DFB laser dynamics and noise characterization by high-resolution and high-dynamic range measurements of its CW optical spectrum

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ABSTRACT

We present results on the characterization of the main parameters of DFB lasers for its use in direct modulation: chirp parameter, linewidth, relaxation frequency and RIN, obtained from measurements of the emitted optical spectrum in continuous operation mode using a high resolution (10 MHz) and high dynamic range (80 dB) optical spectrum analyzer. Results obtained from the characterization of commercial grade available DFB lasers with this method, present typical parameter values, but are also checked with well-know, but more resource demanding, methods involving modulation and optical to electrical conversion.

Keywords: DFB laser, linewidth enhancement factor, relative intensity noise, relaxation oscillations, high-resolution optical spectroscopy

1. INTRODUCTION

Distributed feedback (DFB) lasers are currently the most commonly used devices in metropolitan area networks (MAN). Even thought external modulation schemes have far better performance in terms of frequency chirp, in a very cost-sensitive environment such as the MANs with dense wavelength-division-multiplexing (DWDM), directly modulated lasers (DML) are the most common choice[1], and among them, the most used devices are DFBs.

But directly modulated DFB lasers present a number of issues for their integration in DWDM systems, as they suffer from spectral broadening due to frequency chirp[2], and thus are more affected by dispersion and filtering through the network[3]. Other problems associated to the use of DMLs are the presence of a higher intensity noise, critical in the performance of CATV systems[4], or the nonlinearities associated to the relaxation oscillations.

To perform a complete characterization of the main work parameters of a laser with traditional methods, several experiments should be carried out[5], consuming a lot of time and resources. So, to measure the power versus current function, a power detector or a optical spectrum analyzer (OSA) is to be used; to measure the linewidth, either interferometric techniques or homodyne analysis should be made; for the linewidth enhancement factor, commonly a network analyzer and some hundred kilometers of fibers are needed[6]; for the measurement of the relative intensity noise[7] (RIN) a photodetector and an electrical spectrum analyzer are normally used. In this paper, we will show how to perform all these measurements with a single equipment, a high resolution optical spectrum analyzer, and with a common measurement philosophy.

2. METHODOLOGY

The optical intensity spectrum of a signal contains very significant information, but extracting it is a very hard task, as most of the technologies used for these means have limitations either in the frequency resolution, or in the dynamic range of the power measurement, or in achieving a good compromise between both restrictions. But even with these limitations, optical spectrum analyzers based on diffraction gratings, with resolutions in the order of tens of picometers have proven to be very useful both for laboratory purposes and for network measurements, while the higher resolution obtained with interferometric devices such as Fabry-Perot interferometers is also useful for some characterizations despite it lacks of dynamic range, so there is no doubt that the information contained in the optical spectrum of a signal is relevant and efforts put into measuring it are worthy.

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Not long ago, a new technique for optical spectrum analysis was proposed using narrowband amplification by stimulated Brillouin scattering (SBS)[8]. The equipment resulting of this measurement techniques is called BOSA and has been developed by Aragon Photonics Labs. in collaboration with the Photonics Technology Group of the University of Zaragoza. This analyzer has some interesting properties, associated to the properties of the Brillouin scattering and to the fact that the processing is performed in the optical domain, in opposition to traditional methods, that perform the analysis in the electrical domain, which makes the measurement process very fast. With the BOSA, an analysis filter of 0.08 pm or 10 MHz bandwidth is used to scan the wavelength region of interest. This filter has a Gaussian profile, that makes it steeper than other techniques used for spectral analysis, and thus it obtains a higher optical rejection ratio (±45 MHz @ 40 dB; ±55 MHz @ 60 dB) and a higher dynamic range of around 80 dB.

