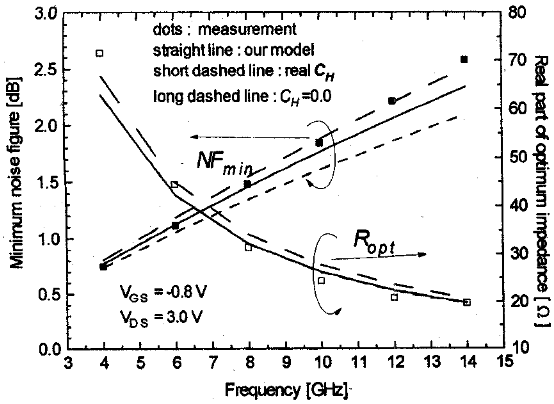
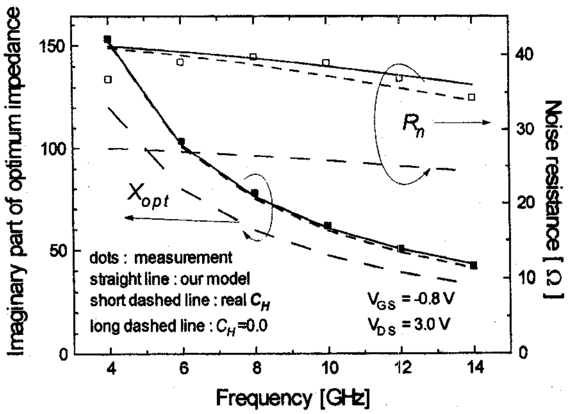


(a)



(b)

Fig. 5. (a) The minimum noise figure and the real part, and (b) the imaginary part of the optimum impedance and the noise resistance at $V_{GS} = -0.8$ V and $V_{DS} = 3.0$ V.

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The Noise-Tee—A Lightwave Device for Microwave Noise Measurements

Rob F. M. van den Brink

***Abstract*—An innovative lightwave method is proposed to insert noise in electronic circuits in favor of microwave noise measurements. The proposed noise-tee has attractive additional features compared to the use of 50 Ω noise sources: 1) The inserted noise level and noise bandwidth is continuously variable over a wide dynamic range; 2) The wideband scaling accuracy of this level, relative to a pre-calibrated level, equals the accuracy of simple dc-current measurements; 3) Level-induced impedance variations are negligible, compared to the 20% impedance variation of a commonly used microwave noise source; and 4) Noise-tees enable the realization of 100% reflective noise sources, in favor of two-port noise-parameter measurements.**

I. Introduction

The characterization of equivalent input noise of amplifiers and systems is of basic importance for various applications. When white noise is supplied to the input of an amplifier under test, the equivalent input noise of that amplifier can easily be determined by comparing its unknown level with the known level of the supplied white noise. This ratio-approach is well known and recommended by IRE/IEEE standards [1]–[6], [8]. Various microwave noise sources are commercially available for this purpose, but are commonly restricted to two fixed noise levels ("hot" and "cold") and to a "fixed" output impedance (usually 50) that varies with the switched noise level. Undesired variations of 20% have been observed in practice, as demonstrated in Fig. 4. They deteriorate the accuracy of simple equivalent noise measurements at a specified source impedance. Mathematical correction for this effect will improve the measurement accuracy [3], [6], [7] but requires additional measurements to determine the associated gain and noise variation of the amplifier under test.

We propose the use of p-i-n photodiodes to insert white noise in a measurement setup, generated by a *synthetic noise generator*. This is a new lightwave instrument, as reported in [9], [11], and [12], having a fiber-optic output to illuminate the photodiode. Insertion of levels 40 dB above the thermal noise level of 50-Ω resistors is feasible.

The proposed method has attractive additional features, compared to conventional 50-Ω noise sources, including:

1) Continuous variation of inserted noise level, over a wide dynamic range using lightwave attenuation.
2) Simple relative scaling of inserted noise level, using dc-current measurements.
3) Variable bandwidth of inserted noise, ranging from several MHz to the photodiode bandwidth.
4) Negligible disturbance of source impedance, when insertion level varies over a wide dynamic range.

