Flicker Noise of Microwave Power Detectors

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I. Introduction

A microwave power detector is a diode used in the quadratic region. In this region the resistance is proportional to voltage, and therefore the filtered output voltage is proportional to the mean square input voltage. Tunnel diodes [1], [2], [3] and Schottky diodes are used in practice. Tunnel diodes are preferable because of their high gain, up to 1400 V/W, and of because of their suitability to cryogenic environment. Yet, they are easily damaged in case of to power overload. Schottky diodes work only at room temperature, with a gain of the order of 300 V/W. If overloaded, the Schottky detector turns into a peak-voltage detector, which is still useful to measure the power if the signal can be assumed to be sinusoidal. On the other hand, the overloaded detector cannot be used as a demodulator by exploiting the beat note between a pump carrier and a probe signal. Simple mathematics tells us that $1/f$ noise turns into a flat floor of the two-sample (Allan) deviation. Hence, the $1/f$ noise of power detectors is related to the power stability floor of the device, which is an important issue in a number of high-precision applications involving the measurement or stabilization of a RF/microwave power, the measurement of a beat note, and the Pound frequency-locking of an oscillator to a reference resonator. Nonetheless, the literature on this subject is totally absent.

II. Power detector and AM noise

A microwave power detector uses the nonlinear response to a diode to turn the input power P to a DC voltage v_d. For small input power, the transfer function is

$$v_d = k_d P \tag{1}$$

which defines the detector gain. The technical unit in the datasheets is V/W, which corresponds to the physical dimension A^{-1}. For higher input power , the detector response turns smoothly from quadratic to linear like that of the old good AM (envelope) demodulator. Figure 1 shows the response of a two-diode Schottky power detector.

Figure 2 shows the typical scheme of the diode detectors. The input resistor matches the high input impedance of the diode network to the standard value $R_0 = 50\Omega$ over the bandwidth and over the power range. The output capacitor filters the video signal, eliminating the carrier.

Let us consider microwave sinusoidal

$$v(t) = V_0[1 + \alpha(t)]cos[\omega_0 t + \varphi(t)] \tag{2}$$

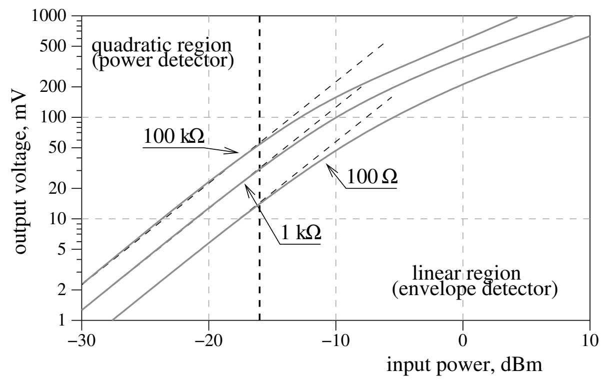

Fig. 1. Two-diode Schottky power detector response

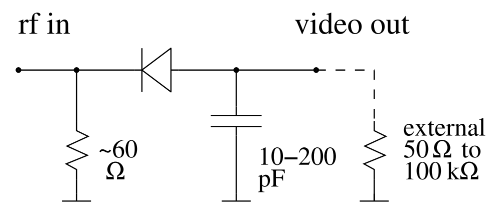

Fig. 2. Diode power detector principle

where $\alpha(t)$ and $\varphi(t)$ are the fractional amplitude and phase fluctuations respectaly. In low noise condition ($\alpha(t) \ll 1$), the power is

$$P \approx \frac{V_0}{2R}(1 + 2\alpha(t)) = P_0 + \delta P \tag{3}$$

The amplitude fluctuations are obtained from the measurement of the power fluctuation δP

$$\alpha(t) = \frac{1}{2}\frac{\delta P}{P_0} \tag{4}$$

In optics, the power fluctuations $\frac{\delta P}{P_0}$ is called Relative Intensity Noise (RIN) [4], [5]. Taking the power spectral densities eq. 4 yield

$$S_\alpha(f) = \frac{1}{4}S_{\frac{\delta P}{P_0}} = \frac{1}{4P_0^2}S_{\delta P} \tag{5}$$

In the case of amplitiude noise, generally the spectrum contains only white noise $h_0 f^0$, flicker noise $h_{-1}f^{-1}$, and random walk $h_{-2}f^{-2}$.