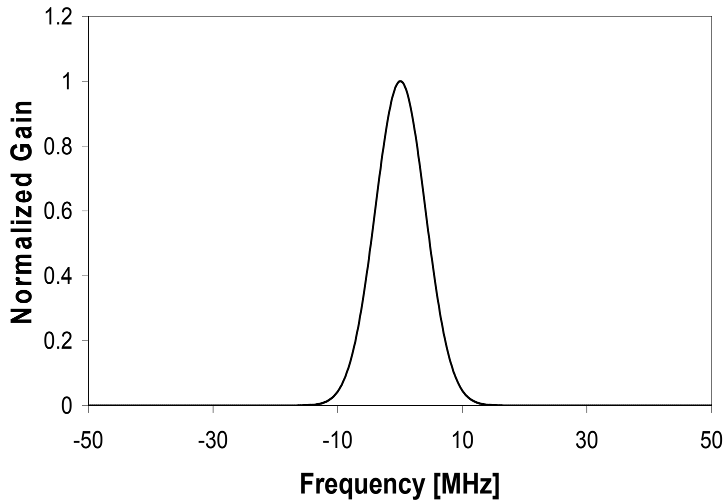


Fig. 1: Normalized transfer function of the BOSA's analysis filter.

The Gaussian profile of the BOSA's analysis filter makes it easier to extract information from the measured spectra, as its convolution with other typical profiles of optical signals are well known in signal processing theory. For the case of DFB lasers, that have a very well defined Lorentzian shape, the resulting measurement gives a Voigt profile, defined as:

$$K(a,b) = \frac{b}{\pi}\int_{-\infty}^{\infty} \frac{e^{-t^2}}{(a-t)^2 + b^2}\,dt \tag{1}$$

with $a = \sqrt{\ln 2} \cdot (\lambda - \lambda_0)/\gamma_G$ and $b = \sqrt{\ln 2} \cdot (\gamma_L / \gamma_G)$, where λ_0 is the central wavelength of the laser, γ_G is the width of the analysis filter assuming Gaussian profile and γ_L is the linewidth of the laser. This fact is only really important in the proximities of the central emission wavelength, that is where the width of the laser shape can be of the order of the analysis filter. As we move towards lower power levels, laser shape is quite wider, so this is no longer relevant for the functional forms of the measurements and only a magnitude correction must be made if spectral power density (PSD, in dBm/Hz) is desired to be measured. In this case, effective width of the analysis filter is to be considered, i.e. the width of an equivalent square filter that would give the save power measurement. For the Gaussian shape, this effective width is 1.06 times the measured width at 3 dB, resulting in a relation of 70.25 dB from the power measured with the intrument and the PSD of the spectrum, given the case that the spectral distribution is wide enough to take this approximation. This is also useful to measure full emission power, that can be calculated as the integral of the calculated PSD, and thus avoiding the contribution of the suppressed side modes that distort the measurements close to threshold when using an photodetector.

Measuring the optical spectrum with this scope reveals details that cannot be measured by other means, as are normally not resolved either in frequency or in power. The measurements performed here are the closest to the "ideal" optical spectrum with theoretical infinite resolution to our knowledge. However, the optical spectrum we present are well known from literature and optical communications simulators, so there is a lot of information about them and thus a very precise analysis of the measurement can be made.

3. DATA

For this work, two commercial DFB lasers where measured. One is specified as "low chirp" (from now on, *laser 1*) and the other as "high chirp" (*laser 2*). Laser 1 is intended for modulation up to 2.5 Gbps, while laser 2's target application is to act as a carrier, but it has modulation capabilities.

All the data needed for our analysis is a series of measurements of the laser under test in continuous wave (CW) emission mode under different biasing conditions. The bias current is swept from the lowest the analyzer can measure, that is typically around 5-10 % below threshold for tested devices, to some arbitrary current in the operating range given by the laser manufacturer. The region around threshold must be measured in very small steps, as changes are very fast in this region for most of the properties of the laser. Measured spectra for laser 2 around the threshold region can be seen in Fig. 2.

