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# Phase noise measurement of a narrow linewidth CW laser using delay line approaches

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Two different laser phase noise measurement techniques are compared. One of these two techniques is based on a conventional and low-cost delay line system, which is usually set up for the linewidth measurement of semiconductor lasers. The results obtained with both techniques on a high-spectral-purity laser agree well and confirm the interest of the low-cost technique. Moreover, an extraction of the laser linewidth using computer-aided design tools is performed. © 2011 Optical Society of America

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The delay line technique is a low-cost and efficient approach for the measurement of the frequency fluctuations of frequency sources. Long optical delay lines (a few kilometers) are generally used in optics to reach a complete signal decorrelation and measure the laser linewidth by simply mixing this signal to the original laser signal on a photodiode [1]. In the microwave range, the same long optical delay lines are used in frequency discriminators, thus featuring an ultrahigh sensitivity [2]. When a high-spectral-purity laser is measured on this type of bench, the measurement conditions are similar to the ones observed in microwave frequency discriminators: the coherence length is no longer shorter than the delay line length, and the data measured at the system output are the frequency fluctuation spectrum of the laser [3–5]. However, compared to the frequency discriminator used for microwave source measurement, the use of an optical high sensitivity frequency discriminator faces different problems related to the frequency stability of the laser during the measurement time.

In this Letter, two techniques are compared for the measurement of laser short-term frequency fluctuations using an optical delay line. One of these techniques is based on a homodyne delay line technique, and uses a fast Fourier transform (FFT) signal analyzer; meanwhile, the other technique is based on a self-heterodyne approach and on the spectrum analysis close to an intermediate frequency of 80 MHz using a costly piece of equipment: an RF phase noise measurement bench.

The measurement bench is depicted in Fig. 1. The signal is delayed on one path using a 2 km fiber spool, followed by a polarization controller (optional). In the homodyne approach, this signal is directly recombined with the reference path, and the output of the coupler feeds a photodiode, which performs the quadratic detection.

When the laser under test is a high-quality laser, such as a fiber laser or an externally stabilized semiconductor laser, which typically feature a linewidth smaller than 10 kHz, the signal on both arms remains correlated and the output is proportional to the frequency fluctuations of the laser at low frequency offsets (frequency discriminator).

A classical approach to describe this system is to replace the frequency noise by a deterministic sinusoidal modulation [6]. In this case, the signal in both arms before the coupler can be written as

$$A_1(t) = \frac{A}{2} \cos\left(2\pi f_o(t - \tau) + \frac{\Delta f}{f_m} \cos(2\pi f_m(t - \tau))\right), \quad (1)$$

$$A_2(t) = \frac{A}{2} \cos\left(2\pi f_o t + \frac{\Delta f}{f_m} \cos(2\pi f_m t)\right), \quad (2)$$

where  $\tau$  is the delay between the two arms,  $f_o$  the optical frequency,  $f_m$  the noise frequency, and  $\Delta f$  the modulation amplitude (frequency noise). The quadratic detection leads to (mixing term only)

$$I(t) = S \frac{A^2}{4} \cos(-2\pi f_o \tau + \frac{2\Delta f}{f_m} \sin(\pi f_m \tau) \sin\left(2\pi f_m \left(t - \frac{\tau}{2}\right)\right)), \quad (3)$$

$S$  being the photodiode sensitivity. Equation (3) may be written as

$$I(t) = S \frac{A^2}{4} \cos(\varphi + x), \quad (4)$$

$\varphi$  being a constant phase and  $x$  a small amplitude component (noise). The derivative of this function versus  $x$

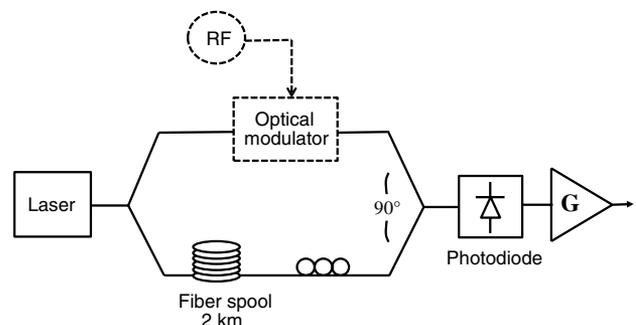


Fig. 1. Measurement bench for both approaches; the acousto-optic modulator is used in the self-heterodyne technique and removed for the homodyne technique. G, amplifier gain.

near  $x = 0$  allows us to linearize the output current and to determine the ratio of the output current amplitude and  $\Delta f$ , which is the sensitivity factor of the frequency discriminator,  $K_m$ :

$$K_m = S \frac{P}{2} \sin(\varphi) 2\pi\tau \frac{\sin(\pi f_m \tau)}{\pi f_m \tau}, \quad (5)$$

$P$  being the optical power received on the photodiode. While varying the phase  $\varphi$ , the output current changes from its minimum, which should be zero in a perfect interferometer, and its maximum  $SP$ . In practice, the minimum is never equal to 0 and  $SP$  is generally approximated by the peak-to-peak excursion of the output current.  $SP/2$  is thus the peak excursion of this current, which we note  $\Delta I_{\text{peak}}$  [1].