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$$S_\alpha(f) = \sum_{i=-2}^{0} h_i f^i \quad (6)$$

$$= h_0 + h_{-1}f^{-1} + h_{-2}f^{-2} \quad (7)$$

The spectrum density can be converted into Allan variance using

$$\sigma^2(\tau) = \frac{h_0}{2\tau} + 2\ln(2)h_{-1} + \frac{4\pi^2}{6}h_{-2}\tau \quad (8)$$

The power stability of the detector is limited by the flicker floor $\sigma = \sqrt{2\ln(2)h_{-1}}$.

Using detector law eq. 1, the ac component of the detected signal is $v_d = k_d \delta P$ which is related to $\alpha(t)$ by

$$v_d = 2k_d P_0 \alpha(t) \quad (9)$$

Turning voltages into spectra, the above becomes

$$S_v(f) = 4k_d^2 P_0^2 S_\alpha(f) \quad (10)$$

Therefore, the spectrum of $\alpha(t)$ can be measured using

$$S_\alpha(f) = \frac{1}{4k_d^2 P_0^2} S_v(f) \quad (11)$$

Where $S_v(f)$ is the data obtained after measurement in $\mathrm{dBV}^2/\mathrm{Hz}$.

III. Experimental method

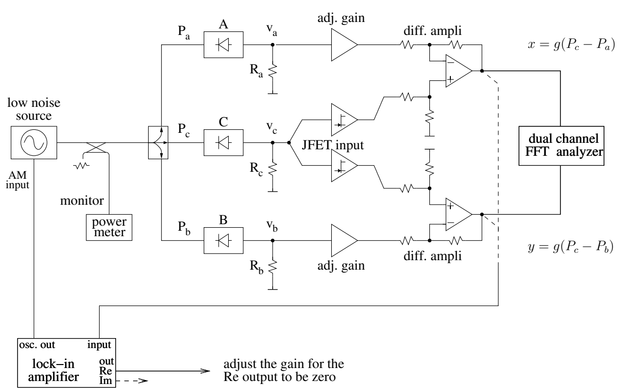

Fig. 3. Measurement scheme

Figure 3 shows the principle of the AM noise measurement. A simple detector can be measured directly only if a reference source is available whose AM noise is lower than the detector noise, and if the amplifier noise can be made negligible. These requirements are unrealistic. A more sophistical approach is to compare two detectors [6], a and b, by taking the differential signal $k_d P_a - k_d P_b$. This method is still unsatisfactory because the noise of the two detectors cannot be divided, so the result relies upon the assumption that the two detectors have equal noise. Hence we got for the scheme of Fig. 3. From the circuit topology, the signal at the upper input of the FFT analyser is $x = g(P_c - (P_a)$ where g is the system gain. For the AM noise of the source to be rejected, we need A and C equal gain in the paths. This is achieved by adjusting the path A, after modulating the source amplitude and inspecting on the null with a lock-in amplifier. Similarly, the signal at the lower input of the FFT analyser is $y = g(P_c - P_b)$, independent of the AM noise of the source. The cross spectral density $< S_{yx} >_m$ convergest the noise of the detector C, after averaging on a sufficient number m of samples. For this to be true, the two amplifiers at the output of the detector C must be fully independent. Referring to Fig. 4 these amplifiers must have the input stage based on JFET transistors because this technology exhibits the lowest current noise, negligible for our purposes. Otherwise, the current noise of the amplifier shows up as a fully-correlated voltage fluctuation across the common load resistor. The load resistor is a part of the detector. Its noise cannot be rejected.

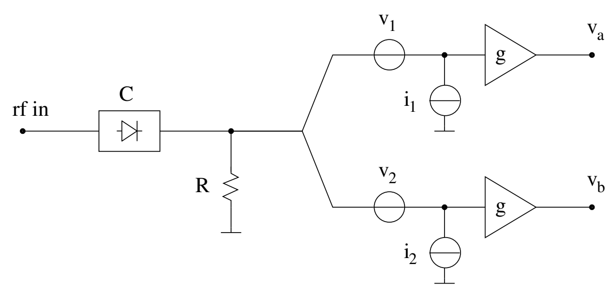

Fig. 4. AM noise measurement principle

The load resistor R is a parameter that can be chosen in an interval from a few tens of Ohms to $100k\Omega$. High speed applications require lower R while higher R yields higher k_d. In the absence of information on the detector noise, we design the system for the lowest flicker of the amplifier alone. This condition is met with a load resistor

$$R = \frac{e_n}{i_n} \quad (12)$$

where e_n and i_n are the $1/f$ voltage-noise and current-noise of the amplifier from the populare Rothe-Dalke model of amplifier [7], found in the datasheet. With the AD743 operational amplifier, the optimum resistor turns out to be of $3.2k\Omega$.