This paper discusses the application of p-i-n diodes in a "noise-tee" configuration for inserting noise in a noise measurement setup.

II. Circuit Description of a Noise-Tee

A noise-tee is a two-port configuration for inserting lightwave generated noise, similar to the insertion of dc-bias-currents using

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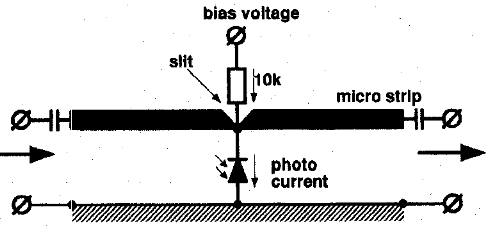

Fig. 1. Basic circuit diagram of a lightwave noise-tee. Noise is generated in the photodiode by illumination with a synthetic noise generator. The microstrip slit compensates for the diode capacitance to minimize mismatch errors in the transmission line.

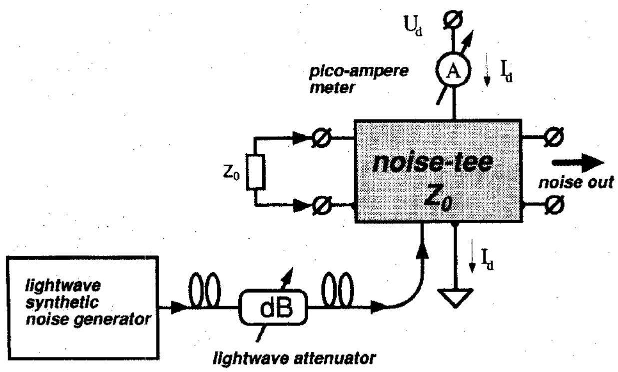

Fig. 2. Matched noise-tee configuration as an implementation of an electrical noise source with variable output level. The ratio between photo current I_d and spectral current density ($\sqrt{S_{ie}}$) of the excess-noise is insensitive to optical power variations.

"bias-tees." Fig. 1 shows that it is a transmission line (e.g., microstrip or stripline), shunted in the middle by a p-i-n photodiode. The p-i-n photodiode is (externally) biased. White noise is inserted in the transmission line by illuminating the photodiode with a lightwave synthetic noise generator.

The high impedance of the biased photodiode causes a minimal degradation of the propagation performance of the transmission line. A microstrip slit (see Fig. 1) is effective in compensating the parasitic capacitance of the p-i-n photodiode, which can be made lower than 0.2pF when using bare chips. Our experimental noise-tee is constructed on a 1.5-mm glass-epoxy board, 4-cm-long, 3-mm-wide microstrip (50 Ω), and a 1-pF photodiode having 2.5-nH series inductance. The overall lightwave responsivity of this construction is made flat up to 1.5 GHz by tuning the depth of the microstrip slit.

III. Basic Noise-Tee Configurations

The two electrical ports of the noise-tee facilitates the support of a variety of applications, including the through-put of signals. This section discusses two applications.

A. Matched Noise Source Configuration

Fig. 2 shows a noise-tee configuration of a stand-alone matched noise source. The left port is externally matched to the characteristic impedance Z_0 of the internal transmission line of the noise-tee (see Fig. 1). The output impedance at the right port is therefore Z_0 as well. This configuration enables the measurement of equivalent input noise in amplifiers under test, at fixed (Z_0) source impedance [1].

The lightwave output signal of the synthetic noise generator in Fig. 2 illuminates the noise-tee using a variable optical attenuator and an optical fiber. This illumination generates a white noise current in the p-i-n photodiode. Levels, exceeding the thermal noise level (room temperature) of Z_0 with 40 dB are feasible.

