Measurement of Gain in Pump Diode Lasers Using a Low-Coherence Source and Synchronous Detection

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***Abstract*—A novel method for determining gain in long-cavity Fabry–Pérot diode lasers is presented. Gain is extracted from a return-loss measurement via a simple model. The experimental setup is based on the injection of a low-coherence probe signal into the laser cavity and synchronous detection of the reflected light. Using a fiber-optics setup, gain can be determined in commercial fiber-coupled laser modules. The novel technique is particularly suitable for diode lasers with very long cavities. To illustrate the method, the gain spectra of a 980-nm pump diode laser with 1800-μm cavity length are determined. Gain saturation due to probe signal injection is addressed.**

***Index Terms*—Fabry–Pérot pump diode laser, fiber optics, gain saturation, modal gain, modeling, return loss, synchronous detection.**

I. Introduction

THE optical gain is undoubtedly one of the most important parameters in semiconductor lasers and semiconductor optical amplifiers (SOAs) and, as such, has been the subject of numerous extensive studies in the past. The most popular method for *measuring* the spectral gain in Fabry–Pérot diode lasers was introduced by Hakki and Paoli during the 1970s [1], [2]. The gain spectrum is determined from the laser spontaneous emission, which is spectrally modulated by the cavity resonances. The modes are traced with the help of a high-resolution monochromator. A modification of this technique that puts less stringent requirements on wavelength resolution was presented by Cassidy [3]. In this regard, modern diffraction-grating-based optical spectrum analyzers (OSAs) provide up to 0.01-nm resolution, depending on wavelength. As a rule of thumb, having in mind that the mode spacing scales with the inverse of the cavity length, it can be said that Hakki–Paoli's and Cassidy's methods work well when the laser cavity length is in the submillimeter range.

Several other methods extract the gain from the spontaneous emission spectrum and do not require high wavelength resolution, but they are more complicated to apply than Hakki–Paoli's or Cassidy's methods and, thus, are less commonly used [4], [5].

Today's diode laser modules for pumping erbium-doped fiber amplifiers (EDFAs) at 980-nm wavelength provide output powers of several hundreds of milliwatts [6]. The laser cavity length in these high power devices may be several millimeters, meaning that the mode spacing is very low. For instance, for state-of-the-art diode lasers with an approximate cavity length of 2 mm, the mode spacing is only 0.06 nm. In these conditions, the gain cannot be determined correctly with Hakki–Paoli's or Cassidy's techniques.

This paper presents a novel method for measuring gain in 980-nm pump modules and other long-cavity Fabry–Pérot lasers. A low-coherent probe signal is injected into the diode laser, and the reflected signal measured via synchronous detection. The gain can be determined subsequently from the output-to-input power ratio (i.e., the return loss) by means of a simple model. The method is comparable to the techniques commonly used for measuring gain in SOAs [7]–[9], which make use of a tunable laser probe source and detect the transmitted light.

This paper is organized as follows. The model presented in Section II shows that laser gain can be determined from a return-loss measurement. Section III introduces the experimental setup used to measure return loss. Section IV illustrates the method with an example. Several return loss and gain spectra of a 980-nm pump diode laser are shown. Section V is devoted to the conclusions.

II. Model

This section derives a mathematical relationship between the return loss and the gain in a Fabry–Pérot diode laser. Fig. 1 represents schematically the type of diode laser device used in the experiment. It is a high-power laser module with a long cavity (i.e., $L = 1800$ μm), commonly used for pumping EDFAs at 980 nm, mostly in combination with an external fiber Bragg grating (FBG). The FBG provides feedback for wavelength locking [6].