Ideally, the phase  $\varphi$  between the two arms should be adjusted to  $\pm\pi/2$  in order to maximize the frequency fluctuation detection. This is what is classically performed in a microwave frequency discriminator. However, in an optical experiment, such a precise phase control after a 2 km delay is impossible because of temperature variations. The phase  $\varphi$  rotations due to the slow temperature drift of the fiber spool can be observed at the system output. In our case,  $360^\circ$  rotations were reached every 200 or 300 ms. This means that, on a 15 min acquisition time, the complete phase rotations will reach 4000. Because of such a large number of phase rotations, and using also a large number of averaged spectrum (about 200 spectra), we expect the phase states to be equally spaced on  $360^\circ$  during the measurement. Such an approach is very close to the one of [4], in which a phase modulator had been introduced in the system. However, with kilometer-long delay lines, the phase modulator is no longer necessary: a natural phase shift occurs due to the slow temperature drift of the fiber spool. When a large set of phase state is considered, the effective  $K_m$  can be calculated from Eq. (5) by integrating on a complete phase rotation the quadratic value of  $K_m$  (it is a power spectrum that is detected):

$$K_{\text{meff}} = \frac{K_m}{\sqrt{2}} = \frac{\Delta I_{\text{peak}}}{\sqrt{2}} 2\pi\tau \frac{\sin(\pi f_m \tau)}{\pi f_m \tau}. \quad (6)$$

In our experiment, the photodiode is loaded on a resistance  $R$ , and the voltage signal is measured on a 100 kHz FFT spectrum analyzer (Advantest R9211B). The system calibration is performed by measuring  $\Delta I_{\text{peak}}$  using the oscilloscope mode of the FFT analyzer, and then  $K_{\text{meff}}$  is computed for a set of frequency  $f_m$ . In our case, the delay resulting from the optical line is  $9.5 \mu\text{s}$ . The laser frequency fluctuation spectrum is then calculated,

$$S_{\Delta f} = \frac{S_{V_{\text{output}}}}{R^2 K_{\text{meff}}^2}, \quad (7)$$

and the single-sideband phase noise spectrum can be calculated from the frequency noise spectrum,

$$L(f_m)_{\text{dBc/Hz}} = 10 \log \left( \frac{S_{\Delta f}(f_m)}{2f_m^2} \right). \quad (8)$$

The system sensitivity is determined by  $K_{\text{meff}}$  and the output noise due to any source of noise different from  $S_{\Delta f}$ : laser amplitude modulation (AM) noise, photodiode noise, Brillouin scattering in the fiber, etc. Generally, laser AM noise and photodiode noise are negligible in a long-line interferometer. However, with a delay in the kilometer range, the Brillouin threshold is lowered, and this noise may become the system noise floor. A compromise has thus to be found between long delay (high  $K_{\text{meff}}$ ), high optical power, and the setting up of scattering phenomena in the fiber.

The self-heterodyne technique applied to high-quality lasers has already been presented in [7] and will thus be described here very briefly. The measurement bench is depicted in Fig. 1, adding this time the optical acousto-optic modulator in order to shift the output signal around the RF, which in our case is 80 MHz. Then the signal is analyzed using a phase noise measurement bench at 80 MHz. Using the same approach developed for the homodyne case, it can be demonstrated [7] that the phase fluctuations of this 80 MHz RF signal are proportional to the laser frequency fluctuations  $S_{\Delta f}$  at low frequency offsets. More precisely,

$$L_{\text{RF}}(f_m) = 20 \log \left( \sqrt{2} \pi \tau \frac{\sin(\pi f_m \tau)}{\pi f_m \tau} \right) + 10 \log(S_{\Delta f}). \quad (9)$$

Using Eqs. (8) and (9), we may calculate the laser phase noise from the measured RF signal phase noise  $L_{\text{RF}}(f_m)$  in dBc/Hz:

$$L_{\text{laser}}(f_m) = L_{\text{RF}}(f_m) - 20 \log(2 \sin(\pi f_m \tau)). \quad (10)$$

The calibration in this case is performed by replacing the 80 MHz output signal by a frequency-modulated source of the same frequency and amplitude than the source under test, which is automatically performed in modern phase noise measurement benches. Compared to the first approach, this approach is quite easy but requires much more sophisticated and costly equipment, particularly an RF phase noise measurement bench.

To compare the two approaches, the phase noise characterization of a commercial  $1.55 \mu\text{m}$  fiber laser (Koheras Adjustik) has been performed.

Using the homodyne approach, 200 spectra are averaged on three different and overlapping frequency bandwidths (600 spectra for the whole measurement). The acquisition time (10 to 15 min) allows the random phase repartition, and the spectrum becomes remarkably well defined and stable after about 50 averages. The FFT analyzer is a relatively low-cost piece of equipment, and, moreover, no RF synthesizer or optical modulator is required.