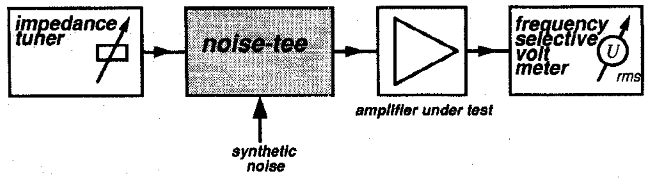

Fig. 3. Mismatched noise-tee configuration for noise measurements at specified source impedance on amplifiers under test. This configuration enables two-port noise-parameter measurements.

1) The spectral noise level of this current is continuously *variable* with the external optical attenuation, and proportional to the illuminated optical power. Measuring the photo current (bias current) with a pico-ampere meter enables accurate scaling of this noise level, relative to a calibrated reference level.
2) The noise bandwidth of the setup is user-definable and continuously variable. This is a standard feature of lightwave synthetic noise generators [11], [12] and enables the minimization of measurement errors caused by spurious response effects.

The maximum bandwidth and spectral flatness of the noise is mainly limited by the lightwave frequency response of the noise-tee, because lightwave synthetic noise generators generate noise that can be made white up to several GHz and probably hundreds of GHz [11], [12]. The lightwave frequency response of the noise-tee is optimally flat when both ports are terminated with Z_0. Bandwidths of more than 20 GHz are probably feasible when dedicated p-i-n photodiodes are used.

B. Mismatched Noise Source Configuration

Fig. 3 shows a noise-tee configuration of a mismatched noise source. This configuration enables the measurement of the four noise parameters of a two-port under test [2]–[6], [8], using different noise levels and different (mismatched) source impedances.

The left port of the noise-tee is terminated with a (one-port) impedance tuner to vary the output impedance of the (two-port) noise-tee, observed at its right port.

1) Our noise-tee configuration facilitates the realization of 100% reflective sources, such as offset opens and offset shorts. Highly reflecting sources that are capable of signal generation are considered as conflicting requirements [5] when using a traditional approach [2]. This is because the noise signal flow from a (one-port) 50-Ω noise source, through a two-port impedance tuner [2], will be blocked by the tuner when relative high or low output impedances are required.
2) Another advantage of our noise-tee approach is that one-port tuners are more simple than (electronic controlled) two-port tuners. In addition, when the noise-tee is not in use for noise insertion, it is equivalent to a pure transmission line, with no need to remove it.

IV. Performance of Output Noise Level

One of the most attractive features of inserting noise with noise-tees is that the inserted noise level is continuously variable, within a wide dynamic range. This enables accuracy enhancement by redundant measurements, with respect to simple hot–cold sources.

A. Minimum Cold Noise Level

The cold noise mainly originates from thermal noise in the external (50-Ω) termination on the left port of the noise-tee in Fig. 2. Because the noise-tee is a lossless two-port, a significant reduction of cold noise level ($\sqrt{S_{ic}}$) can be achieved from cooling this external 50-Ω termination. This is an attractive feature of noise-tees when measuring the noise of ultra-low-noise amplifiers, since the noise-tee

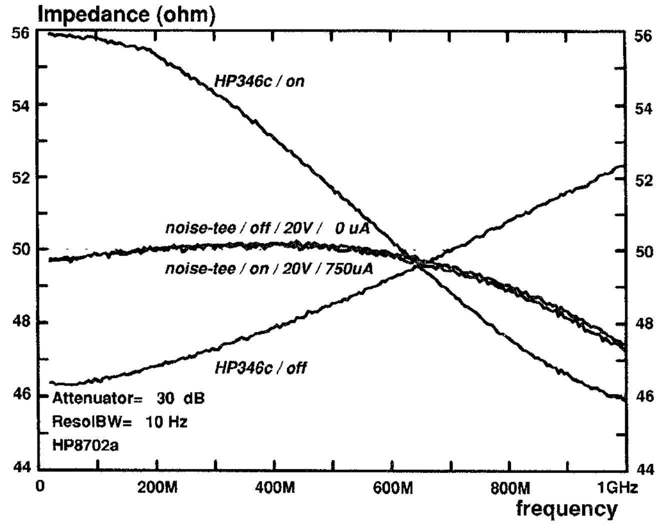

Fig. 4. Output impedance measurements on a matched noise-tee configuration (Fig. 2) and a conventional noise source (HP346c). The p-i-n photodiode is biased at a constant voltage of 20 V. The dc photo current at maximum illumination level is 750 μA.

makes switching between cooled resistors and noise sources at room temperature superfluous. The minimum cold noise level is limited by the thermal noise originating from the internal bias resistors, which can be made 10 kΩ or higher.

