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Measurement of Reflectivity of Butt-Joint Active–Passive Interfaces in Integrated Extended Cavity Lasers

Y. Barbarin, E. A. J. M. Bente, C. Marquet, E. J. S. Leclère, J. J. M. Binsma, and M. K. Smit

Abstract—A method and measurement results are presented for the determination of the reflectivity of butt-joint active–passive interfaces in a series of extended cavity Fabry–Pérot lasers. The method is based on the analysis of subthreshold laser spectra. The small reflections at the two intracavity active–passive interfaces modify the mode structure of the laser. By fitting the calculated subthreshold mode structure to the recorded data, values of the reflectivities are extracted. An average value of $9 \cdot 10^{-5}$ has been determined. The value of the reflectivity of those interfaces is relevant for photonic integrated circuits and particularly integrated mode-locked lasers.

Index Terms—Active–passive integration, integrated optics, laser, semiconductor waveguide.

I. INTRODUCTION

LOW butt-joint loss and low butt-joint reflection values on active–passive interfaces are essential in photonic integrated circuits [1]. Reflections down to 10^{-5} affect the operation of integrated lasers [2] and lead to a modification of the mode structure. Mode-locked lasers (MLLs) [3] in particular have a strict requirement on intracavity reflections. For their development, measurements of small reflectivity values on butt-joint active–passive interfaces are needed. Measurement of reflectivity based on the Hakki–Paoli method has been reported in single cavities [4]. But in the case of butt-joint reflectivity measurements inside a cavity, a full analysis of the subthreshold optical spectrum is required. In this letter, we present a method and measurement results of the reflectivity of butt-joint active–passive interfaces in a series of extended cavity Fabry–Pérot lasers. An average value of $9 \cdot 10^{-5}$ has been determined.

II. METHOD

The method is based on the analysis of subthreshold spectra of lasers with intracavity reflections. These spectra show a series of resonances at a regular spacing (free-spectral range of

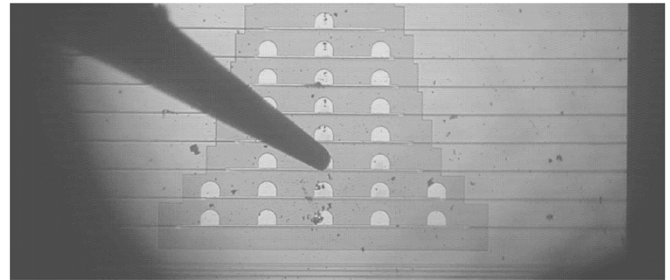


Fig. 1. Picture of part of the chip with the series of ECLs. A probe is visible that supplies current to one of the SOAs.

the total cavity). The intracavity reflections create a number of periodic modulations of the intensity of the resonances peaks. The modulation depth is directly related to the reflectivity of the interfaces. The frequency of a modulation is inversely proportional to the distances between the reflection points. Both frequencies and modulation depths are easily observed in the Fourier transform (FT) of the spectrum [5]. By fitting a simulated subthreshold spectrum to the recorded data, values of the reflectivities have been extracted.

A series of integrated extended cavity lasers (ECLs) has been produced. These lasers consist of a semiconductor optical amplifier (SOA) waveguide connected to two passive waveguides terminated by cleaved mirrors. Each device has a different length of SOA (Fig. 1). Details of the fabrication are given in [6]. The small reflections at the two intracavity active–passive interfaces modify the mode structure. A typical transformed spectrum is plotted in Fig. 2, where the time axis has been translated into physical distance. Analyzing this graph, the highest peak corresponds to the longitudinal mode of the total cavity (3.736 mm). Other peaks belong to the intracavities formed by the two passive waveguides. Only cavities containing at least one cleaved facet are observed; the possible cavity formed by the SOA alone (L2) is not visible.