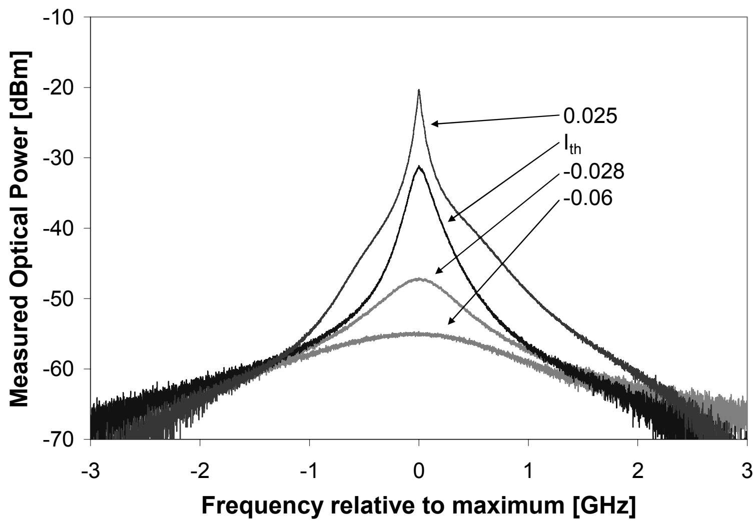


Fig. 2: Measured spectra of laser 2 for different bias currents around threshold. Deviation of the center wavelength has been eliminated for clarity of the representation. Curve labels refer to the normalized bias current ($I_{bias}/I_{th} - 1$)

The lower curves correspond to spontaneous emission below threshold and they have a typical Gaussian lineshape[9], with a width in the order of the GHz. As bias current is increased, stimulated emission becomes dominant and the width of the spectrum decreases. Also the lineshape suffers some changes, resulting in a very well fitted Lorentzian function around threshold. At this point, only the phase noise of the laser is considered. If we look at the linewidth of the laser, we can see how it decreases rapidly when approximating to threshold, and then this decreasing continues, but at a softer rate.

If we continue rising the bias current, an additional phenomenon can be observed as a certain deformation in the Lorentzian shape of the spectrum, as can be seen in the upper curve in Fig. 2. At higher bias currents, this effects becomes quite more recognizable, as its behavior follows clearly the theory of laser intensity noise[10], as can be seen in Fig. 3, where a higher range of bias current values is represented. The laser intensity noise appears as a soft increase of the power spectral density at frequencies far from the peak of power where the spectral density due to phase noise has fallen very low. The sum of phase noise and intensity noise forms a certain PSD plateau that continues until a maximum is reached and then decreases sharply.

The frequency separation between the peak of power and the maximum of the intensity noise varies with the value of the bias current, following the well-known linear relationship between the squared frequency and the bias current[11]. The other consequence of the increasing bias current is reflected in the decreasing of the intensity noise PSD, that is coherent with the typical behavior of the relative intensity noise (RIN).