B. Scaling of Excess Noise Level

The excess-noise originates from the illumination by the lightwave synthetic noise generator. The spectral amplitude of this current ($\sqrt{S_{ie}}$) is proportional to the illuminating power and the associated dc photocurrent I_d. The noise current ratio $\mu = (\sqrt{S_{ie}})/(I_d)$ is a constant over a wide dynamic range, as we have verified experimentally [10]. This property is of great value when varying the excess-noise level by optical attenuators. The spectral amplitude of the hot noise level, equals $\sqrt{S_{ih}} = \sqrt{(S_{ic} + S_{ie})}$, and represents the total output noise of the illuminated tee.

Once calibrated at a specific reference noise level S_{ie0}, the excess-noise of the setup in Fig. 2 is accurately scaled to an arbitrary noise level: $\sqrt{S_{ieX}} = (I_{dX}/I_{d0}) \cdot \sqrt{S_{ie0}} = \mu \cdot I_{dX}$. A low-cost (pico)-ampere meter, that measures the dc photo current in the noise-tee, is adequate for accurate wideband scaling of this level.

C. Maximum Excess Noise Level

The maximum excess-noise of a 50-Ω noise-tee configuration at room temperature is significantly higher than applies for noise sources such as an HP346c (50 Ω, ENR = 13 dB, 10 MHz–26 GHz). This is an advantage, since high ENR values improve the resolution of noise measurements.

Synthetic noise generation is a power efficient process [11], [12]. Up to 70% of the dc photo current I_d is also available as rms noise $i_{\rm rms}$ and is equally spread out over a user definable bandwidth B [11], [12]. The (single sided) spectral density of the excess noise is therefore $S_{ie} = (i_{\rm rms})^2/B$, accordingly to the well-known Parseval identity for spectra.

Let us consider a lightwave synthetic noise generator providing synthetic noise over $B = 50$ GHz bandwidth using a 1-mW laser. Under these circumstances, the maximum mean (dc) photo current in the noise-tee is roughly $I_{d0} = 0.5$ mA, which makes the maximum excess noise level $\sqrt{S_{ie}} \approx 1.6$ nA/$\sqrt{\rm Hz}$. This value is more than 87 times higher (ENR $\approx$ 39 dB) than the cold noise level $\sqrt{S_{ie}} \approx$ 18 pA/$\sqrt{\rm Hz}$ of 50-Ω resistors at room temperature.

V. Performance of Output Impedance

The output impedance of a matched noise-tee configuration (Fig. 2) is highly insensitive to wide range variations of the output noise level. Fig. 4 demonstrates this impedance invariance in competition with an HP346c noise source. The change in output impedance is negligible for the proposed noise-tee, while the HP346c noise source is liable to 20% ($\pm$10%) impedance variations when switched between hot and cold. We observed that the output impedance of the noise-tee is (nearly) insensitive to bias voltage variations, ranging from 5 V to 20 V. Nevertheless, the highest precision (e.g., less than 0.01 dB variation) will be obtained when the p-i-n photodiode voltage is sensed and adjusted to a constant value with a dc feedback loop.

VI. Conclusion

Noise-tees facilitate the insertion of continuous variable noise levels over a wide dynamic range and associated with a minimum of level-dependent impedance variation. They enable the realization of 100% reflective noise sources, having a variable mismatched source impedance. When not in use, the noise-tee is equivalent with a pure transmission line, with no need to remove it.

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