As seen in Fig. 1, the reflected light from the diode laser P_{out} consists of the reflection at the laser front facet and multiple round-trip reflections inside the laser cavity. The light is assumed transverse electric (TE) or transverse magnetic (TM) polarized. When the various contributions are added in power, the ratio Q between reflected and injected power reads

$$\begin{aligned} Q(\lambda) &\equiv \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} \\ &= \kappa R_2 + \eta^2 \frac{(1-R_2)^2}{R_2} \\ &\quad \times \sum_{q=1}^{\infty} \left(R_1 R_2 \exp\left\{(\Gamma g(\lambda) - \alpha)\, 2L\right\}\right)^q . \end{aligned} \quad (1)$$

Manuscript received April 29, 2003; revised August 13, 2003.

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Digital Object Identifier 10.1109/JLT.2003.822711

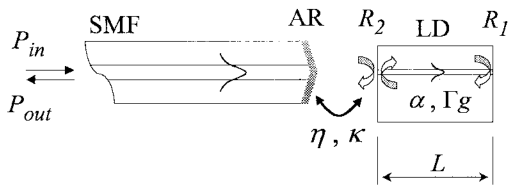

Fig. 1. Schematic of a fiber-coupled pump diode laser. P_{in} and P_{out} are the probe input and output power levels, respectively. The SMF is a single-mode optical fiber with an antireflection (AR)-coated fiber lens on the chip side. LD is the laser diode with the cavity length L, the facet reflectivities R_1 and R_2, the internal loss α, and the modal gain Γg. η and κ stand for coupling efficiencies, as explained in the main text.

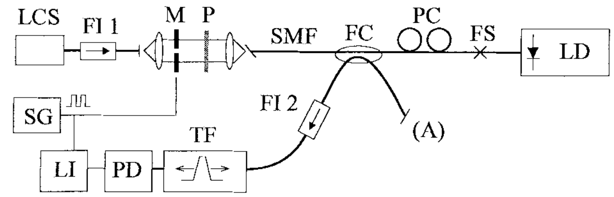

Fig. 2. Return loss experimental setup. LCS: Unpolarized, low-coherence source. FI 1, 2: Polarization-independent fiber-coupled isolators. M: Modulator. P: Polarizer. SMF: Single-mode fiber. FC: Fiber coupler. PC: Polarization controller. FS: Fiber splice. LD: Laser diode. SG: Signal generator. LI: Lock-in amplifier. TF: Tunable filter. PD: Photodetector.

R_1 and R_2 are the laser back and front facet power reflectivities for the selected polarization, L is the cavity length, α is the internal loss per unit length, and Γg is the wavelength-dependent (TE or TM) modal gain per unit length. Γg is the product of the mode confinement factor Γ and the material gain g. η is the power coupling efficiency between the guided mode in the SMF and the diode-laser single-mode waveguide. κR_2 is the part of reflected light at the laser front facet that is coupled back into the SMF. The ratio between reflected and injected probe power is related to the return loss by $RL_{\text{dB}} \equiv -10\log_{10}(Q)$.

Equation (1) was derived by summing up the various reflections in power, that is, regardless of the phase. This approach needs to be clarified. Using the scattering matrix method [10], which takes account of the phase, it can be shown (set $\kappa = 1$, $\eta = 1$) that the power ratio Q in (1) is the *average* value over an integer number m of cavity modes, i.e.,

$$Q \stackrel{!}{=} \left\langle \frac{P_{\text{out}}}{P_{\text{in}}} \right\rangle_m \equiv \frac{1}{\frac{m\pi}{L}} \int_{\frac{m\pi}{L}} |S_{22}|^2 d\beta \tag{2}$$

where π/L is the mode spacing in β-space, and S_{22} is the input–output scattering coefficient related with the laser front facet.

Experimentally, it is difficult to measure the average power ratio Q accurately. The maximum relative error in measuring Q due to incorrect integration limits amounts to $1/2m$. It is produced when the integration extends between $m + 1/2$ modes instead of m modes. By taking the average over many modes (large m), this error can be reduced so to have minor impact on modal gain. In this respect, note that in writing (2), the gain and the probe spectral power were assumed constant over the integration width, which is a valid assumption only over a limited number of modes.

