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CHARACTERIZATION OF THE PYROMETERS TO THE SUBJECT OF PREAMPLIFIER GAIN NONLINEARITY

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Abstract – dc-operated radiation thermometers, due to their high-speed response, simple and rigid optical and electrical systems are widely used in industry and science. Practically, in all metrology laboratories the realization and dissemination of the temperature scale (by means of radiation temperature) is carried out using the dc-operated transfer standard radiation thermometers. Therefore, the actuality of the accurate characterization of all aspects of the pyrometer system is evidently clear.

This paper describes the systematic error contribution of the gain non-linearity of well-designed preamplifiers in the signal processing of the dc-operated radiation thermometers.

Keywords: radiation thermometer, preamplifier gain nonlinearity, noise equivalent temperature.

1. INTRODUCTION

The current temperature scale - ITS-90 defined the temperature measurements above the silver point (961.78°C) by means of radiation thermometry. On other hand, radiation thermometry provides the most convenient, practical and fast method for determining the thermo-dynamical temperature below the silver fixed point [1] and used in many fields of industry, such as steel, glass, paper, ceramics industries, food and health sectors. Today, radiation thermometer's working range covered the temperatures from –50 °C up to 3000 °C.

A pyrometer is an instrument, which collects optical radiation from a target under measurement and produces a measurable, usually electrical, output signal (whose utilizing is based on the fact that the spectral radiance from an incandescent body is a function of temperature, which can be represented by the Planck's equation). The key components of radiation thermometers are detectors. There are many types of detectors (thermopiles, bolometers, pyroelectrics, etc.) utilizing various principles for converting incident radiation to a measurable parameter. Last years, due to their high sensitivity, fast responsivity, low 1/f noise and etc., photon detectors are widely used in radiation thermometry. Photon detectors are those, in which photons coming from target, excite carriers in the detector material from a non-conducting to a conducting state and in that way causes a change in the electronic state of the detector.

In dependence on the photon energy (to overcome the gap energy between the bands of detector materials), different types of detectors are used in pyrometers. For example, for measurements of high temperatures (above 1000°C) – Si detectors are used, for middle temperatures (150°C - 1000°C) – InGaAs or Ge, and for the lower temperatures (-30°C - 150°C) – InSb detectors [2].

2. BRIEF DESCRIPTION OF CURRENT-TO-VOLTAGE PREAMPLIFIER

In general, pyrometer acts as radiation to electrical signal transducer with photocurrent output signal. Mainly, for precise temperature measurements dc-mode signal was used. For precise measurements, the dc-photocurrent from detector is converted to a voltage by a following amplification using the trans-impedance preamplifiers and measured by a digital multimeter. For this reason preamplifiers play an important role in signal processing part of pyrometers.

The primary function of preamplifiers is to extract the photocurrent from detector and pass to multimeter without significantly degrading the intrinsic signal-to-noise ratio.

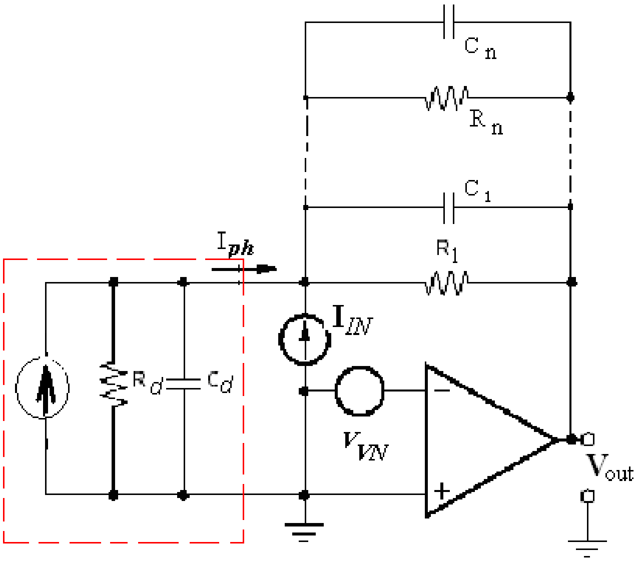

Fig. 1. Simplified diagram of equivalent photodetector circuit and preamplifier

In Fig.1 is shown a simplified diagram of equivalent photodetector circuit (dashed rectangular) and preamplifier. The photon detectors can be represented as an electrical circuit, in which a shunt resistance R_D and a junction capacitance C_D together produce the photodiode impedance. This circuit may be considered as short-circuit arrangement, which operates without bias voltage, and under falling onto photons photodiode produces an electrical current I_p. Used in preamplifiers (Fig.1.) operational amplifier can be considered as an electrometer-grade device with sufficiently high input impedance and a sufficiently low input bias current. The current to voltage conversation can be described by the trans-impedance gain [3]

$$A_i = \frac{V}{I_p} = R_i \frac{1}{1+j\omega R_i C_i} = R_i \frac{1}{1+G^{-1}} \qquad (1)$$

where, G is a loop gain. As one can see, for the dc signal ($\omega = 0$) the amplifier gain - is the ratio of the output voltage V to the input photocurrent and is equal to the value of feedback resistor R_j.

