Flicker noise in high-speed photodetectors

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***Abstract*— We report on the measurement of the spectra of the phase noise φ and of the amplitude noise α of high-speed *p-i-n* photodetectors in the presence of microwave modulated optical input. Beside shot noise (white), the spectral densities $S_\varphi(f)$ and $S_\alpha(f)$ show flicker noise, which is proportional to $1/f$. The $1/f$ coefficient is of the order of -120 dB[rad^2]/Hz for both $S_\varphi(f)$ and $S_\alpha(f)$. The experiments indicate that mechanical and electrical isolation from the environment is not simple to achieve, and that optical phenomena in the fiber are easily mistaken for noise in the detector.**

I. Introduction

Many high performance applications of microwave photonics and optics are impacted by phase noise of the microwave signals carried as sidebands on the optical beam. Examples of such applications include optical frequency transfer systems for LIGO [1] and VIRGO [2], the frequency distribution system in the NASA Deep Space Network [3], very long baseline radio astronomy interferometry arrays (VLBI) [4], laboratory time and frequency comparisons [5], [6], photonic oscillators [7], [8], and laser metrology [9], [10]. The contributions of nearly all microwave and photonics circuit elements to the phase noise is well understood, or at least determined experimentally. This is not the case for the contributions of the photodetector to the close-to-carrier phase noise. Many high performance systems such as those mentioned above could be limited by the close-in noise of the photodetector, yet only scarce information regarding this topic is available in the literature [11]. In this paper we describe a sensitive measurement technique for the close-in phase, as well as the amplitude, noise of several photodetectors used to detect microwave (10 GHz) sidebands of optical carriers. More details about this topic are in the References [12], [13].

When a light beam is modulated in intensity by a microwave signal and fed into a photodetector, the detector delivers a copy of the microwave signal, with added noise. Flicker noise is the random fluctuations of the microwave phase and fractional amplitude, $\varphi(t)$ and $\alpha(t)$, with power spectrum density $S(f)$ proportional to $1/f$. This refers to the representation $V_0[1+\alpha(t)]\cos[2\pi\nu_\mu t+\varphi(t)]$. The phase noise spectrum $S_\varphi(f)$ is of paramount importance because φ is related to time, which is the most precisely measured physical quantity. For a review on phase noise see Ref. [14].

Close-in noise is a parametric effect that results from the near-dc flickering that modulates the microwave carrier. This is related to the simple fact that the microwave spectrum is white at zero or very low microwave carrier power P_μ, and that noise sidebands can appear around the microwave frequency ν_μ only when P_μ increases. Referring the sideband power to P_μ, phase modulation results in a flicker noise $S_\varphi(f)$ independent of P_μ if no 2nd order effect takes place. This was experimentally observed for amplifiers [15].

II. Experimental method

A preliminary survey of the available detectors shows that none provides sufficient power to use with a saturated mixer as the phase detector, and that typical photodetectors have lower noise than common microwave amplifiers. Hence we opt for a bridge (interferometric) method for phase noise measurement to suppress the noise of the amplifiers required for saturating the mixer, as extensively described in Ref. [16]. The scheme employed (Fig. 1) is based on a modified configuration, taylored for low-power signals [17]. In short, the two photodetector outputs are matched in amplitude and phase to balance the bridge, thus to null the carrier at the Δ port of the hybrid junction. The noise sidebands, not affected by the equilibrium, are amplified and converted to dc by the mixer. By energy conservation, all the carrier power goes to the Σ port of the hybrid junction, where the signal is used to pump the mixer. The mixer detects $\alpha(t)$ or $\varphi(t)$, depending on the phase γ. The gain is $k=v/\alpha=v/\varphi=\sqrt{gP_\mu R_0/\ell_m}$ minus losses; g is the amplifier gain, $R_0=50\,\Omega$ the characteristic resistance, and ℓ the mixer ssb loss. Under the conditions of our setup (see below) the gain is $k=43$ dBV[/rad], including the dc preamplifier. A fast Fourier transform (FFT) analyzer measures the output spectrum, thus $S_\varphi(f)$ and $S_\alpha(f)$. The Δ amplifier can not flicker because no noise up-conversion takes place at a carrier power close to zero. The Σ amplifier flickers, but this noise is not converted to dc because there is no carrier power on the other side of the mixer [17].

