Improved Lightwave Synthetic Noise Generator Using Noise Injection and Triangular Modulation

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***Abstract*—Synthetic noise generators facilitate the generation of white noise in photo diodes. They simplify noise measurements on lightwave receivers significantly, compared to direct methods, shot noise methods, spontaneous emission methods, and laser-RIN methods. Previously reported generators required more than 1 km fiber delay length, to smooth the synthetic spectrum into a white noise spectrum. This letter proposes injection of electrical noise and triangular FM modulation to enable the use of narrow line width lasers in combination with short delay length.**

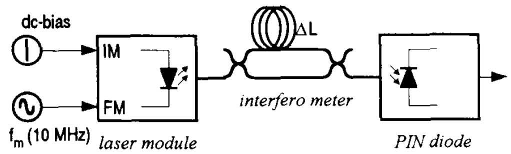

Fig. 1. Basic setup of a synthetic noise generator. $\Delta L = 10$ m, 1530 nm DFB laser, 60 dB isolation.

I. Introduction

NOISE measurements on lightwave receivers, using white noise sources with known noise levels, are simple and accurate. Similar electrical noise measurements are commonly used and recommended by IRE standards [1]. A convenient and commercially available lightwave noise generator is lacking, and therefore noise measurements on *lightwave* receivers are usually restricted to direct measurements.

- Direct methods require a separated measurement of receiver gain, to reconstruct the input noise from the measured output noise. As a result, they suffer from limited accuracy since the additional gain measurement must accurately incorporate all mismatch errors and all noise detection errors in the detected noise.
- An example of a white noise method is shot noise, generated by a laser [2], an LED [3] or an incandescent lamp [5]. Laser and LED methods are restricted to *balanced* pairs of photo diodes to suppress (unknown) laser RIN. All shot noise methods require large dc photo currents to generate adequate noise levels. This may overload unbalanced receivers.
- Amplified spontaneous emission [4] may provide higher noise levels for comparative dc currents. Nevertheless, the noise power is spread out over thousands of GHz.
- Lasers modulated with white electrical noise or lasers with high RIN may provide higher noise levels, however they are not white over a wide frequency band.
- Synthetic noise methods are most convenient for lightwave receiver noise measurements [5] and also applicable for electrical noise measurements [6]. The major advantages are that (1) the total rms-noise current is as high as 70% of the dc photo current and that (2) nearly all white noise power is applicable because the synthetic noise bandwidth is user definable. This makes the synthetic noise method superior to the previous methods.

The noise generator used in [5], was similar to the source proposed by Wang [7] for bandwidth measurements. Wang generated a synthetic white spectrum using the delayed self-homodyne spectrum of a DFB laser, which is well-known from laser linewidth measurements [8], [9]. Additionally, they modulated the laser frequency with a sinusoidal signal to spread out the homodyne spectrum over a very wide frequency band. The Wang experiment [7], however, required more than 1 km fiber length for adequate smoothing the synthetic noise spectrum.

We propose injection of electrical noise to reduce this delay length significantly. This enables the application of narrow linewidth lasers in synthetic noise generators, including multi section lasers. These lasers are preferred rather than DFB lasers due to their superior FM modulation performance. Without noise injection, their smaller linewidth would require several kilometers delay length to smooth the synthetic noise spectrum.

II. Basic Principle

Fig. 1 shows the basic principle of a synthetic noise generator. The laser output is FM modulated by a periodic modulation current (frequency f_m) over several GHz. The laser beam is split, one beam is delayed (τ) and both beams are combined in a fiber optic interferometer. The composite lightwave signal is essentially the composition of two FM modulated lightwave signals. When $f_m = 1/(2\tau)$, then their momentaneous frequencies oscillate symmetrically around a common mean value. A PIN photo diode illuminated with this composite signal generates a photo current that has essentially an FM line spectrum (see Fig. 2).

We extended the analysis of Wang to assess the spectral ripple, and simulated the FM spectrum using well-known FFT techniques (see Fig. 2). Fig. 3 shows the measured spectrum of the photo current, in case of sinusoidal and of triangular

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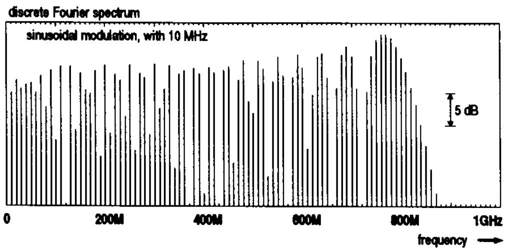

Fig. 2. The photo current has essentially an FM line spectrum, with equidistant lines.

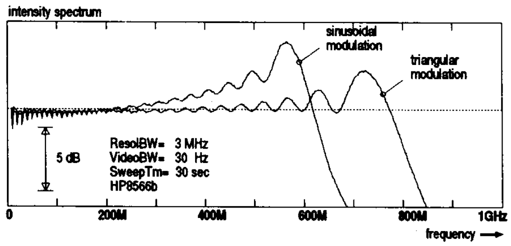

Fig. 3. Measured output spectrum of the synthetic noise source with 10 MHz modulation, 17 MHz linewidth laser, approximately 10 m differential delay and 0.8% bias current modulation.

modulation. The individual comb-lines are smoothed out by the laser line width, and the remaining ripple demonstrates a bumpy envelope of the synthetic noise spectrum. Section IV discusses additional smoothing methods to improve the spectral flatness.