III. MODELING OF THE SUBTHRESHOLD SPECTRUM

The modeling of the subthreshold spectrum is explained using the scheme in Fig. 3. We model the generation of the amplified spontaneous emission from the SOA by introducing a low reflectivity beam splitter ($T = 1 - 10^{-7}$) that couples light into the cavity from an external monochromatic source. The propagation of the field through WG 1, amplifier, and WG 2 and back is calculated using a transmission matrix T_{Total} . The

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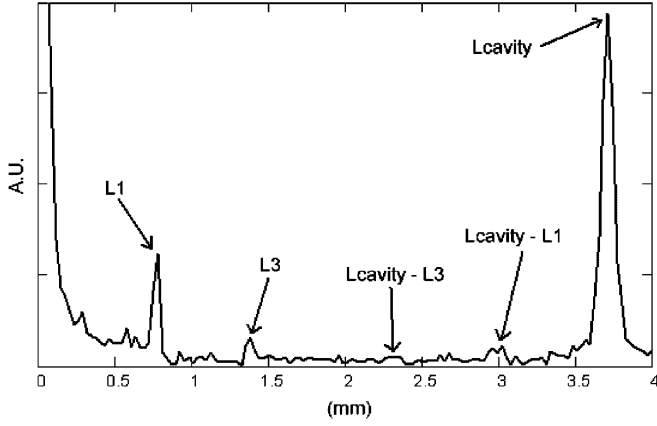


Fig. 2. FT of a 12-nm span ECL spectrum, $I_{soa} = 76.5$ mA and $L_{soa} = 1500$ μ m.

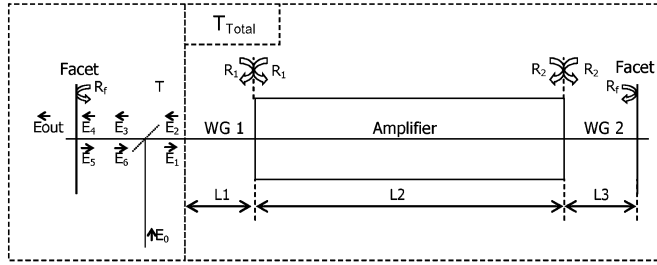


Fig. 3. Schematic representation of an ECL in the model with definition of normalized fields and power reflectivity coefficients.

field E_{out} from the left cleaved facet can then be calculated for a range of wavelengths of the injected light

$$E_{OUT} = E_0 \cdot \frac{T_{total1,0} \cdot \sqrt{T} \cdot \sqrt{1-T} \cdot \sqrt{1-R_f}}{T_{total0,0} - (T_{total1,0} \cdot T \cdot \sqrt{R_f})} \quad (1)$$

where R_f represents the power reflectivity at the cleaved mirrors ($R_f = 0.34$). The T-matrix T_{total} used is

$$T_{Total} = T_{WG1} \cdot T_{Int_Loss1} \cdot T_{Ref1} \cdot T_{SOA} \cdot T_{Ref2} \cdot T_{Int_Loss2} \cdot T_{WG2} \cdot T_{Ref_F} \quad (2)$$

where T_{WG1} and T_{WG2} describe the passive waveguide sections, T_{SOA} the amplifier, T_{Int_Loss1} and T_{Int_Loss2} the interface losses, T_{Ref1} and T_{Ref2} the interface reflections, and T_{Ref_F} the facet reflection

$$T_{WG} = \begin{bmatrix} e^{Att+i \cdot \left(\frac{2 \cdot \pi \cdot Ng_{WG} \cdot L_{WG}}{\lambda}\right)} & 0 \\ 0 & e^{-Att-i \cdot \left(\frac{2 \cdot \pi \cdot Ng_{WG} \cdot L_{WG}}{\lambda}\right)} \end{bmatrix} \quad (3)$$

$$T_{Int_Loss}(LOSS_{int}) = \begin{bmatrix} e^{LOSS_{int}} & 0 \\ 0 & e^{-LOSS_{int}} \end{bmatrix} \quad (4)$$

$$T_{Ref}(R) = \frac{1}{\sqrt{1-R^2}} \begin{bmatrix} 1 & -R \\ -R & 1 \end{bmatrix} \quad (5)$$

$$T_{SOA} = \begin{bmatrix} e^{-G(\lambda)+i \cdot \left(\frac{2 \cdot \pi \cdot Ng_{SOA} \cdot L_{SOA}}{\lambda}\right)} & 0 \\ 0 & e^{G(\lambda)-i \cdot \left(\frac{2 \cdot \pi \cdot Ng_{SOA} \cdot L_{SOA}}{\lambda}\right)} \end{bmatrix} \quad (6)$$

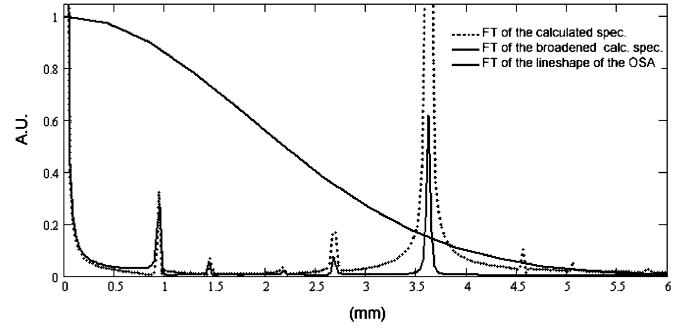


Fig. 4. Effect of the finite bandwidth of the OSA on the FT of the optical spectrum.