$$A_i = R_i \qquad (2)$$

(2) clearly shows the role of feedback resistors in designing and characterization of the preamplifiers.

The preamplifier contains two main noise sources: input voltage noise V_{VN} and input current noise I_{IN}. The first is the effective voltage fluctuation at the input terminal of the amplifier and the principal source of the 1/f noise. The second – white noise, is caused by the fluctuation of the input bias current of the amplifier. Therefore, keeping the photodiode and preamplifier temperatures stable, locating the preamplifier as close as possible to the detector, using high isolated and screened house and cables will reduce the noise in output signal and consequently, noise equivalent temperature (NET) of the pyrometer.

3. PYROMETER EQUATION

The thermodynamic temperature T can be measured using a system whose equation of state (working equation) can be written down explicitly in such a way that it does not contain any unknown temperature dependent parameters.

The general form of a pyrometers working equation is a function of temperature *T* and a number of temperature independent parameters X_n and Y_n,

$$S = f(T, X_n, Y_n), \qquad (3)$$

where, *S* is the measured pyrometer output signal, X_n contains the parameters which directly used in the realizing of the working equation, whereas Y_n contains the parameters which may be used as a correction to the working equation.

Radiation thermometers are calibrated against the reference temperatures by measuring the reference signals S_{ref} and having assured a sufficient constancy of the sensitivity all components versus light intensity as well as versus time within a certain range. After that they used for temperature measurements as a comparator of radiation intensity ratios in terms of output signal - S/S_{ref}.

The establishing of the working equation of the pyrometer requires an accurate determination of the all aspects of the pyrometer system (optical and signal processing) to be fully characterized to ensure all sources of systematic error are taken into account.

3.1. Uncertainty due to preamplifier gain

In the Guide to the Expression of Uncertainty in Measurement [4] the combined standard uncertainty $u_c(y)$ defined as the positive square root of the combined variance $u_c^2(y)$:

$$u_c^{\,2}(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) \qquad (4)$$

where, $u(x_i)$ is a standard uncertainty component and the quantities df/dx_i are the partial derivatives of *y*, often referred to as sensitive coefficients.

For the pyrometer, all uncertainty contributions expressed as $\Delta S/S$, lead to a temperature uncertainty in scale

$$\Delta T = \frac{\lambda T^2}{c_2} \frac{\Delta S(\lambda, T)}{S(\lambda, T)}, \qquad (5)$$

where, λ is the working wavelength, c_2 – second radiation constant [5].

From (1) and (2) by assuming that the nonlinearity of the detector is known (or negligible) one can find a standard uncertainty component contributed by the preamplifier gain to temperature uncertainty:

$$\frac{dT}{dA(I/V)} = \frac{\lambda T^2}{c_2} \frac{1}{A(I/V)}, \qquad (6)$$

where, A(I/V) – preamplifier gain.

It's important to notice that, here $dA(I)$ contains both – the deviations related to the nonlinearity of the current-to-voltage transformation in the single gain range of the preamplifier and to the gain ratio between different ranges.

4. MEASUREMENT

As it was found in (2), in ideal case, the values of the feedback resistances determine the amplification factor in the above-mentioned preamplifiers. Nevertheless, value of feedback resistor is usually different from its nominal value and required to be determined. For this reason was carried out a set of measurements, the main goals of which were to check the amplifiers performances for the next test subjects:

- determination of the gain value (value of feedback resistors) in full operating range
- non-linearity in single gain range
- short term stability

- dependence of the dark signal of pyrometer from ambient temperature at each gain range.

Two preamplifiers were tested. The first was commercially available preamplifier with - OPA 128 LM operational amplifier and for the gain range from 10^3 to10^7 are used feedback resistors with ±0.1 %/50 ppm/°C tolerance /temperature coefficient and for the 10^8 gain range ±0.1 %/100 ppm/°C feedback resistor. This amplifier is used in Si photodetector based pyrometer. The required working range of preamplifier is the photocurrent range from 0.2nA up to 100 mA.