When

$$\Gamma g < \alpha + \frac{1}{2L} \log\left(\frac{1}{R_1 R_2}\right)$$

the geometric series in (1) converges so that

$$Q = \kappa R_2 + \eta^2 \frac{(1-R_2)^2}{R_2} \frac{R_1 R_2 \exp\{(\Gamma g - \alpha)2L\}}{1 - R_1 R_2 \exp\{(\Gamma g - \alpha)2L\}}. \tag{3}$$

Equation (3) provides a direct relationship between return loss and gain. Solving for the laser modal gain Γg yields

$$\Gamma g = \alpha + \frac{1}{2L} \log\left\{\frac{1}{R_1 R_2}\right\} - \frac{1}{2L} \log\left\{1 + \frac{\frac{\eta^2(1-R_2)^2}{R_2}}{Q - \kappa R_2}\right\}. \tag{4}$$

The modal gain is the sum of the internal and mirror losses, complemented by a third term, which describes the amplification of the probe signal in the diode laser. On the one hand, the modal gain becomes negative when Q approaches κR_2. Physically, the reflected light mainly consists of the reflection at the laser front facet because the cavity-injected probe light is attenuated by absorption. On the other hand, the laser has reached threshold when $Q \gg 1$. Equation (4) then simplifies to the laser threshold condition for the modal gain, that is, $\Gamma g = \alpha + (1/2L)\log(1/R_1 R_2)$.

III. Experimental Setup

Fig. 2 is a schematic view of the fiber-optics experimental setup for measuring the return loss in a Fabry–Pérot laser diode (LD) module. The SMF is a Puremode HI1060 from Corning.

The module incorporates an InGaAs–AlGaAs compressively strained single-quantum-well diode laser with a ridge waveguide. $L = 1800$ μm, $R_1 = 0.92$, $R_2 = 0.005$ (at 980 nm) [anti-reflection-coated front facet], $\alpha = 2.5$ cm^{-1}, $\eta = 0.73$, $\kappa = 0.79$. The value of the internal loss α was determined in a separate experiment from the dependence of the laser differential quantum efficiency on the cavity length (see [10] and [11]). The ratio of fiber-coupled power to the output power of the laser chip at a given current yielded the coupling efficiency η. The value of κ was estimated using Gaussian beam propagation theory and measured indirectly via the return loss at short wavelengths (see Section IV). The coupling efficiencies can be assumed constant between 940 and 1020 nm, the spectral range in which the measurements are being made. The device is operated at a heat-sink temperature of 25 °C, where the longitudinally multimode emission spectrum is centered at 980 nm.

A superluminescent diode is used as a low-coherence broad-band source emitting the probe signal. The radiation is unpolarized, centered at 980 nm, and has 30-nm full-width at half-maximum (FWHM) spectral bandwidth. The probe signal is modulated at 600 Hz approximately by means of a chopper, linearly polarized, and transmitted through the fiber coupler to the LD. The extinction ratio of the polarizer is 30 dB.

To determine the TE modal gain, the return loss for TE-polarized light has to be measured. The PC is adjusted accordingly, as described in [12]. In this respect, the PC induces linear birefringence in the optical fiber, which alters the state of polarization of the probe wave as it travels through the fiber. Because the change in polarization is wavelength-dependent, the probe light at the input of the diode laser cannot be polarized TE concurrently at all wavelengths. In fact, whereas the TE versus TM polarization extinction ratio is 30 dB at 980 nm, it is expected to diminish to 18 dB at the limits of the measurement range, i.e., at 940 and 1020 nm.

Only TE modal gain is considered in this paper. TM gain turned out to be negligible in the compressively strained quantum-well device, as expected from the theory (e.g., see [10]). TM return loss can be measured on the TE-adjusted setup after a 90° rotation of the polarizer. High polarization extinction between TE and TM is required when the TM modal gain is significantly lower than the TE gain, to make sure that the amplified residual TE component stays well below the TM-polarized actual signal.

