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TR2015-017 March 2015

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Optical Fiber Communication Conference and Exposition (OFC)

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Separation of semiconductor laser intrinsic linewidth and 1/f noise using multiple fiber lengths with the delayed self-heterodyne method

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Abstract:
We proposed a method of measuring the intrinsic linewidth of semiconductor lasers, by using self-heterodyne method with multiple measurements of different delay fiber lengths. By eliminating the $1/f$ noise effects, the linewidth becomes much smaller than the conventional measurement method.

OCIS codes: 230.3120 Integrated optics devices; 120.3688 Lightwave analyzers; 140.5960 Semiconductor lasers.

1. Introduction

Semiconductor lasers for coherent communications require narrow spectral linewidth. What affects coherent communications most is the so-called white frequency-modulation (FM) noise, or intrinsic linewidth, originating from the fundamental quantum mechanics. This component is flat from very low frequency to very high frequency. Typical and most convenient way of measuring the laser linewidth is to use a delayed self-heterodyne interferometer (DSHI) [1], in which the original laser light and its frequency-shifted and delayed replica are combined together. This is a widely used method. However, the laser FM noise components consists of the white FM noise and so-called $1/f$ noise, and the spectrum obtained by DSHI cannot distinguish them [2, 3]. In a coherent communication systems, the effect of low frequency noise can be eliminated by proper signal processing [4]. Therefore, it is important to separate the two components.

A method of measuring FM spectra have been proposed [5]. This is a direct way to separate the white FM noise and $1/f$ noise. However, it is not easy to maintain the laser wavelength at a certain point of the frequency discriminator, and active feedback is required. Alternatively, a method of using a coherent receiver and a reference narrow linewidth laser was proposed [6]. However, setting up a coherent receiver with a separate local oscillator requires extra effort. We propose a method of using multiple delay fiber lengths and separate the two components. In addition, we offer an analytical formula for calculating the convoluted linewidth instead of integrating fast oscillating functions.

2. Linewidth formulation

Using the most common method, i.e., delayed self-heterodyne method, the output signal spectrum $I(f)$ is given by [3]

$$I(f) = \mathscr{F}\left[\exp\left\{-4\int_0^\infty S(f')\frac{\sin^2 \pi f' t}{f'^2}(1-\cos 2\pi f'\tau_d)\,\mathrm{d}f'\right\}\right], \tag{1}$$

where f is a measured frequency, $\mathscr{F}$ is the Fourier transform, and the FM noise spectrum $S(f)$ is expressed as

$$S(f) = \Delta\nu/\pi + K/f, \tag{2}$$

where $\Delta\nu$ is the intrinsic laser linewidth and the first term represents the so-called white FM noise, whose intensity is constant across the whole frequency range, while the second term K/f is a so-called $1/f$ noise, whose intensity increases as the frequency becomes lower.

Typically, the effect of the K/f term is ignored, and the laser linewidth is measured just by measuring the HWHM (Half-width full maximum) of the measured spectrum $I(f)$.

This is acceptable if the term $\Delta\nu/\pi$ is dominant, but as the laser power P increases, $\Delta\nu$ becomes smaller as $1/P$, and the effect of the K/f term cannot be ignored. In fact, even if the laser power is increased, the laser linewidth does not decrease and sometimes increases (re-broadens).

In calculating Eq. (1) combined with Eq. (2), the most time consuming part is the integration. Therefore, instead of integrating numerically, we used a closed form integration as follows, which saves a large amount of computational time.

$$\int_0^\infty \frac{\sin^2 \pi f' t}{f'^2}(1-\cos 2\pi f'\tau_d)\,\mathrm{d}f' = \frac{1}{4}\pi^2(2|t| - |\tau-\tau_d| + 2|\tau_d| - |\tau+\tau_d|), \tag{3}$$

$$\int_0^\infty \frac{1}{f'}\frac{\sin^2 \pi f' t}{f'^2}(1-\cos 2\pi f'\tau_d)\,\mathrm{d}f' = \begin{cases} \frac{1}{2}\pi^2\left(4\,\tau\,\tau_d\,\mathrm{atanh}(\tau_d/\tau) + \tau_d^2\,\ln(-1+\frac{\tau^2}{\tau_d^2}) + \tau^2\,\ln(1-\frac{\tau_d^2}{\tau^2})\right), & (\tau_d^2 < \tau^2), \\ 2\pi^2\,\tau_d^2\,\ln(2), & (\tau_d^2 = \tau^2\ \&\ \tau_d > 0), \\ \frac{1}{2}\pi^2\left(4\,\tau\,\tau_d\,\mathrm{atanh}(\tau/\tau_d) + \tau_d^2\,\ln(1-\frac{\tau^2}{\tau_d^2}) + \tau^2\,\ln(-1+\frac{\tau_d^2}{\tau^2})\right), & (\tau_d^2 > \tau^2). \end{cases} \tag{4}$$

In this paper, multiple self-heterodyne measurement will be conducted, with different delay fiber lengths. In this way, $\tau_d = L_f n/c$ is changed at each measurement, where L_f is the fiber length, n is the refractive index of the optical fiber, and c is the speed of light. Then we obtain different spectrum $I(f)$ at each measurement.

3. Measurement

We used one element of 12-element tunable DFB laser array. Each element is a 1200 μm-long DFB laser. The threshold current was 24.2 mA. The slope efficiency was 0.067 W/A, monitored from the back side of the DFB laser.