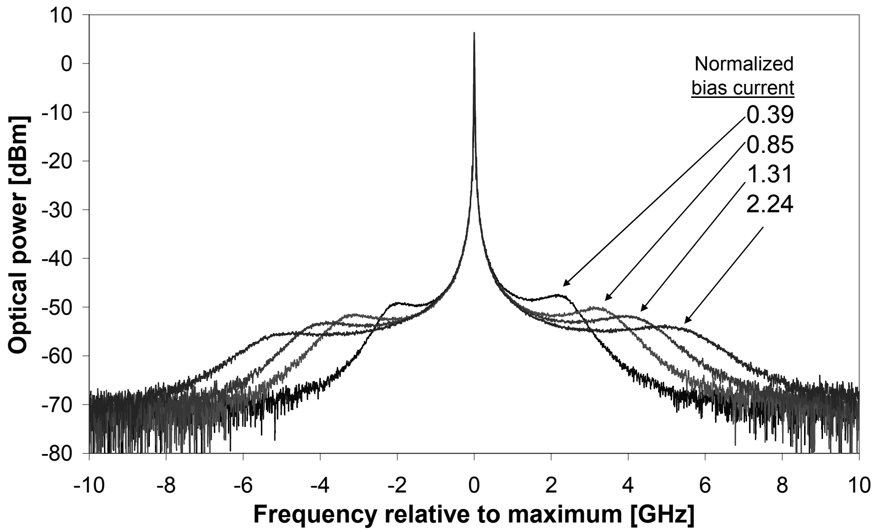


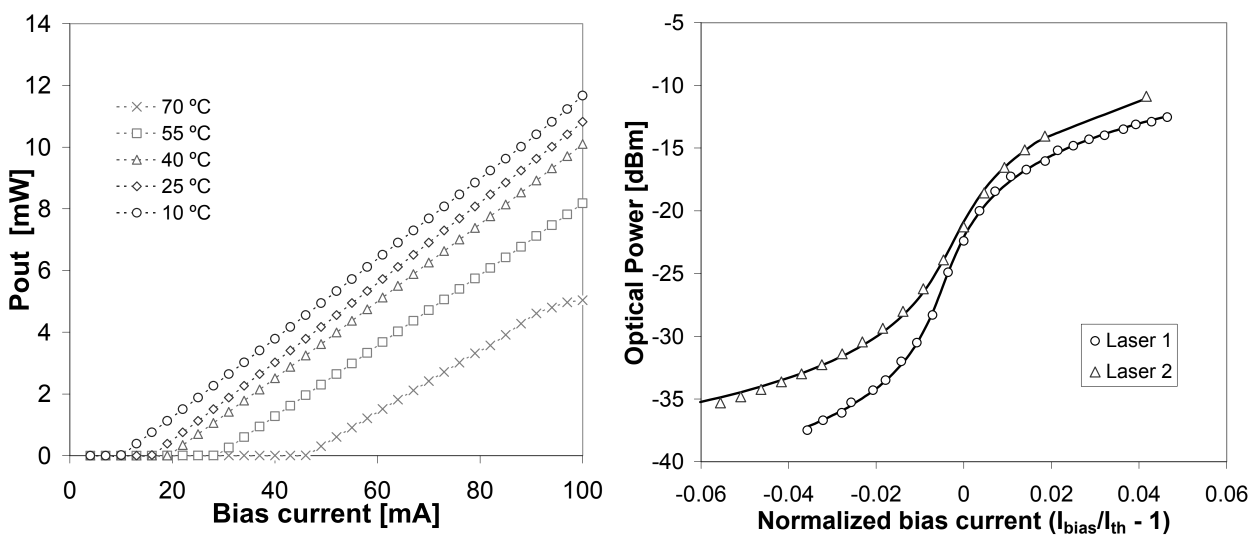
Fig. 3: Measured spectra of laser 2 for different bias currents (I_{bias}/I_{th} - 1) far from threshold.

4. RESULTS

Until now, spectra of the DFB lasers have been measured and analyzed qualitatively. In this section, the goodness of the measurements will be evaluated by fitting them to theoretical expressions. We will begin with the power response.

4.1. Power response

As explained in the past section, we calculate the power contained in the lasing mode by integrating the PSD in the wavelength region where it is located. The measurement are shown in next figure. Fig. 4a shows the power response curves in linear scale for different temperatures, and their fitting to the first order approximation of the power response: $P = (I_{bias} - I_{th})/F$, with F being the inverse of the power to bias current ratio far above threshold, given in A/W.



(a) (b)

Fig. 4: Measured power of the lasing mode by integration of the PSD for laser 1 and 2. (a) Measurement over the operating range for different temperatures (laser 1). (b) Measurements in the threshold region and fitting to (2).