The power of the microwave source is set for the maximum modulation index m, which is the Bessel function $J_1(\cdot)$ that results from the sinusoidal response of the electro-optic modulator (EOM). This choice also ensures rejection of the AM noise of the microwave source. The PM noise is rejected because the differential delay of the signal path is small (nanoseconds). The photodetectors are operated at some 0.5 mW of input power, which is low enough for the detectors to be linear. This makes high carrier rejection (50–60 dB) possible in Δ, and in turn provides for the rejection of the laser RIN and of the noise of the Δ amplifier. The coherence

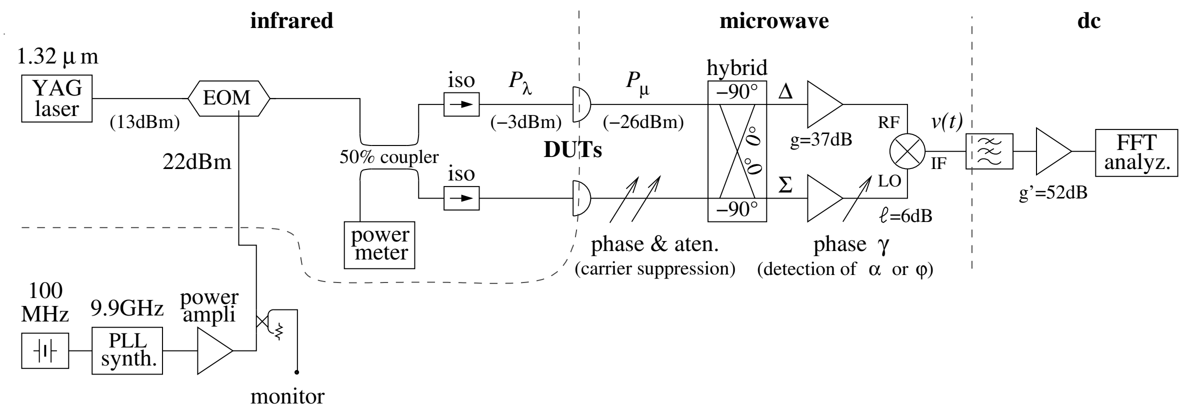

Fig. 1. Scheme of the measurement system.

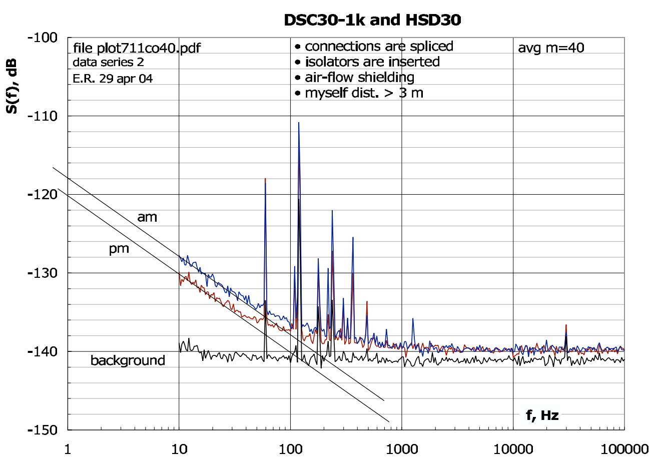

Fig. 2. Example of measured spectra $S_\alpha(f)$ and $S_\varphi(f)$.

length of the YAG laser used in our experiment is about 1 km, for all optical signals in the system are highly coherent.

III. Results and Discussion

The $1/f$ noise of the measurement system is a critical parameter. It is first measured by replacing the two photodetector outputs with microwave signals of the same power, derived from the main source. A more subtle mechanism, which still remains, is due to the fluctuation of the mixer offset voltage induced by the fluctuation of the LO power [18]. This effect is measured in a second test by restoring the photodetectors and cutting the input of the Δ amplifier. The worse of the two results places an upper bound for the background noise. The white noise is mainly due to the Δ amplifier, and is only used as a check.

We tested three photodetectors, a Fermionics HSD30, a Discovery Semiconductors DSC30-1k, and a Lasertron QDMH3. These devices are chosen because they are routinely used in our photonic oscillators [7], [8] and related experiments. Each measurement was repeated numerous times with different averaging samples in order to detect any degradation from low-frequency or non-stationary phenomena, if present. Figure 2 shows an example of the measured spectra. We account for a random uncertainty of 0.5 dB in the differential measurements, due to parametric spectral estimation (Ref. [19], chap. 9), and to the measurement of the photodetector output power. In addition, we account for a systematic uncertainty of 1 dB due to the calibration of the gain. Combining the experimental data, we calculate the flicker of each device, as shown in Table I. Unfortunately, this process amplifies the uncertainty, which in one case (HSD30) becomes quite large.