The self-heterodyne approach has been performed using a high-power 80 MHz source to drive the acousto-optic modulator, and the signal is measured at the output using an Agilent E5052B signal source analyzer, which is a high-performance phase noise test set that includes a self-calibration procedure.

The result of both measurements is depicted in Fig. 2. A good agreement is observed, which validates our approach for the homodyne technique.

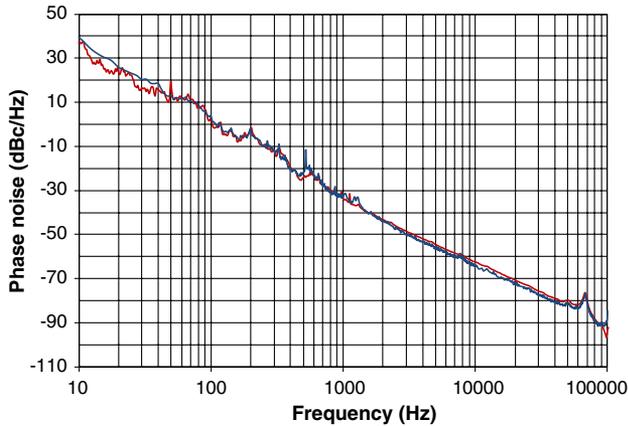


Fig. 2. (Color online) Phase noise measurement of a high-quality fiber laser (Koheras Adjustik) delivering 30 mW optical power at  $\lambda = 1.55 \mu\text{m}$  using the two techniques (homodyne technique in blue and self-heterodyne technique in red).

From the frequency noise or the phase noise spectrum, it is possible to evaluate the laser linewidth. It is indeed common to specify a laser through its linewidth, although for very-high-spectral-purity sources this parameter cannot be measured directly and has thus a very limited practical interest. What is measured effectively is the frequency noise or the phase noise spectrum, and the linewidth evaluation requires a computation process from these data. Such a link between phase noise and power spectrum is a complex problem that has been the purpose of many papers, and [8–12] only represent a short selection of these papers. The only case that can be computed analytically is the one of white frequency noise [8], which leads to a Lorentzian line shape. However, for the type of laser concerned in this Letter, almost all the laser power is determined by the  $1/f$  part of the spectrum, and the Lorentzian formula is useless. The computation of the linewidth in the case of pure  $1/f$  noise is more complex [9–12], and only a computer-based approach may solve the problem for an arbitrary phase noise spectrum with a combination of different slopes [11].

To get an estimate of the laser linewidth, we have used an original approach based on the simulation of the power spectrum using a commercially available microwave computer-aided design software, Agilent Advanced Design System. This software allows the description of a noisy frequency source through its phase noise spectrum. Moreover, it includes a simulation module based on the envelope technique [13], which allows the computation of slow perturbations of the carrier, such as modulations by deterministic or noisy signals. The result of the simulated spectrum for our laser is represented in Fig. 3. As the simulated spectrum changes with the window used for both the phase noise description and the base-band temporal analysis window, we have considered for the simulation the phase noise data between 100 Hz and 100 kHz, and we have set a maximum computation time of 0.5 s. The simulated result is a 3 dB full linewidth of about 5 kHz. This result has been compared to the simplified approach of [12]. The frequency noise spectral

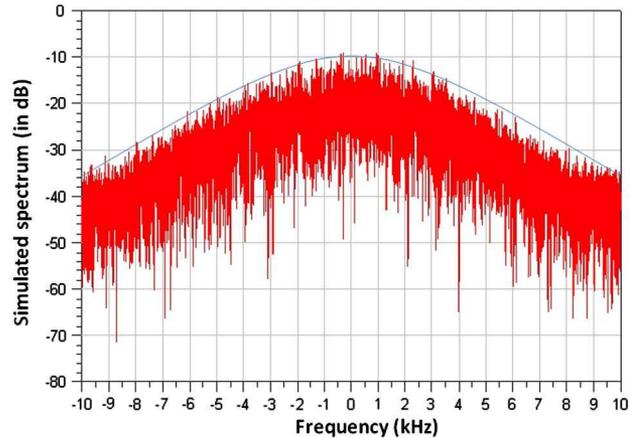


Fig. 3. (Color online) Laser power spectrum versus the offset from the carrier frequency simulated from the phase noise data using Agilent Advanced Design System and the envelope simulation technique.

density of our laser can be roughly described by the following equation:

$$S_{\Delta f}(f) = \frac{k}{f} \quad \text{with } k = 10^6 \text{ (Hz}^2\text{)}. \quad (11)$$

Using Eq. (12) of [12] and taking into account an integration time  $T_o = 0.5 \text{ s}$ , a linewidth of 6 kHz is computed for this laser, which is in relatively good agreement with the result of the envelope simulation approach.

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