Characterisation of Laser Phase Noise using a Digital Coherent Receiver

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Abstract: We describe the use of a digital coherent receiver to measure laser phase noise by recording the simultaneously beat signal of the laser under test with two independent reference lasers. The corrections for the non-ideal nature of the measurement equipment and the method to extract the FM noise spectrum of the test laser alone from the three beat signals is described. The FM noise spectrum of a DFB laser and an external cavity grating tuned laser are presented.

1. Introduction.

Laser phase noise represents the deviation of the phase of the laser output electric field from that of an idealised electromagnetic simple harmonic oscillator. The effect of this phase noise is to broaden the lasing line width and reduce the optical coherence length. The drive towards more spectrally efficient modulation formats with coherent optical detection has led to the data being coded onto the carrier phase as well as its amplitude. It is estimated that the product of line width and symbol period must be less than 1.6×10^{-3} for QPSK[1] and less than 1×10^{-4} for 16QAM[2] to ensure that the data can be recovered with minimal penalty. The requirements on the carrier phase noise are even more stringent for Coherent Optical-OFDM as a result of the longer sub-carrier symbol periods[3] .

Many techniques have been developed to measure the phase noise of optical sources. These include frequency discriminator techniques based on unbalanced Michelson interferometers[4] or Fabry Perot filters, optical phase locked loops[5], delayed self homodyne, delayed self heterodyne and recirculating delayed self heterodyne techniques[6], and those based on the heterodyne beat with a reference laser[7]. In this paper the measurements are made using the later technique.

There are numerous techniques available to analyse the frequency stability of an oscillator [8]. The simplest specification for a laser is through the line width. A more detailed description requires knowledge of the power spectral density of the laser frequency fluctuations as a function of frequency, the FM noise spectrum. A white FM noise spectrum leads to a Lorentzian line shape however at lower frequencies the 1/f flicker noise and $1/f^2$ random walk noise dominate and these result in a laser line width that is a function of the observation time.

2. Measurements.

The basic measurement method is to use a digital coherent optical receiver to measure the in-phase and quadrature phase components of the laser field under test by mixing with the local oscillator field from two low phase noise reference lasers. The in-phase and quadrature phase components are digitized by a fast real time digital oscilloscope for later analysis. A RF synthesiser is used to provide a stable electrical reference phase.

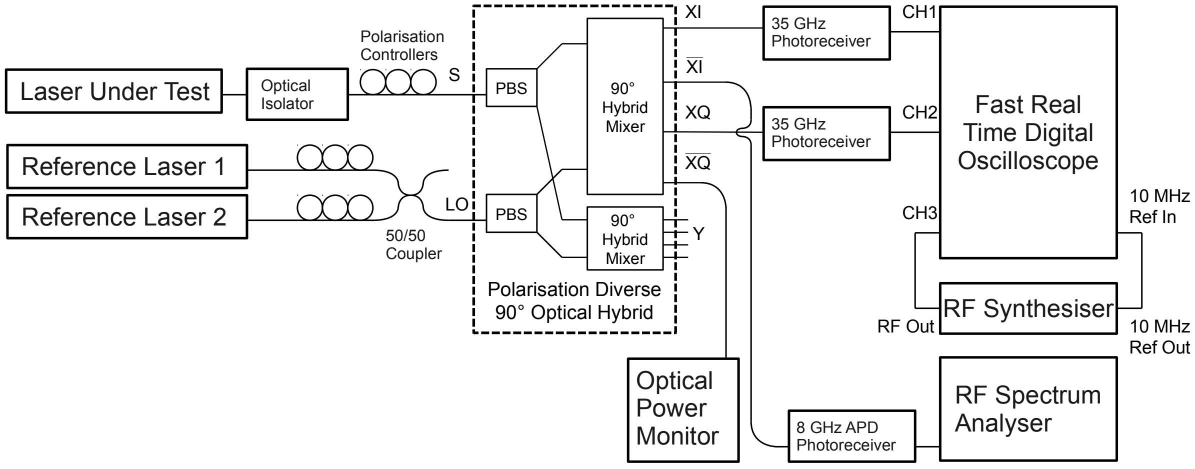

Figure 1, Experimental arrangement.

