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Refined procedure for gain measurement in Fabry-Perot semiconductor lasers

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Abstract: A refined procedure is proposed to extract the optical gain in Fabry-Perot semiconductor lasers. The gain-reflectivity product is extracted with a straightforward technique without requiring ultrahigh-resolution measurements. It further reduces systematic error due to the finite resolution of the instrument, compared to previous methods.

1. Introduction

The optical gain is a fundamental parameter of a laser. Besides characterizing the quality of the active region, it determines the lasing threshold and the maximum output power. It is therefore very important to have an accurate value for the optical gain to characterize the laser design and to measure its performance.

The net modal gain g_{net} in Fabry-Perot semiconductor lasers is commonly extracted from amplified spontaneous emission (ASE) spectra measured below lasing threshold. Precisely, the following parameter is extracted: $b_\mu = r\exp(g_{\mathrm{net},\mu}L)$, where r is the product of the facet reflectivities and L is the length of the active region. The subscript μ indicates that the corresponding parameter is evaluated at the wavelength λ_μ. The finite resolution of the optical spectrum analyzer (OSA) reduces the measured intensity $\tilde{I}_\mu$ of the ASE peaks I_μ and increases the measured intensity $\tilde{I}_{\mu'}$ of the ASE dips $I_{\mu'}$ (see Fig. 1). Therefore, the parameter b as extracted from the "max-min" method [1]:

$$\tilde{b}_\mu^{\mathrm{HP}} = \frac{\sqrt{\tilde{I}_\mu / \tilde{I}_{\mu'}} - 1}{\sqrt{\tilde{I}_\mu / \tilde{I}_{\mu'}} + 1}, \tag{1}$$

is systematically under-estimated. Reduced error, but also systematically under-estimated, is obtained with the "sum-min" method [2]:

$$\tilde{b}_{\mu'}^{\mathrm{C}} = \frac{\sigma_{\mu'} - \tilde{I}_{\mu'}\mathrm{FSR}_{\mu'}}{\sigma_{\mu'} + \tilde{I}_{\mu'}\mathrm{FSR}_{\mu'}}, \tag{2}$$

where the parameter σ and the free spectral range (FSR) are defined in Fig. 1. Further methods have been reported [3], but they either involve cumbersome multi-parameter fitting procedures or necessitate ASE data taken with very high resolution [4]. This paper presents a refined method to extract b in a straightforward way, without under-estimation and only requires an OSA with a moderate resolution.

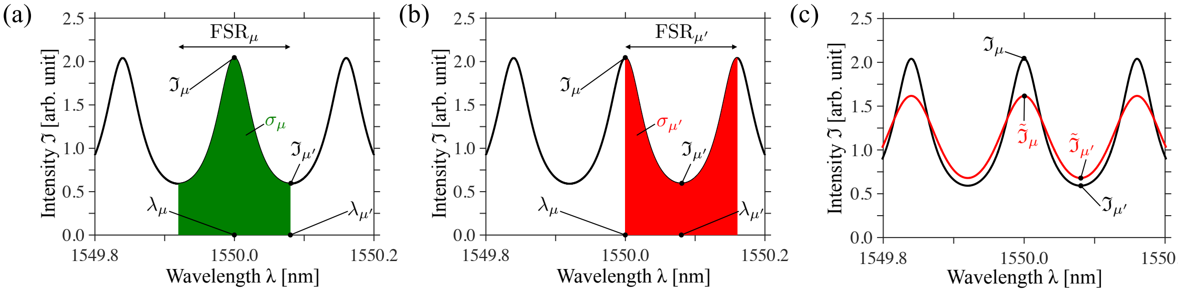

Fig. 1. ASE spectrum (black curves) simulated with an Airy function ($b = 0.3$, FSR = 20 GHz). The red curve in (c) is the obtained ASE spectrum that would be measured with a 50-pm resolution, assuming an OSA with a Gaussian response function.

2. Refined theory and experimental analysis

It is worth noting that besides (1) or (2), the b parameter can also be extracted with the "sum-max" method:

$$\tilde{b}_\mu = \frac{\tilde{I}_\mu\mathrm{FSR}_\mu - \sigma_\mu}{\tilde{I}_\mu\mathrm{FSR}_\mu + \sigma_\mu}, \tag{3}$$

which necessitates an ASE intensity peak and the integrated area under it. Unlike (1) and (2), the sum-max method (3) can be employed for lasers with a very large FSR, or equivalently, with a very small cavity thickness like in VCSELs.