TABLE I

Flicker noise of the photodetectors.

photodetector	$S_\alpha(1\,\text{Hz})$		$S_\varphi(1\,\text{Hz})$	
HSD30	-122.7	$^{-7.1}_{+3.4}$	-127.6	$^{-8.6}_{+3.6}$
DSC30-1K	-119.8	$^{-3.1}_{+2.4}$	-120.8	$^{-1.8}_{+1.7}$
QDMH3	-114.3	$^{-1.5}_{+1.4}$	-120.2	$^{-1.7}_{+1.6}$
unit	dB/Hz		dB rad^2/Hz	

The electrooptic modulator (EOM) requires a high microwave power (20 dBm or more), which is some 50 dB higher than the photodetector output, but the isolation in the microwave circuits is scarcely higher than about 120 dB. Thus crosstalk, influenced by the fluctuating dielectric constant of the environment, turns into a detectable signal. In practical terms, the system clearly senses the experimenter waving a hand at a distance of 3 m. Air flow affects the delay of the optical fibers, thus some isolation is necessary to mitigate this effect. All our attempts failed until we inserted optical isolators in series with the photodetectors, and spliced all the fiber junctions (except the laser output). After this, the back-reflected light at the unused port of the coupler was below the sensitivity of the power-meter, which is 1 nW. Without isolation and splicing, individual spectra show spikes appearing at random times that still yield a smooth average spectra, that nevertheless is not correct. Beside the mechanics

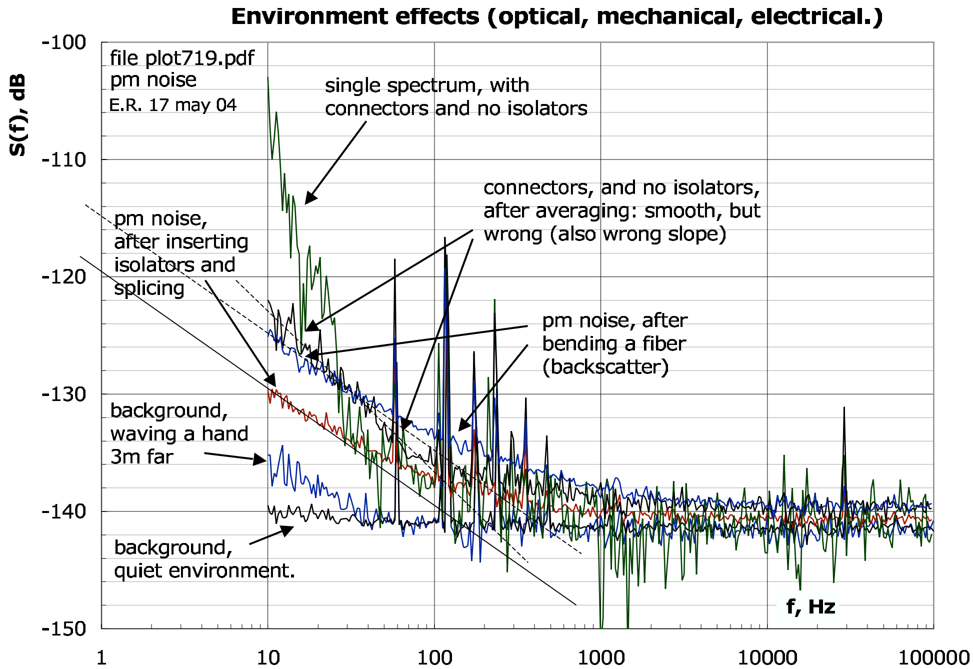

Fig. 3. Examples of environmental effects.

of the connectors, we attribute this effect to reflection noise in the optical fibers [20], [21]. Even after isolating and splicing, we observed that bending a fiber may result in increased flickering, and in increased fluctuations in the spectrum, even if the number of averages is the same. We interpret this as a change in the interference pattern in the fiber due to polarization. The observed increase in noise is clearly systematic, although reproducing the results takes some effort. Figure 3 shows an example of the above effects.

For practical reasons, we selected the configurations that give repeatable spectra and is not influenced by the sample averaging size, and with low and smooth $1/f$ noise. Repeatability is connected to smoothness because technical noise shows up at very low frequencies, while we expect from semiconductors smooth $1/f$ noise in a wide frequency range. Smoothness was verified by comparison with a database of trusted spectra.

IV. Conclusions

The $1/f$ spectra of the detectors we measured are similar, and a value of $-120\ \mathrm{dB[rad^2]/Hz}$ at $f = 1$ Hz can be taken as representative of both amplitude and phase noise. This $1/f$ phase noise, converted into the two-sample (Allan) deviation $\sigma_l(\tau)$ of the optical length l, is equivalent to 3.7 nm, independent of the measurement time τ. The experimental difficulties we encountered are due to various forms of technical noise, which may exceed the detector noise unless great care is taken. Yet some problems might be easier in a different context, like that of microtechnology. The low close-in noise that we measured indicates that the photodetector has an unexploited potential for emerging or new applications.

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