IV. Results

The preliminary results were obtained with some Schottky diodes Herotek DZR400KA. Figures 5 and 6 show the transfer function and the gain of four power detectors.

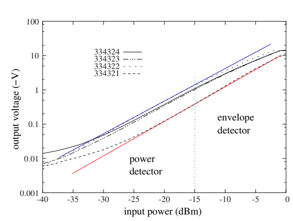

Fig. 5. Transfer functions of 4 Schottky diode power detectors

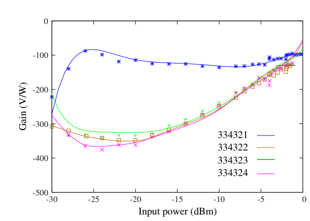

Fig. 6. Gain of 4 Schottky diode power detectors

The AM noise was measured at -6, -10 (envelope detector region) and -20dBm (power detector region) input powers at 10GHz. Tab I summerizes the gain of a few detectors in different conditions.

TABLE I
HEROTEK DZR400KA GAIN (V/W)

S/N	P_{in}=-20dBm	P_{in}=-10dBm	P_{in}=-6dBm
334321	-117	-133	-126
334322	-342	-274	-206
334323	-333	-242	-184
334324	-356	-248	-184

The preliminary measurements were done with the diodes 334321 and 334323. The measured spectra are to be validated by checking on two parameters: 1) the residual of the master oscillator AM noise must be lower than the observed cross-spectrum, and 2) the observed cross-spectrum must be higher than the statistical limit given by the single channel noise divided by $\sqrt{m}$. The master oscillator AM rejection K is evaluated as

$$K = \frac{\alpha_{mod}}{\alpha_{C-A}} \tag{13}$$

where α_{mod} is a amplitude modulation implemented in the synthesizer, and α_{C-A} the readout of the lock-in amplifier converted into α at the output of the detectors. Of course, the same thing is done with the output $C - B$. In our experiments, the rejection turns out to be between 80 to 100dB. The AM noise of the synthesizer (Wiltron 69137A at 10GHz) is measured through the cross-spectrum of the channels A and B, by passing the differential amplifiers. The flicker noise h_{-1} is -105dB which corresponds to a flicker floor of $\sigma_\alpha = 6.6 \times 10^{-6}$ of the Allan deviation (see Fig. 7).

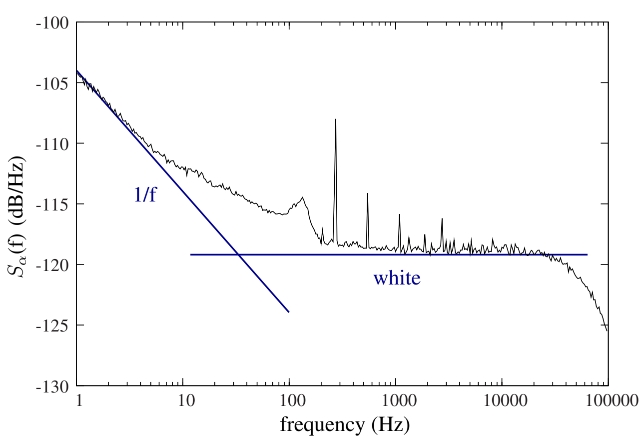

Fig. 7. AM noise $S_\alpha(f)$ of the Wiltron 69137A synthesizer at 10GHz

Figure 8 shows the results of the AM noise measuremnt of the Schottky diode power detectors.

For the Schottky diode power detector 334321, a flicker noise $h_{-1} = -115$dB is obtained which corresponds at a flicker floor $\sigma_\alpha = 2.1 \times 10^{-6}$ of the Allan deviation. With the other detector 334321, we measured $h_{-1} = -115dB$ for an input power of -20dBm ($\sigma_\alpha = 2.1 \times 10^{-6}$) and $h_{-1} = -120$dB at -10dBm ($\sigma_\alpha = 1.2 \times 10^{-6}$). The measurement of the detector S/N 334321 is not fully trusted because envelope detector region is absent in Fig. 5 and 6. This could be the signature of a loss not accounted for.

