Noise measurements on optical detectors

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The main figure of merit for detectors whose output consists of an electrical signal that is proportional to the radiant signal power is the normalized detectivity D^*, which is directly proportional to the signal-to-noise ratio (SNR). In order to have an accurate value for the signal-to-noise ratio of an optical detector, the noise level of the measurement system and the bias circuit should be small compared to the noise of the device under test. In this paper a low-noise setup to make noise measurements on optical detectors is analyzed and characterized for the specific case of an antenna-coupled microbolometer. The noise floor of the setup was calculated and measured at about $1.3\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$, which gives detector-noise-limited measurements for microbolometers with resistances as low as $200\,\Omega$. This measurement setup was used to characterize the noise of a $200\,\Omega$ antenna-coupled microbolometer made out of chrome. Measurements showed two $1/f^k$ components in this particular device.

Keywords: Antenna-coupled detectors; microbolometers; noise measurements; optical detectors; amplifier design.

El parámetro principal para caracterizar detectores cuya salida consiste en una señal eléctrica proporcional a la potencia luminosa incidente es la detectividad (D^*), que depende directamente de la relacion se ñal-ruido (SNR). Con el objeto de obtener un valor preciso para la relación señal-ruido de cualquier tipo de detectores ópticos, se debe cuidar que el nivel de ruido del sistema de medición y el circuito de polarización sean pequeños en comparación con el ruido del dispositivo que se está caracterizando. En este trabajo se presenta un sistema de caracterización con un nivel bajo de ruido que puede ser utilizado para analizar y caracterizar cualquier tipo de detectores ópticos. Este sistema fue probado específicamente en microbolómetros acoplados a antenas. El ruido del sistema fue medido en $1.3\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ lo que permite realizar mediciones en microboló metros con resistencias tan bajas como $200\,\Omega$. Este sistema de medición fue utilizado para caracterizar el ruido de un microbolómetro de cromo acoplado a una antena y que presentaba una resistencia de $200\,\Omega$. Las mediciones sobre este dispositivo en particular mostraron dos componentes $1/f^k$ en el espectro de ruido obtenido.

Descriptores: Detectores acoplados a antenas; microbolómetros; ruido electrónico; detectores ópticos; diseño de amplificadores.

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1. Introduction

An optical detector can be defined as any process which converts optical energy into another useful form of energy. By far the most widely used optical detectors are those that convert an optical signal into an electrical signal. Noise in optical detectors causes random fluctuations in the output that cannot be distinguished from the signal, so noise degrades the quality of the output signal. There are many sources of noise, some are fundamental and cannot be eliminated, while others are technical in nature and can be reduced. The main sources of noise are either intrinsic to the photon field, attributed to the detector, or associated with the measurement circuit [1].

There are two fundamental classes of detectors: photon detectors, which respond to the number of photons which are absorbed, and thermal detectors, which respond to the energy which is absorbed [1]. Photon detectors absorb radiation by interactions with electrons, either bound to lattice atoms or impurity atoms, or with free electrons. The observed electrical output signal results from the changed electronic energy distribution. Photon detectors show a selective wavelength dependence of the response per unit incident radiation power. They exhibit good signal-to-noise performance and a very fast response. On the other hand, with thermal detectors,

the incident radiation is absorbed to change the temperature of the material, and the resultant change in some physical property is used to generate an electrical output. The signal does not depend upon the photon nature of the incident radiation. Thus thermal effects are generally wavelength independent: the signal depends upon the radiant power (or its range of change) but not upon its spectral content. Thermal detectors are typically operated at room temperature; they are usually characterized by modest sensitivity and slow response (because heating and cooling of a detector element is a relatively slow process) but they are cheap, easy to use and do not require cooling to suppress dark current. They have found widespread use in low-cost applications which do not require high performance and speed [2].

One of the most popular types of thermal detectors are resistive bolometers, which are temperature sensitive resistors made from metals, semiconductors or superconductors which exhibit a high temperature coefficient of resistance (TCR) so that a small amount of absorbed radiation will produce a large change in resistance. These devices are operated by passing a bias current through the detector and monitoring the output voltage. In the case of bolometers, radiant power produces heat within the material, which in turn produces a change in resistance, there is no direct photon-electron interaction [3].

With traditional bolometers the resistive element is not only used to detect the radiation, but the surface is also used to collect it. The problem with this approach is that, in order to collect a substantial amount of infrared radiation, the resistive element needs to have a large capture cross section which translates into a large thermal mass which would yield in slow detectors [4].