The power of the probe signal is set via the coupling of the free-space beam in the optical fiber. Part of the probe signal is reflected in the LD, filtered by the tunable filter and detected. The modulation of the probe is needed to discriminate between the probe signal and the diode laser (continuous-wave) emission.

The tunable filter and detector are part of an OSA. A computer controls the center wavelength of the filter and reads out the demodulated output from the lock-in amplifier. The bandwidth of the tunable filter (monochromator) is set to 1 nm. Within this spectral range, the gain amplitude and probe power do not vary significantly, as required by the model (see Section II). Since the spacing of the laser cavity modes amounts to 0.07 nm, the photodetector integrates the reflected power over 14 modes approximately. Hence, the maximum error in the average power measurement is about 4%. The related error in modal gain is 0.2 cm^{-1}.

Knowing the coupling ratio of the fiber coupler (FC), output (A) can be used to monitor the LD probe injected power. The fiber-coupled polarization-independent isolators each provide 35-dB isolation. The isolator FI 1 is necessary to protect the low-coherence source against light coming back from the LD; FI 2 protects the diode laser from reflections at the tunable filter. To minimize residual reflections in the measurement system, which perturb the diode laser and increase the noise floor, the fiber connections are spliced wherever possible, and angled connections are used elsewhere.

For calibration purposes, a reference fiber mirror with known reflectivity is spliced to the setup prior to the LD module. The return-loss measurement of the mirror serves as an absolute reference for all subsequent measurements.

IV. Results

This section shows some return-loss measurements. Modal gain is determined from that data. Accuracy and limitations of the applied technique are discussed.

Fig. 3 represents the TE return-loss spectra of the fiber-coupled diode laser, which was driven at various currents up to the threshold. The module heat-sink temperature was kept constant at 25 °C. The power of the injected TE-polarized probe signal was set to 15 μW, i.e., an average power spectral density of 0.5 $\mu\text{W/nm}$.

Physically, the data can be interpreted as follows. In the long-wavelength region $(\lambda > \lambda_{\text{bandgap}})$, the gain is zero,

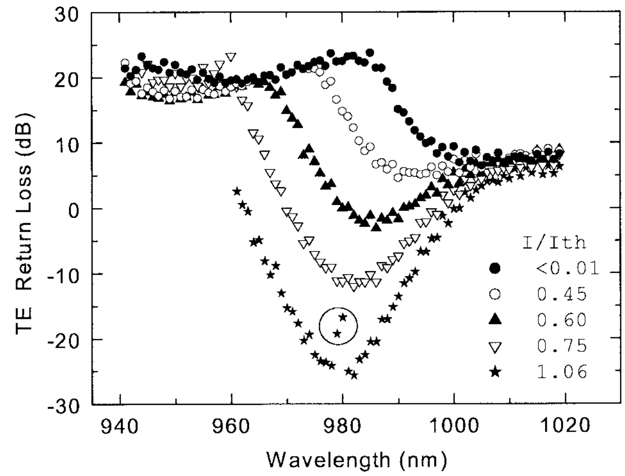

Fig. 3. Measured spectra of the TE return loss in a diode laser under forward-bias operation. The device current is set to $<$ 0.01, 0.45, 0.6, 0.75, and 1.06 times the threshold current, and the heat-sink temperature is 25 °C. The two encircled stars near 980 nm are measurement artifacts due to the onset of lasing.

and the reflected light from the laser back facet contributes much more to the output probe signal than the reflection at the front facet, since $R_1 \gg R_2$. In accordance with (1), the probe output-to-input power ratio approximately reads $\eta^2 \exp(-2\alpha L)R_1$, which translates into a return loss of 7 dB. The measurement data in Fig. 3 agree within ±2 dB with this theoretical estimate.

At short wavelengths $(\lambda < \lambda_{\text{bandgap}})$, the semiconductor absorbs the injected radiation. In this case, the return-loss amounts to 22.5 dB, given by the reflection at the laser front facet κR_2 $(R_2 = 0.007$ at 940 nm). The measured curve with the unpumped device meets this prediction within 1 dB; the other curves are up to 4 dB below that value. When the laser is driven at $1.06 I_{\text{th}}$, i.e., above threshold, the sensitivity of detection is reduced to avoid saturation. In this case, return losses higher than 7 dB could not be measured.

