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NOISE TESTING AND DESIGN OF NIR RADIATION DETECTOR USING PbS PHOTORESISTOR*

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This paper contains application of the linear unbalanced bridge for the construction of near-infrared detector using sulfide-lead photoresistor. The parameters optimization of unbalanced bridge and noise analysis are described. Preliminary measurements of linearity and spectral density of noise are presented.

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1. Introduction

A common way to measure some physical quantities is electrical resistance detector. There are different types of sensors used for measuring stress, pressure, temperature or light intensity which are characterized by dependence between measuring quantity and the detector resistance. The time-honored solution to make accurate measurement of resistance is resistive bridge. A standard resistive bridge is nonlinear and the output voltage of unbalanced bridge is approximately proportional only to the narrow range of resistance changes.

A completely linear unbalanced bridge was suggested by Rostocki *et al.* [1, 2]. The solution is modification of the classic Wheatstone bridge which consists in forcing a constant current (or voltage) on the detector located in one of the arms of the bridge. In practice, this method is one of the simplest for precise measuring of electrical resistance.

This idea has been used to design a precise detection system for near-infrared radiation with sulfide–lead photoresistor (PbS), which was supposed to work in high resolution NIR spectrophotometer. Considering this application, the measuring circuit of detector resistance was required which has wide linear range, low noise and high sensitivity. In order to satisfy this requirements, it was necessary to find optimal operating point of unbalanced

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linear bridge with the highest signal-to-noise ratio. Presented topic was a subject of the author's master thesis [3] and it has been described in this paper.

2. System optimization

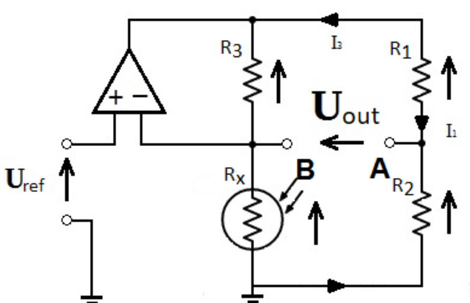
For the PbS photoresistor, intensity of light incident on photosensitive area is directly proportional to the conductance (inverse of the resistance) of the detector. Therefore, the equation describing linear dependence between conductance G_x (resistor R_x in Fig. 1 (a)) and output voltage of linear unbalanced bridge U_{out} is as follows:

$$U_{\text{out}}(G_x) = \frac{U_{\text{ref}}}{G_3\left(1+\frac{G_2}{G_1}\right)} G_x - \frac{U_{\text{ref}}}{\frac{G_1}{G_2}+1}\,, \tag{1}$$

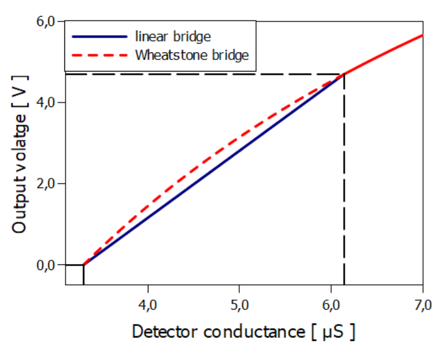
where G_1, G_2 and G_3 are conductance of corresponding resistors in Fig. 1 (a), U_{ref} — reference voltage. The derivative of equation (1) with respect to the detector conductance is called voltage sensitivity S and it is equal to

$$S = \frac{\partial U_{\text{out}}}{\partial G_x} = \frac{(U_{\max} - U_{\text{ref}})(U_0 + U_{\text{ref}})}{(G_{\max} - G_{\text{dark}})U_{\text{ref}} + U_{\max} G_{\text{dark}}}\,, \tag{2}$$

where U_0 is a unbalanced voltage of the bridge defined as $U_{\text{out}}(G_{\text{dark}}) = U_0$ and $U_{\max}$ is a saturation voltage of an error amplifier for which an unbalanced linear bridge becomes a classic Wheatstone bridge such as shown in Fig. 1 (b). Last equation (2) referred to U_{ref} has one maximum of sensitivity, which can be obtained by solving a simple equation $\frac{\partial S}{\partial U_{\text{ref}}} = 0$.