The experimental set up is shown in figure 1. The laser under test is connected through an optical isolator and a polarisation controller to the signal input of the polarisation diverse 90° optical hybrid. The reference lasers were connected through individual polarisation controllers and a 50/50 coupler to the local oscillator input of the polarisation diverse 90° optical hybrid. Only the x-polarisation outputs from the polarisation diverse 90° optical hybrid were used. The in-phase and quadrature phase outputs were connected to two 35 GHz receivers the output of which were connected to the 1st and 2nd channels of a fast real time digital oscilloscope. The inverse in-phase output was connected to an optical power monitor while the inverse quadrature phase output was connected to an 8 GHz APD receiver the output of which was connected to an electrical spectrum analyser. A RF synthesiser was used as a frequency reference by providing a 10 MHz reference and also by providing a pure 1 GHz tone to the 3rd input channel of the fast real time digital oscilloscope.

The laser under test was tuned to give a beat signal at ~1.5 GHz and ~4.5 GHz with the 1st and 2nd reference laser by observing the beat signal on the electrical spectrum analyser . The beat signal between the two reference lasers was at ~3 GHz. The 35 GHz receivers have AC coupled outputs and allow for approximately ± 200 mV of linear swing. In order to maximise the AC component of the signal the laser under test and the reference lasers were set with equal power falling onto the receivers. The receivers had a gain of approximately 600 V/W such that for a detected power of 50 µW from each of the three laser the receiver output will swing from approximately -90 mV to +180 mV. The power of each laser was set by adjusting the polarisation controller so that the x-polarisation component from each laser was 50 µW as observed on the optical power monitor.

The fast real time digital oscilloscope was used to digitise and record the in-phase, quadrature phase and reference tone signals. 10 separate repeated traces were recorded with the signals sampled at 20 GSa.s^{-1} for 32 MSa (an epoch of 1.6 mS).

3. Calculations.

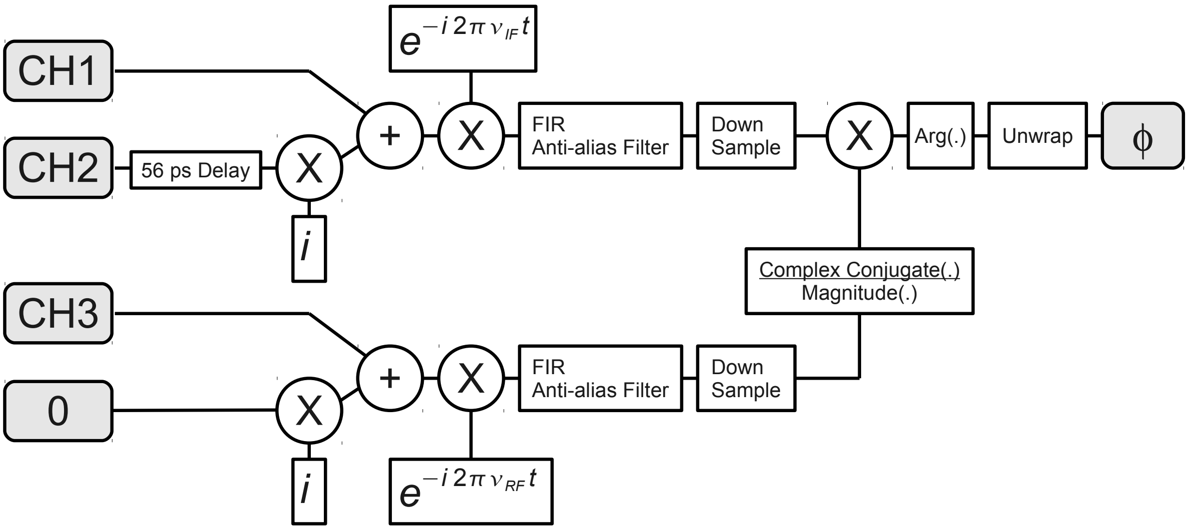

Figure 2, Outline of phase extraction process.