In the spectral region where the probe output signal is composed of the reflection at the laser front facet on the one hand, and multiple round-trip reflections in the cavity on the other hand, the full expression (1) is needed to calculate the return loss properly.

Fig. 4 shows the TE modal gain of the diode laser. The gain is calculated from the return-loss measurements by means of (4) and the laser parameter values specified previously. Probe amplification in spectral regions where cavity modes have reached threshold is affected by heavy power fluctuations, leading to inaccurate measurements. The data points encircled in Fig. 3 were removed accordingly. Moreover, when the reflected light from the front facet overshadows the actual signal from inside the cavity, the gain cannot be extracted from the return-loss measurement. The return loss from the front facet being approximately 20 dB, gain amplitudes below $-14\ \text{cm}^{-1}$ could not be determined.

The gain spectra in Fig. 4 are seen to converge smoothly to the transparency level (zero gain) at long wavelengths. As the current increases from zero to threshold, the gain amplitudes

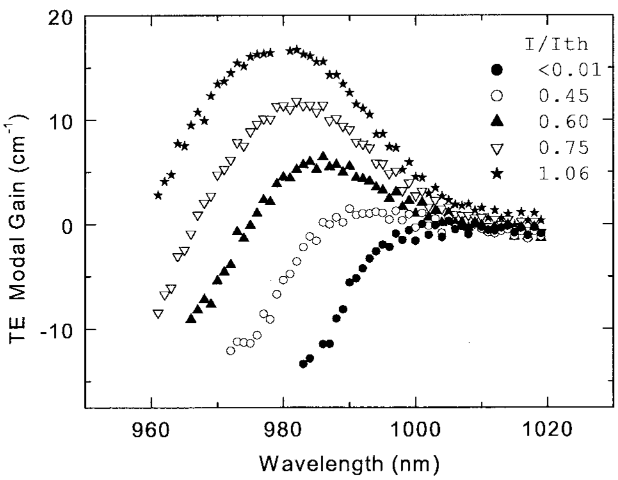

Fig. 4. Laser TE modal gain spectra calculated from return-loss measurements. The device current is the parameter.

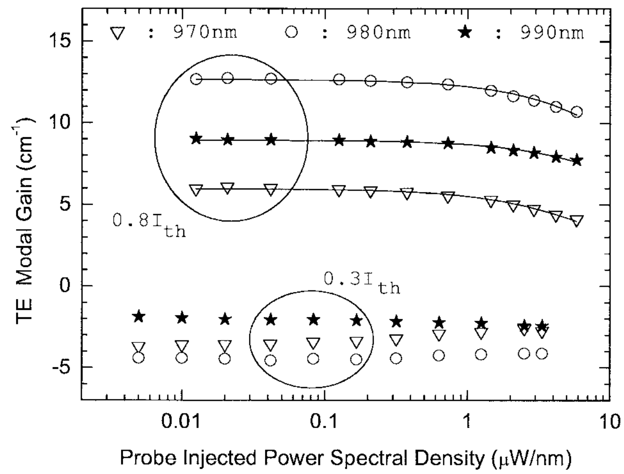

Fig. 5. TE modal gain versus probe power spectral density at three wavelengths and two device bias levels. When the device current is $I = 0.8I_{\rm th}$, the gain gradually declines with increasing power in the probe. The lines are fit functions, defined in the main text. At $I = 0.3I_{\rm th}$, the gain is seen to slowly increase or decrease with the injected power, depending on wavelength.

increase and the spectra broaden and shift toward shorter wavelengths, in response to the increase in the quasi-Fermi level separation, progressive band filling, and broadening of the lineshape function. In virtue of gain clamping, the threshold modal gain can be extracted from the measurement above threshold $(I/I_{\rm th} = 1.06)$. The amplitude amounts to 16.6 cm^{-1}, which is 0.8 cm^{-1} less than the value calculated from $\Gamma g_{\rm th} = \alpha + (1/2L)\log(1/R_1R_2)$. Measurements showed the 0.5-μW/nm probe signal to depress the threshold peak gain by 0.5 cm^{-1} through gain saturation. Residual discrepancy may be ascribed to calibration errors and uncertainties in the device parameter values.