III. Theory of Operation

The sensitivity of the setup in Fig. 1 is significantly higher for FM then for IM modulation. Remaining IM components are suppressed because the modulated laser fields $e(t)$ and $e(t-\tau)$ are 180° out of phase when $f_m = 1/(2\tau)$ holds. As a result, we focus this analysis on FM modulated laser beams.

- *Photo current* The photo current $I_p(t)$ that results from the (in) coherent mix of two interfering FM beams is:

$$I_p(t) = I_{p0} \cdot (\cos(\Delta\alpha(t)) + 1) \tag{1}$$

$$\text{in which:} \quad \Delta(t) \stackrel{\text{def}}{=} \alpha_0 + \Delta\varphi(t) + \Delta\theta(t)$$
$$\varphi(t) \stackrel{\text{def}}{=} \varphi(t) - \varphi(t-\tau) = \text{periodical}$$
$$\theta(t) \stackrel{\text{def}}{=} \theta(t) - \theta(t-\tau) = \text{random}$$

  In which α_0 is an initial phase constant, $\Delta\varphi$ a differential phase due to periodical FM modulation, $\Delta\theta$ a differential phase due to laser phase noise, and I_{p0} a constant.

- *Noise power* When $\Delta\theta_{\text{rms}} \gg \pi$ *(incoherence threshold)*, then (1) shows that the photocurrent is fluctuating at random between zero and $2 \cdot I_{p0}$. Far above this incoherence threshold the rms-value of the random noise current is:

$$(i_{\text{rms}})^2 = I_{p0}{}^2 \cdot \langle \cos^2(\Delta\alpha(t)) \rangle = \frac{1}{2} \cdot I_{p0}^2 \tag{2}$$

  As a result, the rms-value is independent on the FM modulation depth of the beam. Furthermore, up to 70% of the generated dc current I_{p0} is available as noise current.

- *Spectral width* The phase $\varphi(t)$ of the periodical FM modulated laserbeam is:

$$\varphi(t) = 2\pi \cdot M. \int_{-\infty}^{t} I_m(t) \cdot dt \tag{3}$$

  In this expression is M the FM response of the laser and $I_m(t)$ the bias modulation current. When $I_m(t)$ is sinusoidal, and the random differential phase $\Delta\theta(t)$ is zero, then an FFT transform of equation 1 yields a spectrum similar to the FM spectrum in Figure 2. The distance between the comb-lines equals to the modulation frequency f_m. The spectral width of this line spectrum equals roughly to the maximum lightwave frequency difference of the laser fields $e(t)$ and $e(t-\tau)$. This difference is maximal for $f_m = 1/(2 \cdot \tau)$, which makes the spectral width roughly twice the modulation depth:

$$B \approx 2 \cdot M \cdot I_{\text{m,top}} \tag{4}$$

- *Spectral components* Any non-zero random phase $\theta(t)$ will transform the line spectrum in Fig. 2 into a comb spectrum, due to phase noise. Far above incoherence threshold ($\Delta\theta_{\text{rms}} \gg \pi$), spectral calculus simplifies significantly since the spectral intensities $\mathbf{S}\{\cos(\Delta\theta)\}$ and $\frac{1}{2} \cdot \mathbf{S}\{\exp(j \cdot \Delta\theta)\}$ becomes equal. As a result, the total spectral intensity $S_i(f)$ of the photo current $I_p(t)$ is simply the addition of the individual comb spectra, and equals to:

$$S_i(f) = \sum_n \{|Q_n|^2 \cdot S_{\text{ih}}(f + n \cdot f_m)\} \tag{5}$$

  In this expression are Q_n discrete Fourier coefficients, resulting from an FFT transform of $\exp(j \cdot \Delta\varphi)$. They are shown in Figure 2. The spectrum $S_{\text{ih}}(f) = \mathbf{S}\{I_{p0} \cdot \cos(\Delta\theta(t))\}$ is the spectral envelope of each combline in the spectrum. The simplest way to find that spectrum is measurement of $S_i(f)$ when all periodical modulation is switched off *(homodyne spectrum)*. As a result, the overlap of all comb-lines yields a continuous intensity spectrum, as illustrated in Fig. 3.

- *Spectral intensity* (2) demonstrates that far above incoherence threshold the rms-value of the synthetic noise current is invariant to the modulation depth. Using the well-known Parceval identity for spectra, the square of this rms-value equals to the product of the spectral width B and the average spectral intensity S_{i0}. As a result, this synthetic noise level is (in combination with equation 4):

$$S_{i0} \approx \left(\frac{1}{2} \cdot I_{p0}^2\right) \Big/ B \approx (I_{p0}^2)/(4 \cdot M \cdot I_{\text{m,top}}) \tag{6}$$

- *Incoherence restrictions* This analysis is restricted to operation above incoherence threshold. An increase of τ will increase the incoherence between both laser beams. As a result, the incoherence restriction is roughly equivalent with the restriction that the delay time τ must be larger than the coherence time τ_c of the laser.