By coupling an antenna to a small bolometer it is possible to have fast detectors without sacrificing collection area. The antenna will be the collection mechanism and the bolometer will detect the collected radiation. Also when the detector element is small (microbolometer), a small amount of energy will be needed to make a large change in resistance; therefore, a smaller detector will have better responsivity [4, 5].

The main figure of merit for detectors whose output consists of an electrical signal that is proportional to the radiant signal power is the normalized detectivity D^* (or D-star) suggested by Jones [6, 7] and defined as

$$D^* = \frac{SNR \times \sqrt{A_d \Delta f}}{P_{in}},$$ (1)

where SNR is the signal-to-noise ratio, A_d is the area of the detector, Δf is the measurement bandwidth and P_{in} is the radiant input power. The importance of D^* comes from the fact that it permits a comparison of detectors of the same type but with different areas and different measurement bandwidths.

In order to have an accurate value for the signal-to-noise ratio of optical detectors the noise level of the measurement system and the bias circuit should be small compared to the noise of the device under test. In this paper a low-noise setup to make noise measurements on optical detectors is analyzed and characterized using a 200 Ω antenna-coupled microbolometer.

2. Method

Figure 1 shows a schematic representation of the amplification stages used to measure the noise and response of optical detectors. By using amplification stages, the noise level of the measurement equipment relative to the noise of the detector is reduced; for example, amplifying the output signal $1000\times$ will make the noise of the measurement equipment appear $1000\times$ lower in comparison. This will give a more accurate reading; however, the amplification stages introduce some additional noise in to the system which needs to be small compared to the noise of the detector. Two amplification stages and a high-pass filter are needed if amplifications higher than $100\times$ are desired or else the dc-bias voltage (which is usually around $100\,\mathrm{mV}$) will saturate the amplification stage. The noise contribution of the filter will be reduced if it is placed after the first amplification stage. The noise analysis of the circuit shown in Fig. 1 proceeds as follows: the noise at point 1 (n_1) is given by the noise of the bias voltage (n_{bias}) divided by the voltage divider formed by R_L and

R_b plus the noise of the detector (n_b) added in quadrature [8]:

$$n_1 = \sqrt{\left(\frac{n_{bias} R_b}{R_b + R_1}\right)^2 + n_b^2}.$$ (2)

The noise at point 2 (n_2) is given by the noise at point 1 amplified by $10\times$ plus the noise of the amplification stage ($n_{10\times}$) added in quadrature:

$$n_2 = \sqrt{(10 \cdot n_1)^2 + n_{10\times}^2}.$$ (3)

If more than one stage of amplification is required, a high-pass filter should be used between the amplification stages. For a first-order high-pass filter the noise at point 3 (n_3) will be given by the noise at point 2 (n_2) plus the addition in quadrature of the Johnson noise of the resistor used in the high-pass filter (R_{HP}):

$$n_3 = \sqrt{n_2^2 + 4kT R_{HP}},$$ (4)

where k is the Boltzmann constant and T is the absolute temperature. The noise at point 4 (n_4) is given by the noise at point 3 amplified by the gain of the second amplifying stage plus the noise of the amplification stage ($n_{100\times}$) added in quadrature:

$$n_4 = \sqrt{(100 \cdot n_3)^2 + n_{100\times}^2}.$$ (5)
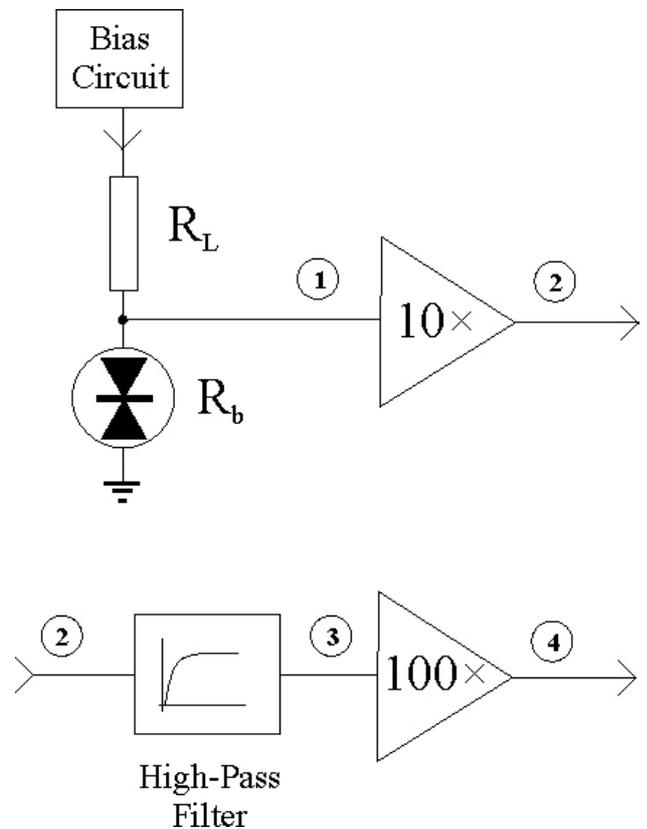
FIGURE 1. Electronic setup to measure optical detectors.
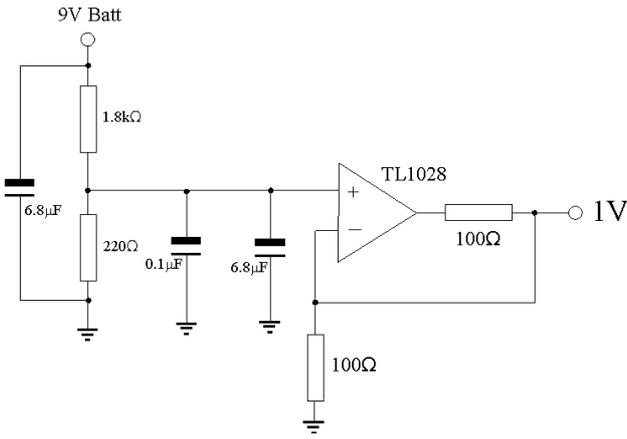
FIGURE 2. Low-noise bias source for optical detectors.
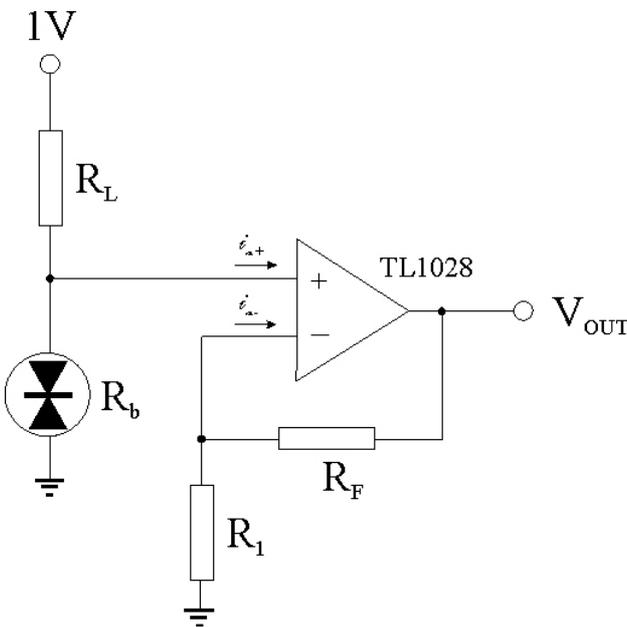
FIGURE 3. Amplification stage for optical detectors.

The total noise of the system referred to the input is the total noise at the output divided by the total amplification, that is: $n_T = n_4/1000$.

The total noise in the circuit shown in Fig. 1 can be reduced by making the noise contributions of the bias voltage and the amplification stages as small as possible. Figure 2 shows the bias circuit used; the use of batteries and decoupling capacitors along with an ultralow noise op-amp (TL1028) helped reduce the noise of the bias voltage to $7 \, \text{nV}/\sqrt{\text{Hz}}$ at 100 Hz. The bias circuit in Fig. 2 gives a 1V fixed output which will be reduced to the desired bias voltage by resistor R_L from Fig. 1; a fixed bias voltage was chosen to avoid the high $1/f$ noise level of potentiometers. Decoupling capacitors are used to reduce the high frequency noise in the system. Batteries power the op-amp and are used instead of regulated power supplies due to their lower noise.