Fig 4b is more interesting as it shows the power transition in the threshold region. The fitting is made to the more precise expression[5]:

$$(FP)^2 - (I - I_{th} - I_s)FP - I_s I = 0 \tag{2}$$

where I_s is a spontaneous emission term. Results of the fitting are given in Table 1.

As can be seen in Fig. 4b, measurements fit very well to the theoretical behavior given by (2). Measuring this with a photodetector normally leads to an overestimation of the mode power, as below threshold all modes contribute to the power, and (2) does not give a good fitting. In the case that the direct measurement of a standard OSA is used, the filter bandwidth must be carefully selected as a broad filter will have a certain power offset due to noise while for a tight one some power may be outside the filter.

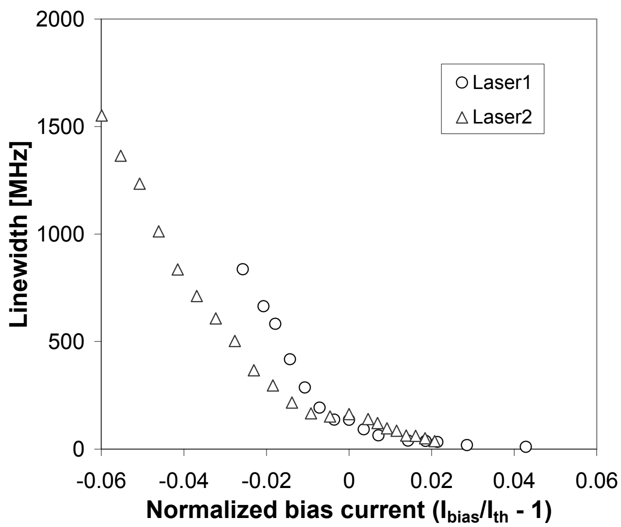
4.2. Laser linewidth and linewidth enhancement factor

The linewidth of the DFB laser can be calculated quite precisely if we take (1) into account. The Voigt function has been extensively studied and we can use an easier expression to calculate laser linewidt[12]:

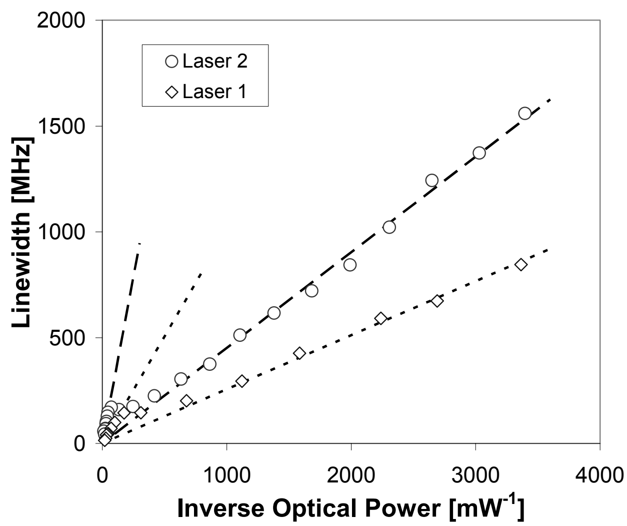
$$\gamma_M = 0.5346\gamma_L + \sqrt{0.2166\gamma_L^2 + \gamma_G^2} \tag{3}$$

where γ_M is the measured linewidth. From (3) we can deduce that the overestimation in the measured linewidth value is only important when the laser linewidth is comparable to the bandwidth of the analysis filter.

Linewidth values corrected with (3) are shown in next figure. The dependence of the linewidth with emitted power is quite complex[13]. We can see how linewidth is much greater below threshold, as the contribution from spontaneous emission is dominant. The threshold region can be identified as a local maximum of the linewidth, and the linewidth continues decreasing.



(a)



(b)

Fig. 5: Measured linewidth in the threshold region, corrected with (3) and represented versus (a) normalized bias current, and (b) inverse optical power. Asymptotic behaviors for (b) are represented with dashed lines.