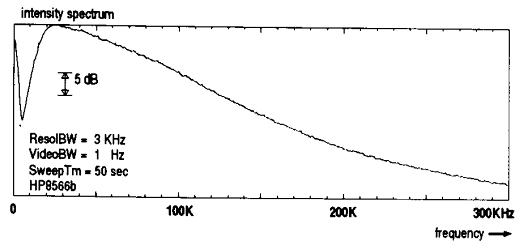

Fig. 4. Measured spectrum of the (pink) noise that was injected to broaden the individual comb-lines.

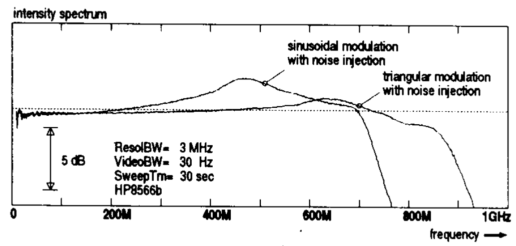

Fig. 5. Measured output spectrum of the synthetic noise source with noise injection. The periodical and random modulation currents were approximately 0.8% and 7% of the laser bias current (60 mA). Increasing the spectral peak offigure 4 to $f = 1/(2 \cdot \tau)$ will relax the injection level requirements.

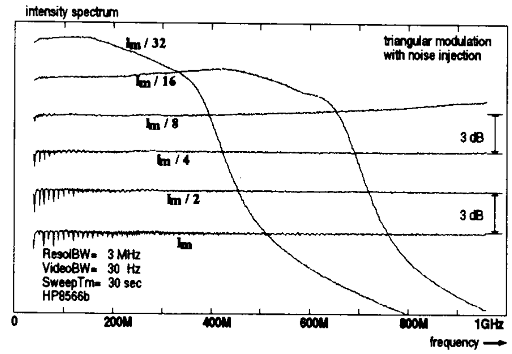

Fig. 6. Measured synthetic noise spectrum for various modulation depths, related to an arbitrary maximum modulation current I_m. (approximately 12%of 60 mA bias current).

IV. Improvements by Noise Injection

The imperfect overlap of the comb lines results in a rippled spectrum. Wang kept this ripple as low as possible by tighter packing of all comb-lines. They lowered the modulation frequency f_m to 100 kHz, and increased the delay length to 1 km, to fulfill $f_m = 1/(2 \cdot \tau)$. They recommended a delay length that is significantly larger than the laser coherence length. We propose a linewidth increase of the individual comb-lines using additional FM modulation with electrical noise. This noise injection will broaden the laser line width, as well as the comblines. The product of the laser FM response (M) and the rms-value of the injected noise is indicative for the resulting laser linewidth.

The major advantage of our approach is that the differential length of the interfero meter can be kept relatively short, even when narrow linewidth lasers are used.

To demonstrate this, we generated the (arbitrary chosen) pink noise spectrum of Fig. 4, and superposed it on the periodic FM modulation signal. Fig. 5 demonstrates how the ripple of Fig. 3 is spread out by the injected noise. It demonstrates that triangular modulation doubles the usable portion of the spectrum, compared to sinusoidal modulation. Injections with other noise spectra are aspects for further investigations.

Fig. 6 demonstrates the synthetic noise spectrum for various modulation currents, using the injection noise level as used in Fig. 5. Above $(I_m/4)$ modulation the spectrum is white up to 1 GHz. Fig. 6 validates the conclusions from equation 6 that doubling the modulation depth will halve the spectral intensity S_i. The spectral width is observed to be $B = 650$ MHz for $(I_m/16)$ modulation. From equation 4 it is concluded that this width is 16 times wider and exceeds $B = 10$ GHz for (I_m) modulation. Approximately 50% of this width is usable as white noise.

The plots of Fig. 6 are reconstructed from raw spectral measurements. The system noise was removed by subtraction on a power base, and the receiver response was equalized by assuming a perfect white spectrum for maximum modulation. The observation that the spectra for $(I_m/2)$ and $(I_m/4)$ are perfectly white too, validates the performed post processing.

The small dips at the low end of the spectra originate from parasitic intensity modulation in the DFB laser. The use of multi section lasers will facilitate wider noise spectra and less degradation due to parasitic IM modulation. The maximum width equals to twice the maximum FM sweep of the laser. The natural linewidth is irrelevant, since the injected noise generates an artificial linewidth.

V. Conclusion

A synthetic white noise generator is demonstrated for measurement purposes. The use of noise injection facilitates a smoothed noise spectrum with minimum ripple, in spite of short delay lines (10 m) and narrow line width lasers. The use of triangular modulation in stead of sinusoidal modulation improves the usable noise bandwidth. The proposed improvements enable the practical use of multi section lasers for noise (and transfer) measurements over several hundreds of gigahertz.

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