Figure 3 shows an amplification stage for optical detectors with a gain given by $(R_F/R_1 + 1)$. The noise analy-

sis for this circuit can be obtained by superposition and by adding the individual noise contributions in quadrature. The noise contribution of the op-amp comes from two sources: its voltage noise and its current noise, which are parameters than can be found in the op-amp's data sheet or measured directly. The voltage noise contribution is given by n_{opamp}, which can generally be found in the opamp's datasheet, and the current-noise contribution is the voltage generated by the current noise flowing through external resistors. In the case of the circuit shown in Fig. 3, the current-noise contribution is given by $i_n(R_L \| R_b)$ and $i_n(R_1 \| R_F)$. The noise due to the external resistors R_L, R_b, R_F and R_1 is given by

$$\sqrt{4kTR_L}\left(\frac{R_b}{R_L + R_b}\right), \quad \sqrt{4kTR_b}\left(\frac{R_L}{R_L + R_b}\right),$$

$$\sqrt{4kTR_F}\left(\frac{R_1}{R_F + R_1}\right) \quad \text{and} \quad \sqrt{4kTR_1}(\frac{R_F}{R_F + R_1}),$$

respectively. All these expressions for noise voltages are referred to the input; therefore, they have to be multiplied by the gain to get the noise at the output of the amplification stage. The total noise of the amplification stage, referred to the input, is given by:

$$n_{amp}^2 = n_{opamp}^2 + i_n^2\left[\left(\frac{R_bR_L}{R_L + R_b}\right)^2 + \left(\frac{R_1R_F}{R_1 + R_F}\right)^2\right]$$

$$+ 4kT\left[R_L\left(\frac{R_b}{R_L + R_b}\right)^2 + R_b\left(\frac{R_L}{R_L + R_b}\right)^2\right.$$

$$\left. + R_F\left(\frac{R_1}{R_F + R_1}\right)^2 + R_1\left(\frac{R_F}{R_F + R_1}\right)^2\right]. \quad (6)$$

For a $10\times$ amplification stage with R_F=499 Ω and R_1=54.9 Ω with a 200Ω-bolometer biased at 100 mV (R_b=200 Ω and R_L=1.8 kΩ) using a TL1028 ultralow noise op-amp ($n_{opamp} = 0.85\text{nV}/\sqrt{\text{Hz}}, i_n = 1.6 \, \text{pA}/\sqrt{\text{Hz}}$ both measured at 100 Hz [9]), the total noise at the output will be given by the contribution of the bias voltage and the noise of the amplification stage:

$$n_{total} = \sqrt{\left(\frac{n_{bias}R_b}{R_b + R_L}\right)^2 + n_{amp}^2}. \quad (7)$$

3. Results

The noise of the bias voltage was measured to be $7 \, \text{nV}/\sqrt{\text{Hz}}$ at 100 Hz, and the theoretical noise contribution of the amplification stage is $2.1 \, \text{nV}/\sqrt{\text{Hz}}$ calculated using Eq. (6). The total noise referred to the input is $2.2 \, \text{nV}/\sqrt{\text{Hz}}$, calculated using Eq. (7); since a 200 Ω resistor has a Johnson noise of $1.8 \, \text{nV}/\sqrt{\text{Hz}}$, the amplification stage shown in Fig. 3 will give detector-noise-limited measurements for microbolometers with resistances as low as 200 Ω.