V. CONCLUSION

We presented the first results on the flicker noise of power microwave detectors. Three channel measurement was used in order to measure the noise of the center detector. With this method, the noise contribution of the amplifier and the source is reduced by measuring the cross-spectrum at the output of two differential amplifiers. Two Shottky diodes detectors (Herotek DZR400KA) were characterized. The first (S/N 334321), showing a gain around 150V/W, present a flicker noise $h_{-1} = -115$dB which corresponds of an Allan deviation $\sigma_\alpha = 2.1 \times 10^{-6}$ at -6, -10 and -20dBm input power but these results are not fully trusted because envelope detector region is absent. The second (S/N 334323), showing a gain around 300V/W, present a flicker noise $h_{-1} = -115$dB (the same as previously) at -20dBm input power (power detector) and a flicker noise $h_{-1} = -120$dB, corresponding of an Allan deviation $\sigma_\alpha = 1.2 \times 10^{-6}$ at -10dBm (envelope detector region). This measures will have an direct impact on the power control/stabilization and Pound frequency/locking control. With these values, we can access to the limit of the error signal. Tunnel diode characterization at room temperature and at some cryogenic temperature is in progress.

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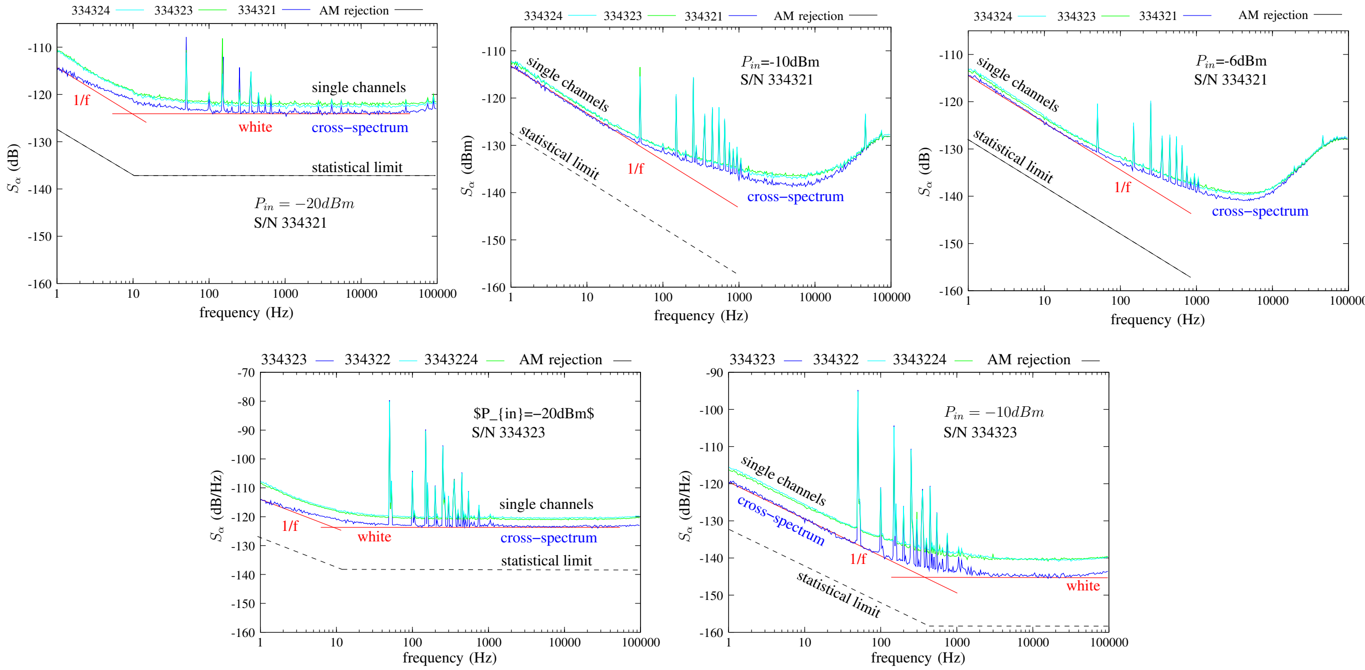

Fig. 8. AM noise $S_\alpha(f)$ of the Schottky diodes (up S/N 334321 and down S/N 334323