(a)



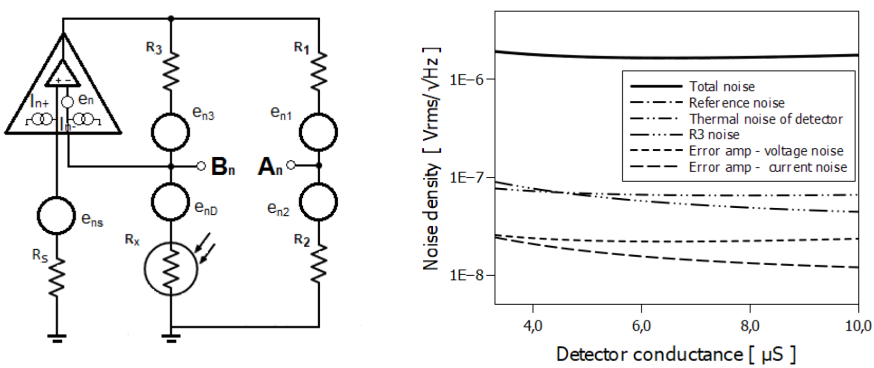
(b)

Fig. 1. (Color online) The design of linear unbalanced conductivity bridge with error amplifier working as current amplifier. (a) Diagram of bridge with photoresistor. (b) Theoretical plot of dependence between the detector conductance and output voltage for linear bridge (solid/blue line) and Wheatstone bridge (dashed/red line).

On the other hand, the sensitivity is limited by the noises, therefore simple model which describe noises sources as voltage e_{n} and current i_{n} sources with respect to the output was prepared [4]. The model was shown in Fig. 2 (a). Noises coming from resistances were described as thermal noises of values $\bar{e}^2_{\mathrm{n}x} = \int 4k_{\mathrm{B}}TR_x\mathrm{d}f$ and noises of error amplifier were read from the technical documentation of the operational amplifier [5]. Finally, the total noise E_{tot} is equal to quadratic sum of the each component (4), where $K_{\mathrm{ninv}} = \frac{R_3}{R_D} + 1$ is non-inverting gain and $K_{\mathrm{inv}} = -\frac{R_3}{R_D}$ is inverting gain. The contribution of this components to output total noises was shown in Fig. 2 (b). The most significant noise source is the noise coming from the reference voltage and it determines the value of the total output noise

$$\bar{E}^2_{\mathrm{n}z} = K^2_{\mathrm{ninv}}\left(\bar{e}^2_{\mathrm{n}s} + \bar{e}^2_{\mathrm{n}} + \bar{i}^2_{\mathrm{n}n}R^2_s\right) + K^2_{\mathrm{inv}}\,\bar{e}^2_{\mathrm{n}D} + \bar{i}^2_{\mathrm{nn}}\,R^2_3 + \bar{e}^2_{\mathrm{n}_3}\,, \tag{3}$$

$$\bar{E}^2_{\mathrm{tot}} = \bar{E}^2_{\mathrm{n}z}\,K^{-2}_{\mathrm{inv}} + \left(\bar{E}^2_{\mathrm{n}z} + \bar{e}^2_{\mathrm{n}_1}\right)\frac{R^2_2}{(R_1+R_2)^2} + \bar{e}^2_{\mathrm{n}_2}\,\frac{R^2_1}{(R_1+R_2)^2}\,. \tag{4}$$



(a) (b)

Fig. 2. Modeling of detection system noises.

The theoretical plot of output signal, and the total noise and signal-to-noise coefficient (in the middle of the linear range) as a function of reference voltage U_{ref} are presented in Fig. 3 (a). Maximum of signal is obtained in extremum of voltage sensitivity. However, if the output noise is taken into account, then maximum of S/N ratio will be shifted slightly towards lower reference voltage, but this will not make any significant changes to the coefficient. Parameter associating voltage sensitivity and noises is called detectivity which is defined as $D_m = \frac{S}{U_n}\sqrt{\Delta f}$ (where Δf is a width of the noise band). Since for the range from G_{dark} to G_{max} the total output noise is not constant, the relationship between the detectivity and the reference voltage is shown by the three curves in Fig. 3 (b), consecutive for minimum, middle and maximum of the output linear range. In addition, it can be observed that there is a triple intersection point of curves for which detectivity is nearly equal.