Figure 4 shows a graph of the total noise of the amplification stage compared to the Johnson noise of the microbolometer as a function of its resistance. The graph also
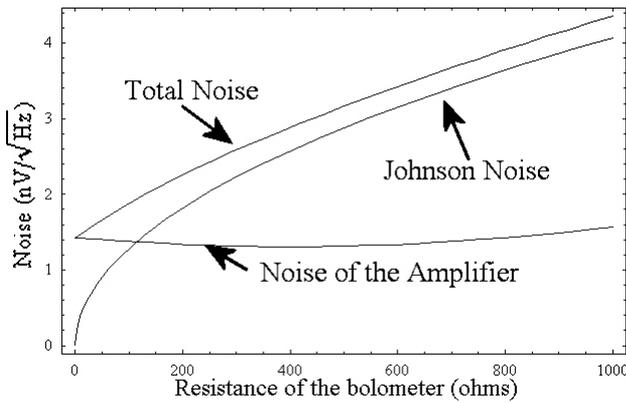
FIGURE 4. Theoretical calculation of the noise of one amplification stage.
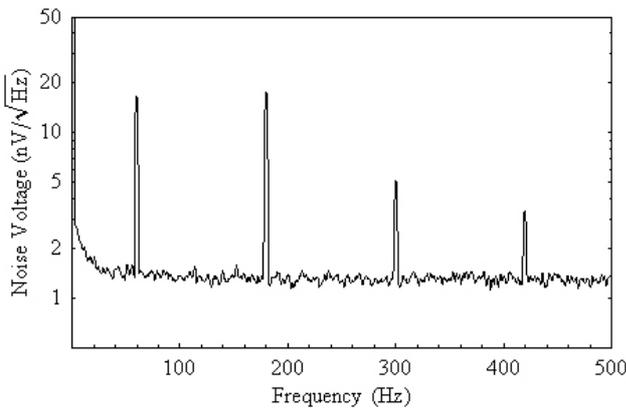
FIGURE 5. Noise floor of the measuring electronics.
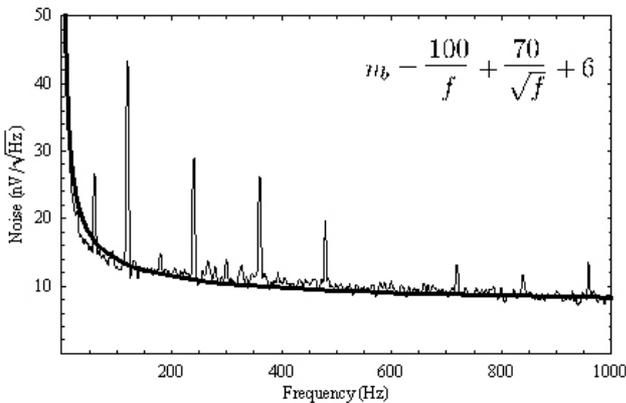
FIGURE 6. Noise spectrum for a 200Ω chrome microbolometer and fitting function.

shows the noise of the electronics, which is obtained by subtracting in quadrature the total noise from the Johnson noise of the microbolometer ($n_{electronics} = \sqrt{n_{total}^2 - 4kTR_b}$). From the figure we can see that the noise of the electronics is around $1.3 \, \mathrm{nV}/\sqrt{\mathrm{Hz}}$.

Noise measurements were made using the setup shown in Fig. 1 and an HP3562A Dynamic Signal Analyzer, which

has a measurement range of 64 μHz to 100 kHz. The noise introduced by the signal analyzer was attenuated $1000\times$ referred to the noise of the detector due to the amplification stages of the test setup. The noise floor of the test setup was measured by shorting the bolometer. The result is shown in Fig. 5, and we can see that the noise floor is very close to the $1.3 \, \mathrm{nV}/\sqrt{\mathrm{Hz}}$ noise expected from the theoretical noise calculations. The spikes in the measurements are 60Hz power-line harmonics introduced into the system.

Using this test setup, a 200 Ω chrome antenna-coupled microbolometer was characterized. The noise characteristics of microbolometers depend on the bolometric material used and its deposition process; devices that are sputtered show lower noise levels than evaporated bolometers, because sputtering provides a better contact between the bolometric material and the gold structures, which reduces $1/f$ noise. Figure 6 shows the noise spectrum of a 200 Ω e-beam evaporated chrome microbolometer obtained using the test setup described above. The noise spectrum obtained was fitted to the following noise function:

$$n_b = \frac{100}{f} + \frac{70}{\sqrt{f}} + 6, \tag{8}$$

which shows two $1/f^k$ components.

4.   Conclusions

A low-noise setup consisting of a bias circuit and amplification stages that can be used to measure the signal-to-noise ratio of optical detectors has been analyzed and characterized using a 200 Ω antenna-coupled microbolometer. The test setup consisted of a bias circuit and several amplification and filter stages; the amplification stages reduced the noise level of the measurement equipment relative to the noise of the detector. The bias circuit was built using batteries and decoupling capacitors along with an ultralow noise op amp (TL1028); all this helped reduce the noise of the bias voltage to $7 \, \mathrm{nV}/\sqrt{\mathrm{Hz}}$ at 100 Hz. Batteries were also used to power the op-amps instead of regulated power supplies due to their lower noise.

The noise floor of the setup was calculated and measured at about $1.3 \, \mathrm{nV}/\sqrt{\mathrm{Hz}}$, which gives detector-noise-limited measurements for microbolometers with resistances as low as 200 Ω. This measurement setup was used to characterize the noise of a 200 Ω antenna-coupled microbolometer made out of chrome. Measurements showed two $1/f^k$ components on this particular device.

Acknowledgments

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