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ASE spectra are measured under different currents below threshold for heterogeneously integrated silicon Fabry-Perot lasers emitting at 1.55 µm. These in-plane lasers have a cavity length of 503 µm and facet reflectivities of 0.3. Fig. 2(a) illustrates these measurements and allows extracting FSR = 80 GHz.

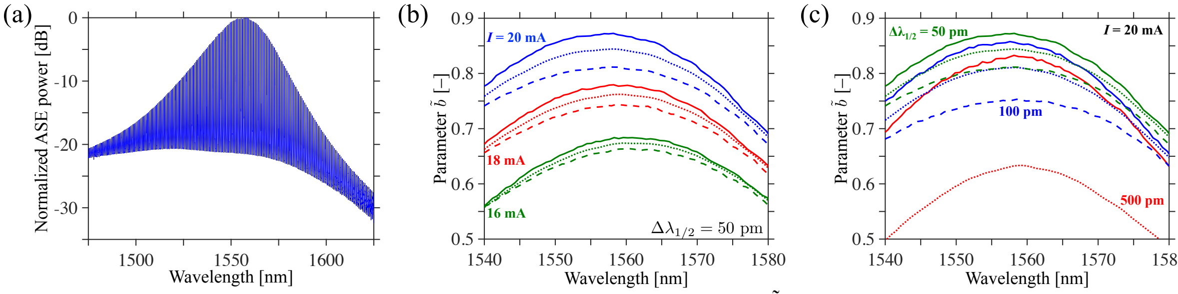

Fig. 2. (a) ASE spectrum measured under 20 mA with a 50-pm resolution. (b)-(c) Parameter $\tilde{b}$ extracted as a function of the wavelength, with the max-min (dotted lines), sum-min (solid lines), or sum-max (dashed lines) method. Data in (b) are extracted from ASE measured with a 50-pm resolution under different currents I, and those in (c) under 20 mA and with different resolutions $\Delta\lambda_{1/2}$.

Fig. 2(b)-(c) show the parameter $\tilde{b}$ extracted with the three above methods, as a function of the wavelength and for different resolutions of the OSA (Yokogawa AQ6370). It is seen in Fig. 2(b) that as the gain increases, the discrepancies between the different methods increase. This is reproduced in Fig. 3(a), where the parameter $\tilde{b}$ is calculated, assuming an OSA with a Gaussian response function. Other shapes of response function (triangular, rectangular) have been investigated as well, and will be discussed in the talk. Fig 3(b) plots the parameter $\tilde{b}$ obtained in Fig. 2(c) at 1560 nm under 20 mA, with the different methods and resolutions. These data points suggest that the dependence of $\tilde{b}$ on the OSA resolution is linear. This behavior is well accounted for in the calculations of Fig. 3(a), for moderate values of the resolution. Straight lines are thus fitted in Fig. 3(b), imposing a common intersection on the vertical axis. This intersection gives the true value of the parameter b, *i.e.* without under-estimation. This linear behavior is observed for all other measured wavelengths. Therefore, to compute the true value of b, it is sufficient to have ASE data taken at two different resolutions. In addition, these resolutions do not need to be ultra-high.

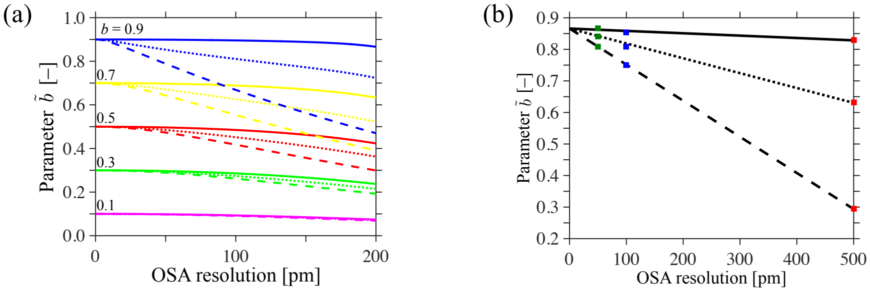

Fig. 3. (a) Parameter $\tilde{b}$ calculated as a function of the OSA resolution, using the min-max (dotted lines), the sum-min (solid lines) or the sum-max (dashed lines) method, and for different values of b (with different colors). (b) Measured parameters $\tilde{b}$ from Fig. 2(c) at 1560 nm (color dots), and extrapolation of the true value b.

3. Conclusion

A simple technique is presented for measuring the gain in Fabry-Perot lasers with reduced error compared to previous methods. Experimental data is analyzed and the b parameter is extracted, validating this method.

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