In Fig. 5b, asymptotic behaviors of the linewidth versus the inverse optical power shown, following the Schawles-Townes[14] and Henry laws[15]. Linewidth enhancement factor, also know just as α parameter can be calculated from those two laws applying[16]:

$$\alpha = \sqrt{2\frac{\Delta\nu_{>}}{\Delta\nu_{<}} - 1} \tag{4}$$

where $\Delta\nu_{>}$ and $\Delta\nu_{<}$ are the slopes above and below threshold respectively. Calculated α parameters using (4) are given in Table 1.

Linewidth enhancement factor can also be measured using a network analyzer and using the transfer function after propagation through some hundreds of kilometers of fiber. This widespread method was proposed by Devaux et al.[6] and it requires typically around 100 km of fiber and a network analyzer with 20 GHz bandwidth. Measurements with this technique gives good agreement.

		Laser 1	Laser 2
Ith	mA	13.9	21.6
Is	mA	7.78e-5	2.24e-4
F	A/W	12.59	12.15
α		2.63	3.60

Table 1: Measured parameters

4.3. Relative intensity noise and relaxation oscillations

The presence of intensity noise was revealed in Fig. 3. The expression of the relative intensity noise is well-known[10]:

$$RIN(\omega) = \frac{2R_{sp}\left\{\left(\Gamma_N^2 + \omega^2\right) + G_N\overline{P}\left[G_N\overline{P}(1 + N/\tau_c R_{sp}\overline{P}) - 2\Gamma_N\right]\right\}}{\overline{P}\left[(\Omega_R - \omega)^2 + \Gamma_R^2\right]\left[(\Omega_R + \omega)^2 + \Gamma_R^2\right]} \tag{5}$$

where R_{sp} is the rate of spontaneous emission into the lasing mode; Γ_N is the decay rate of the carrier fluctuations; G_N is the threshold gain; P is the average photon number; N is the electron number; τ_c is the carrier lifetime ; Ω_R is the relaxation oscillations peak frequency; and Γ_R is the damping rate of the relaxation oscillations.

From (5) we can see that the RIN should exhibit a maximum coinciding with the relaxation oscillations peak frequency. This maximum is observed in Fig. 3 and can be easily measured in the optical spectrum. The common method for the measurement of the relaxation oscillation peak frequency is measuring the laser transfer function with a network analyzer[17].

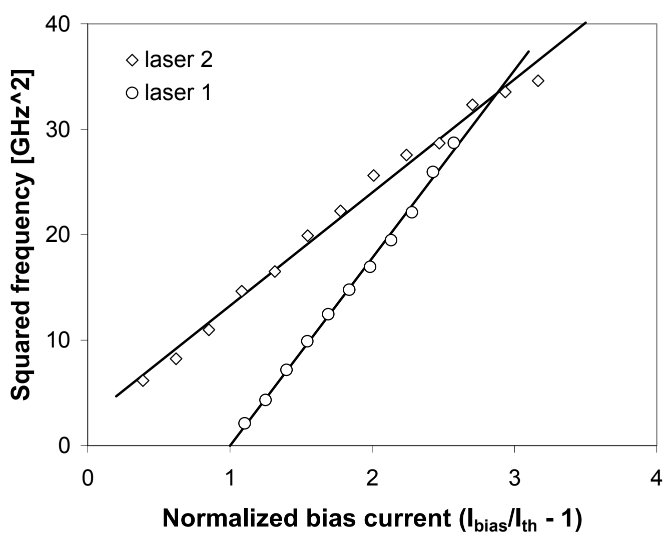


Fig. 6: Measured relaxation oscillations peak frequency (squared) measured from the optical spectrum.