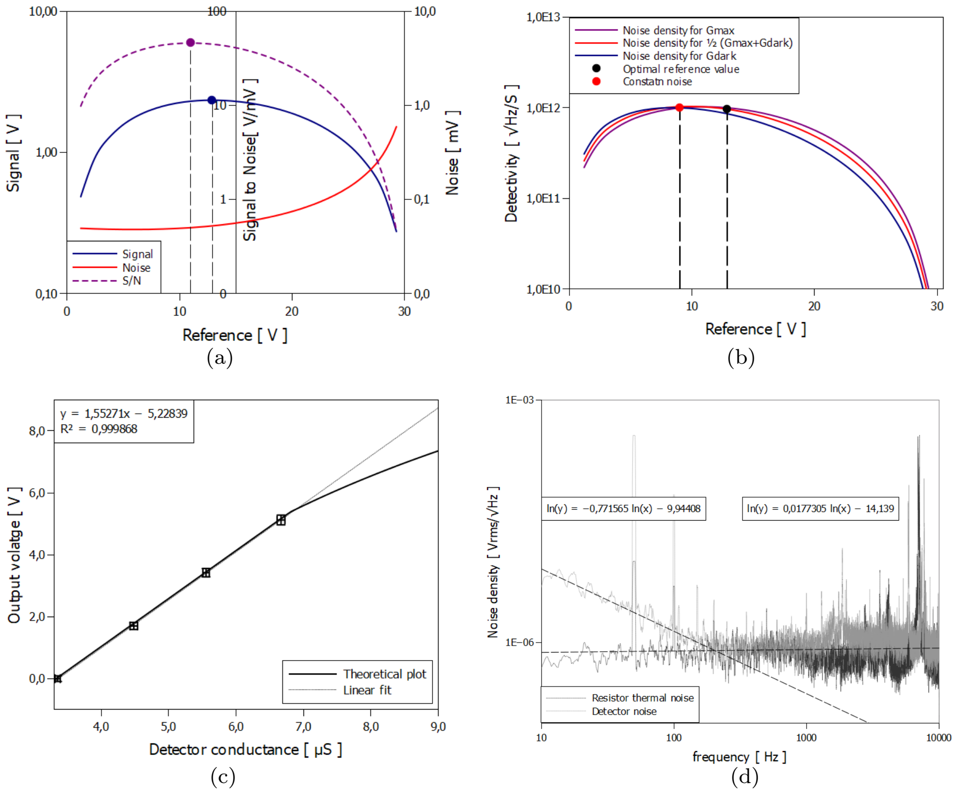


Fig. 3. Optimization of operating point (a) for maximal signal to noise ratio, (b) for the highest detectivity. Preliminary measurements of: (c) bridge linearity and (d) bridge thermal self-noise spectral density (black line) and of bridge with detector noise spectral density (gray line).

3. Summary

Theoretical predictions show that proposed solution is characterized by wide range linear dependence between the detector conductance and output voltage, and low sensitivity to self-noises.

In order to approve the theoretical analysis, some simple measurements were made. The first one consisted in measure of output voltage consecutively for four standard resistors, which were placed in the bridge instead of the detector. As a result, a voltage sensitivity of bridge has been obtained, value of which is equal to a slope of a straight line fitted to measuring points. Relative error between theoretical and experimental value is approximately equal to 0.2%, which is within the limits of measurement uncertainties. All results was presented in Fig. 3 (c).

Additionally, a spectral density of the noise for two cases has been measured, which was shown in Fig. 3 (d). The first one was made for a resistor with a resistance value corresponding to the dark conductance of the detector. The noise coming from this measurement can be considered as self-noise of the bridge, because resistance generate only a thermal noise. Another measurement represents a noise which is a sum of the detector noise (without illuminate) and the bridge self-noise. Detector noise is characterized by the occurrence of $1/f^n$ noise for which a noise power is decreasing with the frequency. In both cases noise density is highly similar, so this system can be successfully used in instruments for spectroscopy.

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