In our model, the wavelength dependence of the gain in the SOA $G(\lambda)$ and the intensity of the spontaneous emission $E_0(\lambda)$ have been successfully fitted to the same Gaussian shape. Att is the loss in the passive waveguides. Ng_{WG} and Ng_{SOA} are the wavelength-dependent group indexes. Dispersion in the different waveguides needed to be included to obtain agreement with the experiment are

$$Ng_{WG}(\lambda) = N_0^{WG} + \frac{N_1}{\lambda^2} \quad (7)$$

$$Ng_{SOA}(\lambda) = N_0^{WG} + C + \frac{N_1}{\lambda^2}. \quad (8)$$

The dispersion is assumed to be equal for the active and passive waveguides (N_1). The constant difference (C) between the group index of the active and passive waveguide has been measured separately by measuring the laser mode frequencies with a high resolution multiwavelength meter (ANDO AQ6141). The optical spectrum analyzer (OSA) used shows a linear deviation in its wavelength scale, which is indirectly simulated by increasing the dispersion.

Passive losses of 4 dB/cm and a 0.2-dB butt-joint loss have been measured on passive regrown structures. The linewidth of the OSA has been determined using a single-mode 500-kHz linewidth continuous-wave laser. The linewidth of the OSA fitted well to a Gaussian function with a bandwidth of 0.07-nm full-width at half-maximum. The effect of the finite bandwidth of the OSA is illustrated in Fig. 4. Here the FTs are given of 1) a theoretical spectrum not including the effect of the OSA broadening, 2) the same spectrum including the broadening, and 3) the spectrum of the OSA transmission function. The intensities of the intracavity peaks are reduced by the instrumental broadening. The two peaks corresponding to the passive waveguides (L1 and L3) are not strongly affected. However, the peak for the total cavity is attenuated by a factor of 5.5. The amplitude of this peak serves as the reference for the relative normalization of the FT of the theoretical spectrum to the FT of the experimental one. This normalization is required to obtain the reflection values from the peaks in the transformed experimental spectrum. Therefore, knowledge of the exact linewidth of the OSA is essential.

The theoretical spectrum is fitted to the recorded data as follows. First, it is broadened to simulate the finite bandwidth of the spectrum analyzer (0.07 nm). Then, the coefficients of the group index are adjusted to fit the position of the modes along

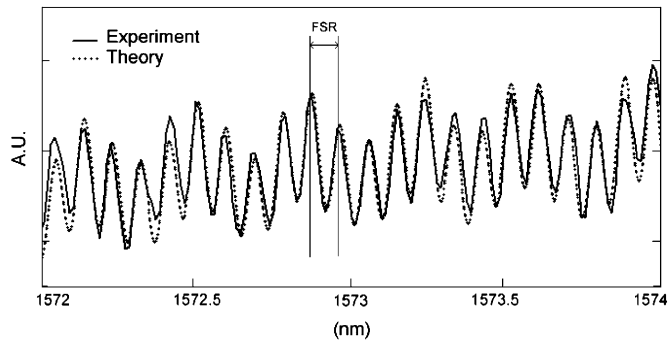


Fig. 5. Central 2-nm part of a theoretical and experimental ECL subthreshold spectrum ($L_{soa} = 1250 \mu\text{m}$ $I_{soa} = 70 \text{ mA}$). The free-spectral range (FSR) for the total cavity is indicated.

the spectrum. Adjusting the gain of the amplifier and its wavelength dependency reproduces the coarse shape of the spectrum. Afterwards, the reflectivity parameters are varied to optimize the agreement between the FTs of the measured and theoretical spectra. Finally, the cavity lengths are fitted to the original data. This sequence is repeated at least two times.