In general, too-low gain amplitudes result from gain saturation, which may be caused by the injection of the probe signal. In fact, a semiconductor laser biased below threshold is essentially an optical amplifier and as such is prone to gain saturation. To avoid gain saturation, the power of the probe signal must be set with caution. Gain saturation is also dependent on the spectrum of the probe signal. Fig. 5 presents the modal gain in the diode laser as a function of the power in the probe signal, at three wavelengths (970, 980, and 990 nm) and two bias levels $(0.3I_{\rm th}$ and $0.8I_{\rm th})$. When the device is biased at $0.8I_{\rm th}$, the gain is seen to decrease with the probe power. The reduction in gain amplitude, due to gain saturation, is less than 1 cm^{-1} for a probe signal below 2 μW/nm. The fit function used is $\Gamma g = G_0/(1 + P_{in}/P_S)$, where G_0 and P_S are two fitting parameters. This functional description of gain saturation is frequently used in SOAs [11].

Gain saturation depends on the device bias level. It is less pronounced at $0.3I_{\rm th}$ than at $0.8I_{\rm th}$, as shown in Fig. 5. At low bias, the gain may increase with the injected power, depending on the wavelength. In fact, when the probe signal is too strong, it not only saturates the gain but also distorts the laser emission spectrum as a whole, and it also affects the threshold. Because of this, the probe power should be kept as low as possible. The lower limit is set by the sensitivity of the measurement setup. The injected probe signal may be low $(< 0.5\ \mu$W/nm$)$ when dealing with high gain, because the output signal is amplified and therefore easily detected. However, measuring negative gain (i.e., absorbing medium) requires more probe power $(> 1\ \mu$W/nm$)$ for the reflected signal to be detectable.

Qualitatively, gain saturation is expected to be similar in other combinations of diode laser and probe source. However, 0.5-μW/nm probe power density is appropriate in this experiment, but may be inadequate in other device-probe configurations.

The device measured in this paper did not include an optical isolator in contrast to most telecom signal diode lasers. The absence of an isolator simplifies the model and makes it easier experimentally to inject a probe signal into the laser cavity. Nevertheless, the presented method can also be applied to a device with an isolator. The isolator can easily be included in the model. In the experiment, a more powerful probe signal is needed to compensate for the loss in the isolator.

V. Conclusion

A novel method for determining gain in long-cavity Fabry–Pérot diode lasers from a return-loss measurement has been presented and successfully applied. Particularly for state-of-the-art long-cavity semiconductor pump lasers, the method has inherent advantages over classical techniques.

The return loss is measured by means of a low-coherence modulated probe wave, which is injected into the laser cavity. Lock-in detection is used to discriminate between the amplified reflected probe signal and the laser emission. The gain is calculated from the ratio between averaged reflected and injected signal powers.

Several spectra of TE modal gain in a high-power 980-nm Fabry–Pérot diode laser with 1800-μm cavity length have been determined. Gain saturation by probe injection has been shown to be manageable. Gain amplitudes have been determined over a range of 30 cm^{-1} with accuracy better than 1 cm^{-1}. The amplitude range and measurement accuracy can be increased by properly setting the probe power. The spectral range can be extended using a probe source with enhanced bandwidth.

ACKNOWLEDGMENT

The author would like to thank T. Pliska, N. Matuschek, B. Sverdlov, A. Fily, S. Mohrdiek, and C. Harder, of Bookham Technology (Switzerland) AG, Zurich, Switzerland, for their constant support and many fruitful discussions.

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