with respect to carrier density. Assuming small variations of the carrier density, the injection-induced gain change is then accompanied by a steady-state variation of the real refractive index $\Delta n' = -\alpha_H \Delta n''$.

Direct analysis of the OLCR measurements permits the determination of both, the real and imaginary parts of the refractive index changes due to external optical injection of a DFB laser, thus, yielding the linewidth enhancement factor α_H. The injection conditions imposed to the SL by the ML are chosen so as to ensure operation in a locked state. This means that locked oscillations at the ML frequency overcome amplification of spontaneous emission at the free-running frequency. The effect of external injection on the OLCR results manifests in two ways. On the one hand, an optical length change $\Delta L_{\rm opt}$ is observed, thus, providing a mean to obtain the optically induced modification of the real refractive index $\Delta n' = \Delta L_{\rm opt}/L_{\rm phy}$. On the other hand, the logarithmic difference between the injected and free-running laser reflectograms determines the injection-induced net gain change Δg in decibels [9]. The imaginary part of the refractive index change is then straightforwardly obtained for the emission wavelength λ_0. Fig. 4 represents the measured variation of the complex refractive index as a function of the injection rate for a small frequency detuning (~500 MHz). A mean linewidth enhancement factor $\alpha_H = 2.86$ is obtained in full agreement with measurements made with a Mach–Zehnder interferometer technique based on small signal modulation [10]. For the theoretical calculation of the reflectogram, the reflectivity of the front facet was substituted with the equivalent facet reflectivity to include the optical injection conditions [11]. This induced a change of the net gain and of the optical length in the cavity, assuring a correspondence with experimental conditions.

The significance of the α_H-parameter estimation may be questioned because it is well known that it has a high dispersion [12]. The α_H parameter obtained corresponds to an averaged effective value given by $\alpha_{H,\rm meas} = 1/\Delta\omega \int_{-\infty}^{+\infty} \alpha_H(\omega) S(\omega) r_{\rm eqv}(\omega) d\omega$, where the product $S(\omega) r_{\rm eqv}(\omega)$ can be considered as the linear response of a narrow-band filter with a $\Delta\omega$ bandwidth determined by the structure and operating conditions of the laser. As a consequence, only the BBS wavelengths around the emission wavelength λ_0 are reflected from the SL back into the OLCR setup, thus, minimizing the uncertainty on the α_H estimation.

IV. Conclusion

It has been shown that the OLCR technique is a versatile method for determining active device parameters such as the linewidth enhancement factor or the grating coupling coefficient otherwise accessible only by measurements coming from separate optical setups. For a DFB laser, theory and experiments were reconciled yielding realistic values of the cavity loss, group refractive index, and grating coupling factor. More importantly, the OLCR measurements provided direct access to modal parameters, simultaneously including effects from the material, waveguide, spatial hole burning, etc., with appropriate modal distribution averaging. Particularly, precise determination of the complex-modal index changes permitted an estimation of the linewidth enhancement factor.

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