IV. MEASUREMENTS AND FITTING RESULTS

Measurements and fits have been performed on a series of extended cavity Fabry-Pérot lasers with a fixed total length. The chip was soldered on a temperature-controlled copper mount (20°C). Light from a laser output waveguide was collected using a lensed fiber and led to an OSA (ANDO AQ6315A). The spectra were recorded over a 12-nm span which is sufficient to resolve the reflection peaks in the Fourier transformed spectrum. The fitting has been performed for six devices and at different currents. To illustrate the quality of the fitting of the simulation Fig. 5 presents the central 2-nm part of the experimental and simulated spectra. The positions of the mode match perfectly.

The modulation over the modes due to the butt-joints reflections is simulated correctly along the spectrum. In Table I, the results for the different devices are summarized.

Measured SOA lengths and waveguides lengths (L1 and L3) were used in the model as initial values and fitted with an accuracy of 5 nm.

For each device, values for R1 and R2 have the same order of magnitude. Reflection values vary from $2 \cdot 10^{-5}$ to $15 \cdot 10^{-5}$. The average measured value of reflection is $9 \cdot 10^{-5}$. For 1-mA differences in SOA current, we have noticed that all extracted reflectivity values fell within a range of $1 \cdot 10^{-5}$. The determined reflectivities depend only weakly on the values used for the butt-joint loss or the waveguide losses. A $\pm 0.05\text{-dB}$ change of the 0.2-dB butt-joint loss or a $\pm 0.5\text{-dB/cm}$ change of the

TABLE I
RESULTS FOR THE SERIES OF INTEGRATED ECLS

L_{soa} (μm)	L1 (μm)	L2 (μm)	L3 (μm)	R1 (10^{-5})	R2 (10^{-5})
600	1305.30	599.95	1829.01	2	8
700	1256.26	700.10	1777.64	5	11
900	1156.96	899.95	1677.10	7	3
1000	1104.83	999.99	1628.31	11	6
1250	980.12	1249.90	1503.90	12	8
1500	855.97	1500.00	1378.03	13	15

4.0-dB/cm passive waveguide losses modify the reflectivities values obtained by $1 \cdot 10^{-5}$.

Our method can fit similar devices with cavity lengths between $400 \mu\text{m}$ and 6 mm, using the same equipment. The minimum length is limited by the number of modes needed in the spectrum and its total width. The maximum device length depends on the resolution of the OSA (typically 0.05 nm).

V. CONCLUSION

A method and measurement results have been presented for the determination of the reflectivity of butt-joint active-passive interfaces in a series of extended cavity Fabry-Pérot lasers. The method is based on a spectral analysis of subthreshold laser spectra. An average value for the reflectivity of $9 \cdot 10^{-5}$ (-40 dB) has been determined. We have demonstrated that this method is well suited for characterizing active-passive butt-joint reflectivity. The absolute value of the interface reflectivity is particularly relevant for the extended cavity integrated MLLs that we are developing.

REFERENCES

- [1] J. J. M. Binsma, M. van Geemert, F. Heinrichsdorf, T. van Dongen, R. G. Broeke, and M. K. Smit, "MOVPE waveguide regrowth in InGaAsP/InP with extremely low butt joint loss," in *Proc. IEEE/LEOS Symp. Benelux Chap.*, 2001, pp. 245-248.
- [2] R. W. Tkach and A. R. Chraplyvy, "Regimes of feedback effects in 1.5 μm distributed feedback lasers," *J. Lightw. Technol.*, vol. LT-4, no. 11, pp. 1655-1661, Nov. 1986.
- [3] Y. Barbarin, E. A. J. M. Bente, M. J. R. Heck, D. Lenstra, J. H. den Besten, M. K. Smit, and J. J. M. Binsma, "Modeling and experimental results of a 26 GHz integrated passively modelocked ring laser," in *Proc. IEEE/LEOS Symp. Benelux Chap.*, 2004, pp. 13-16.
- [4] I. P. Kaminow, G. Eisenstein, and L. W. Stulz, "Measurement of the modal reflectivity of an antireflection coating on a superluminescent diode," *IEEE J. Quantum Electron.*, vol. 19, no. 4, pp. 493-495, Apr. 1983.
- [5] D. A. Ackerman, L. M. Zhang, L. J.-P. Ketelsen, and J. E. Johnson, "Characterizing residual reflection within semiconductor lasers, integrated sources, and coupling optics," *IEEE J. Quantum Electron.*, vol. 34, no. 7, pp. 1224-1230, Jul. 1998.
- [6] R. G. Broeke, "A Wavelength Converter Integrated with a Discretely Tunable Laser for Wavelength Division Multiplexing Networks," Ph.D. Thesis, Delft Univ. of Tech., 2002.