The recorded data was processed in MATLAB to obtain the phase noise characteristics. The process to obtain the phase difference between each of the laser pairs is illustrated in figure 2. The first stage of data processing was to combine the data from channel 1 and 2 to form a single complex data set, in this process a known delay of 56 ps was added to the quadrature phase (channel 2) signal by simple interpolation. This corrects a hardware delay within the coherent optical receiver. The complex data was analysed three times, once for each of the three beat signals, that between reference 1 and the laser under test, that between reference 2 and the laser under test and that between the two reference lasers. For each beat the intermediate frequency (IF) was removed and the data down sampled by 16 times to give data at 1.25 GSa.s^{-1}. The down sampling was carried out to reduce the overall amount of data for subsequent processing, to improve the signal to noise by effectively averaging over time and to average across the 16 parallel ADC within the oscilloscope which significantly reduced the pattern noise created by variations between the ADCs. An anti-aliasing FIR filter was calculated based on the truncated Fourier transform of a raised cosine frequency response with roll off factor 0.5. A 192 tap filter gave a frequency response that was flat to within ±0.07 dB over half the final down sampled Nyquist frequency (312.5 MHz). The removal of the IF and down sampling was carried out in the time domain to avoid large data arrays. A block of 192 samples was multiplied by $e^{-i2\pi\nu_{IF}t}$ to remove the IF, ν_{IF}, and then multiplied by the FIR filter coefficients before summation over the block to give one down sampled point. The block was moved along in 16 point steps and the calculation repeated to down sample the entire signal. Channel 3 was treated in the same way except that the imaginary part was initially set to zero.

The phase difference between the laser under test and the 1st reference laser was calculated from the down sampled beat signal this was multiplied by the complex conjugate of the down sampled channel 3 and divided by the absolute magnitude of the down sampled channel 3. This corrects for electrical phase errors within the oscilloscope and is possible since the timing errors between the channels appeared to be correlated. The phase of the corrected signal was found from its argument and this was unwrapped to obtain the phase difference. The frequency variation was calculated as the difference between successive phase samples divided by $2\pi\cdot dt$, where dt is the sample interval 0.8 ns. The power spectral density of this FM noise was calculated by multiplying the time dependent frequency variation by a Hann window before Fourier transforming into the frequency domain and calculating the power spectral density.

This gives us the FM noise spectra for the three beat signals. Each FM noise spectra is the summation of the FM noise power from the two lasers creating the beat signal, thus it is possible to extract the FM noise spectra of the laser under test alone using[8],

$$S_{LUT}=\frac{1}{2}\left(S_{R1,LUT}+S_{R2,LUT}-S_{R1,R2}\right) \tag{1}$$

where S is the power spectral density of the FM noise as a function of frequency and the subscripts refer to the lasers producing the beat, 1st reference laser (R1), 2nd reference laser (R2) and the laser under test (LUT). This technique known as the three cornered hat[8] is only reliable if the phase noise of the reference lasers are comparable or lower than that of the laser under test.

4. Results

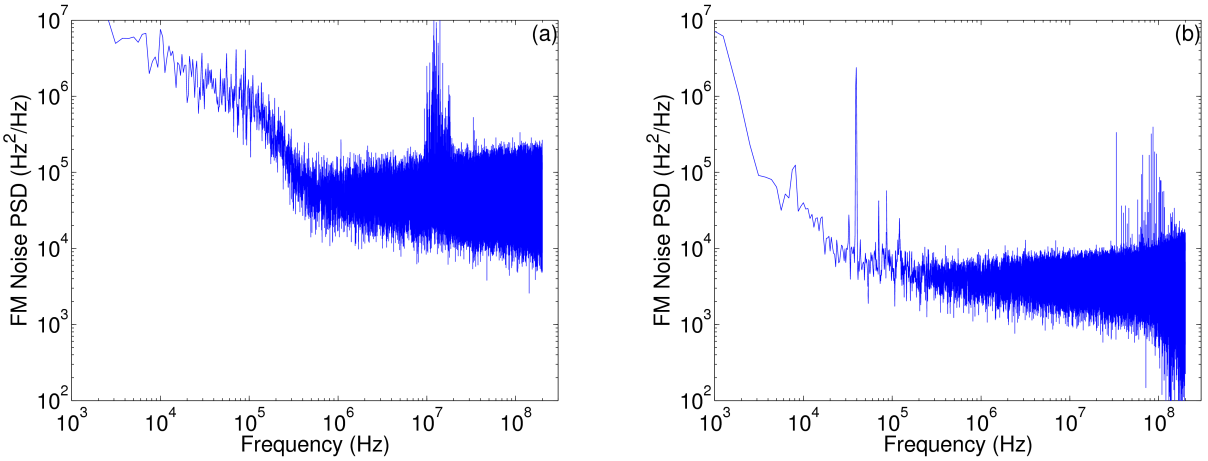

Figure 3, Measure FM Noise spectra of a) a DFB laser and b) a grating tuned external cavity laser.