The measurement of RIN from the high-resolution optical spectrum is also very direct for frequencies far enough from the peak of emission, where it is dominant over laser phase noise. We can apply the following definition of RIN:

$$RIN(f) = \frac{PSD(f)}{< P >} \tag{6}$$

Both the PSD and the average mode power can be measured quite directly as explained in section 2. We have measured the RIN for 3 GHz and the maximum RIN. For 3 GHz measurements, phase noise is comparable to intensity noise and introduces a certain error. That can be corrected subtracting the profile of the phase noise. This is shown in Fig. 7a. The measurements after this slight correction give a linear behavior when represented in logarithmic scale for both axes. Results are shown in Fig. 7b.

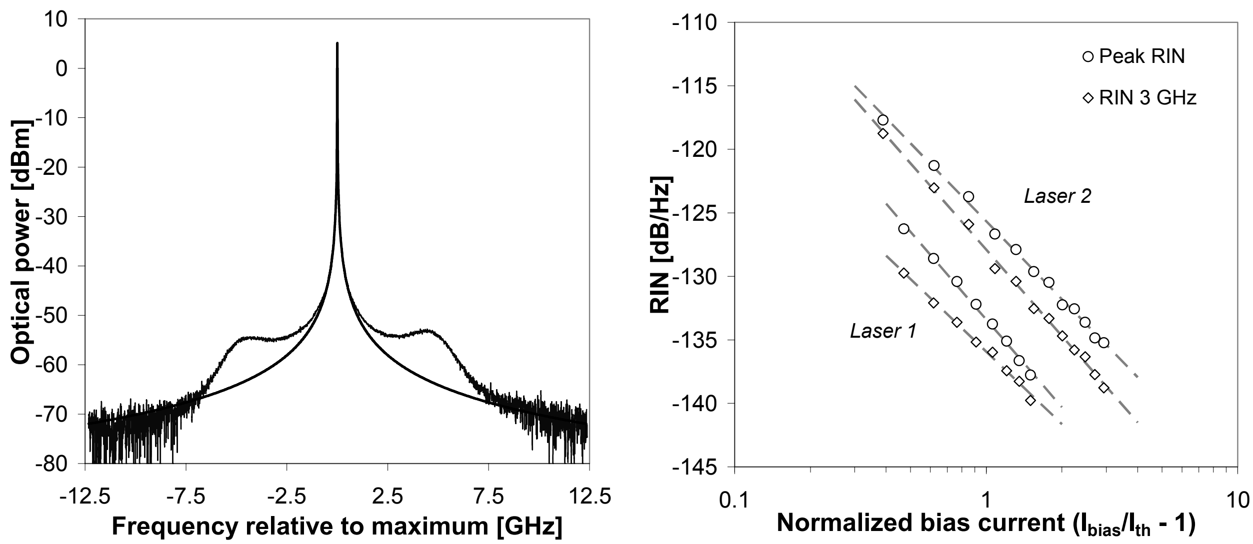


Fig. 7: (a) Optical spectrum of laser 1 and fitted phase noise profile for RIN corrections. (b) Relative intensity noise as a function of the normalized bias current for 3 GHz and maximum RIN.

For a deeper analysis of the RIN as a function of frequency, a fitting of the whole spectrum to the sum of the phase noise profile and the intensity noise should be done, but it will be accomplished elsewhere.

5. CONCLUSSION

We have presented results from the characterization of the main work parameters of two DFB lasers from measurements of its optical spectrum at continuous emission mode, measured with a high-resolution optical spectrum analyzer (BOSA-C from Aragon Photonics). The main advantage of the proposed methods is their inherent simplicity: the lasers have to be manipulated minimally, as only a bias current must be applied, and only one equipment is used for all the measurements. Furthermore, results have proved to be very detailed and are consistent with other more traditional methods of measurement.

The measurement of the power response, the linewidth and linewidth enhancement factor, the relaxation oscillations (and thus the maximum modulation frequency) and the relative intensity noise have been accomplished. This combined with some more direct measurements that can be performed also in CW operation, such as the emission wavelength and its shift with bias current and temperature, give a very precise characterization of the laser properties for its use in communications systems or to perform accurate simulations.

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