Square points in Fig. 1 shows a 3 dB BW (half width) measured using the delayed self-heterodyne method, with the delay fiber length of $2, 3, 10$, and 25 km, respectively. The red line is the linewidth, calculated using $\Delta\nu = 157$ kHz, and $K = 1.47 \times 10^9$ Hz^2.

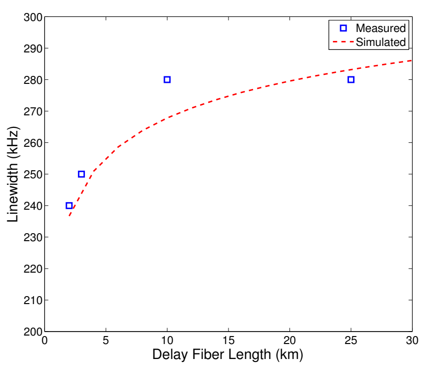

Fig. 1: Linewidth measured with delayed self-heterodyne method, and the fitting curve based on the values obtained from Fig. 2

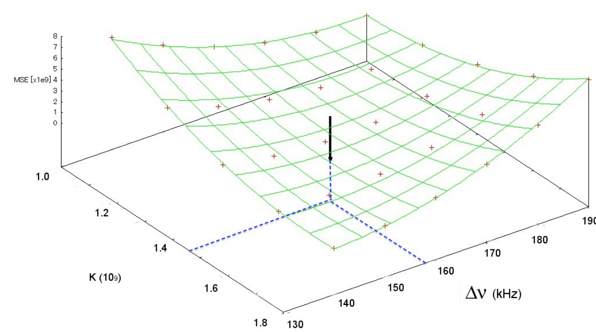

Fig. 2: Linewidth measured with delayed self-heterodyne method, and the fitting curve based on the values obtained

There may be multiple ways to separate $\Delta\nu$ and K by comparing the simulation and measurement results. The method we used is to calculate the 3 dB spectral width with different $\Delta\nu$ and K using Eq. (1), and extract parameters (such as 3 dB width, etc). (i.e., create a look up table.) For each combination of $\Delta\nu$ and K, we calculate the mean-square errors (MSE) for each measurements. The error surface can be fitted with a nonlinear function (for example, $ax^2 + bxy + cy^2 + dx + ey + f$) using least-squares fitting, and the best fit can be estimated from the global minimum of the curve surface easily. This is faster than calculating the spectrum each time, and try to find the best fit while updating the parameters.

Note that in some cases, low frequency noise can be described in a different way, such as K'/f^2 [4] or in some cases, multiple low frequency noise terms can appear. However, the same above procedure can be applied to these cases.

In order to validate this methodology, we measured the FM noise spectrum in an independent way. Figure 3 is an FM noise spectrum measured by a commercial equipment as a reference. By fitting Eq. (2), to the measured data, we measured $\Delta\nu = 162$ kHz, and $K = 1.2\times10^9$ Hz^2. This agrees very well with $\Delta\nu = 157$ kHz obtained from our proposed method.

The intrinsic linewidth $\Delta\nu$ obtained from the FM noise spectrum and the proposed method are plotted against the inverse of output power $1/P$ as shown in Fig. 4. They are on a straight line, showing no sign of re-broadening or saturation observed universally when a conventional delayed self-heterodyne method is used. It shows an importance of eliminating the effect of the $1/f$ noise, especially when evaluating very narrow linewidth semiconductor lasers.

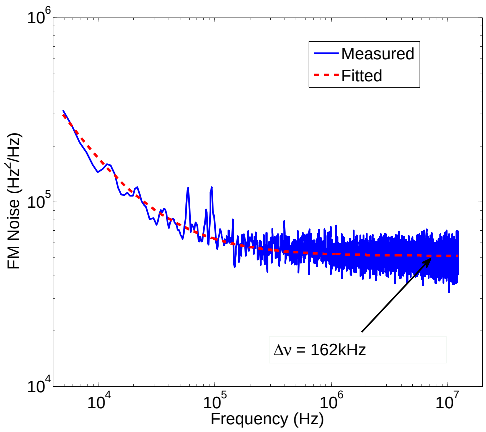

Fig. 3: Measured FM noise spectrum at 250mA injection current, and a fitted data using Eq. (2)

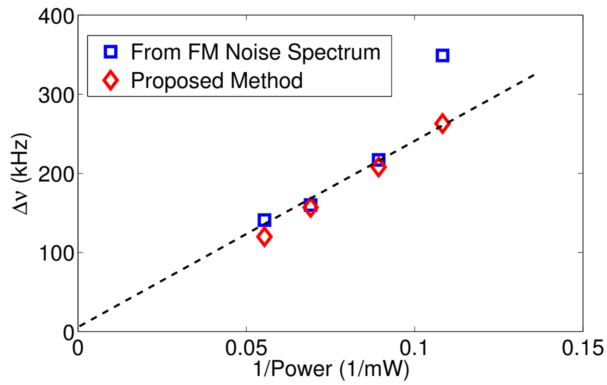

Fig. 4: $\Delta\nu$ obtained from the FM noise spectrum and from the proposed method, plotted against the inverse of output power.

4. Summary

We proposed a method of measuring the intrinsic linewidth of semiconductor lasers, by using the conventional self-heterodyne method, but with multiple measurements with different delay fiber lengths. By comparing this proposed method with a direct FM noise spectrum, we observed good agreements. It confirms that we can eliminate the effect of the $1/f$ noise using the delayed self-heterodyne method, and obtained the intrinsic linewidth around 120 kHz. We also offered an analytical formulate to simplify the calculation.

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