Figure 3a shows the FM Noise spectra of a DFB laser. It clearly demonstrates white frequency noise of 53400 $Hz^2.Hz^{-1}$ equivalent to a Lorentzian line width of 340 KHz with a 1/f flicker noise component visible at lower frequencies. Figure 3b shows the FM noise spectra of a grating tuned external cavity laser again a white frequency noise component of 4140 $Hz^2.Hz^{-1}$ equivalent to a Lorentzian linewidth of 26.0 KHz and a 1/f flicker noise component visible at lower frequencies.

Figure 4 shows the FM noise spectra of the reference lasers. This is half the combined FM noise of the reference 1, reference 2 beat signal. The spectra demonstrates three FM noise components, the white frequency noise of 301 $Hz^2.Hz^{-1}$ equivalent to a Lorentzian linewidth of 1.9 KHz, a 1/f flicker noise component visible at lower frequencies and an f^2 component at higher frequencies. The f^2 component is a white phase noise contribution from the white noise in the measurement equipment.

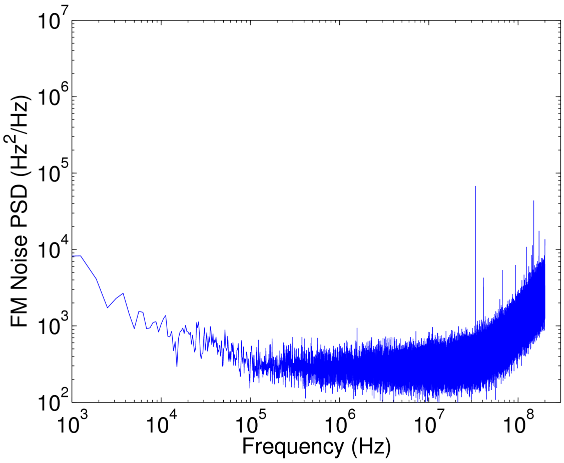

Figure 4, FM Noise spectrum of the reference lasers.

5. Conclusions.

We have described a phase noise measurement system based on a digital coherent receiver. The use of two low phase noise reference lasers allows the FM noise spectrum of the laser under test to be extracted from the measurement. The system has been demonstrated through measurements of the FM spectra of a DFB laser and an external cavity grating tuned laser. The FM noise spectra can be used to calculate the laser linewidth and other phase noise parameters.

Acknowledgments.

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References.

[1] M.G. Taylor, “Phase Estimation Methods for Optical Coherent Detection Using Digital Signal Processing,” *Journal of Lightwave Technology*, vol. 27, Apr. 2009, pp. 901-914.

[2] I. Fatadin, D.J. Ives, and S.J. Savory, “Laser Linewidth Tolerance for 16-QAM Coherent Optical Systems using QPSK Partitioning,” *IEEE Photonics Technology Letters*, vol. 22, Feb. 2010, pp. 631-633.

[3] X. Yi, W. Shieh, and Y. Ma, “Phase Noise Effects on High Spectral Efficiency Coherent Optical OFDM Transmission,” *Journal of Lightwave Technology*, vol. 26, May. 2008, pp. 1309-1316.

[4] Z. Meng, Y. Hu, S. Xiong, G. Stewart, G. Whitenett, and B. Culshaw, “Phase noise characteristics of a diode-pumped Nd:YAG laser in an unbalanced fiber-optic interferometer.,” *Applied optics*, vol. 44, Jun. 2005, pp. 3425-3428.

[5] S. Camatel and V. Ferrero, “Narrow Linewidth CW Laser Phase Noise Characterization Methods for Coherent Transmission System Applications,” *Journal of Lightwave Technology*, vol. 26, Sep. 2008, pp. 3048-3055.

[6] H. Tsuchida, “Characterization of White and Flicker Frequency Modulation Noise in Narrow-Linewidth Laser Diodes,” *IEEE Photonics Technology Letters*, vol. 23, 2011, pp. 727-729.

[7] T. Duthel, G. Clarici, C.R.S. Fludger, J.C. Geyer, C. Schulien, and S. Wiese, “Laser Linewidth Estimation by Means of Coherent Detection,” *IEEE Photonics Technology Letters*, vol. 21, Oct. 2009, pp. 1568-1570.

[8] W.J. Riley, “Handbook of Frequency Stability Analysis”, *NIST Special Publication 1065*, NIST, Boulder, CO 80305: 2008.