The second preamplifier was home made on the base of OPA111BM operational amplifier and feedback resistors with maximum tolerance /temperature coefficient of ±1%/±15 ppm/°C and has the 6 gains from 10^5 to10^{10} which is used in InGaAs photodetector based pyrometer. The required working range of preamplifier is the photocurrent range from 0.03nA up to 1mA.

The calibration of the gain value was made against standard resistors. The simplified block-diagram of measurement set-up is shown in Fig 2. For the determination of the current to voltage gain value two different calibrating methods were used. In the first method as a source was used current source (Keithley 220 programmable current source). In spite of the fact that the dynamic range of this current source was very convenient for measurements, but the results were not acceptable, probably due to the insufficient stability of the source.

In the second method was used a voltage source - DC voltage calibrator. A standard resistor was connected to the input of preamplifier serial resistor R. For matching with the values of feedback resistors were used 1 MOhm, 10 MOhm, 100 MOhm and 1 GOhm standard resistors. The Mohms series standard resistors have the temperature coefficients of less then $5*10^{-6}$ R/°C and 1Gohm - of less then 10^{-5} R/°C. All standard resistors were located in the aluminum-shielded box. The output voltage was measured by the HP-3458 digital multimeter. The DVM was set to integrate for 200 power line cycles for the decreasing bandwidth of the white noise.

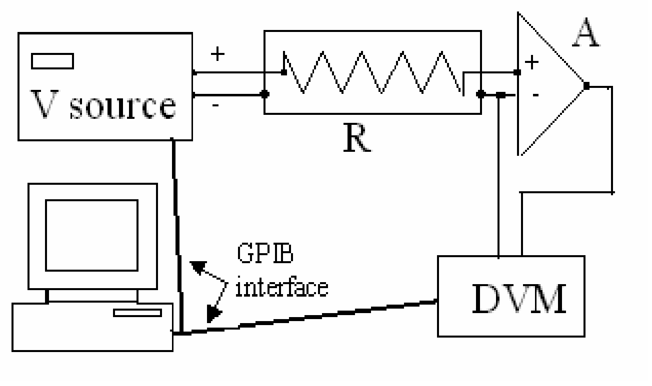

Fig. 2. Block-diagram of measurement set-up.

The maximum output voltage on standard resistors was 100V and power dissipated on the resistors not exceeds 0.1 mW.

The measurement process was fully controlled by the computer. A specially written program set the voltage source to the required value, measured the amplifier output signal and checked the standard resistor temperature. The temperature of standard resistor was controlled within the ±0.1°C and the ambient temperature - ±0.5°C.

In nonlinearity measurements, for every gain range (using only one feedback resistor) the upper range of input current is limited by the saturation of the output voltage of preamplifier. The lower range of input current is selected approximately ten times less then the upper limit of the previous gain.

For the first preamplifier gain ranges 10^5-10^7 the deviation from average of current to voltage converting was found better than 0.008%. The corresponded to these values of gain nonlinearity temperature errors are less then 15 mK. For the - 10^8 gain range the nonlinearity of current to voltage converting is better than 0.05%. In Fig.3 is shown the deviation from average of gain ratios in single gain range 10^8 versus input current. The corresponded to these values of gain nonlinearity temperature error following from (6) is about 7 mK at silver fixed point temperature (961.78°C).

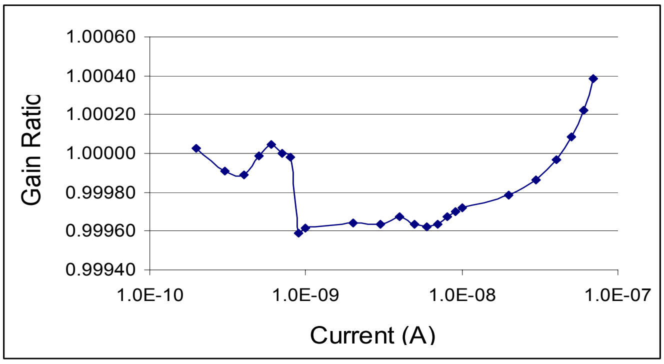

Fig.3. Nonlinearity of 10^8 gain versus input current

For the second preamplifier the deviation from average ranges 10^5-10^7 gain range was around 0.002%. In terms of temperature this means that the error contributed by the gain nonlinearity is less than the pyrometer NET in corresponding working range. For example, in Fig.4 is shown the deviation from average of gain ratios in single

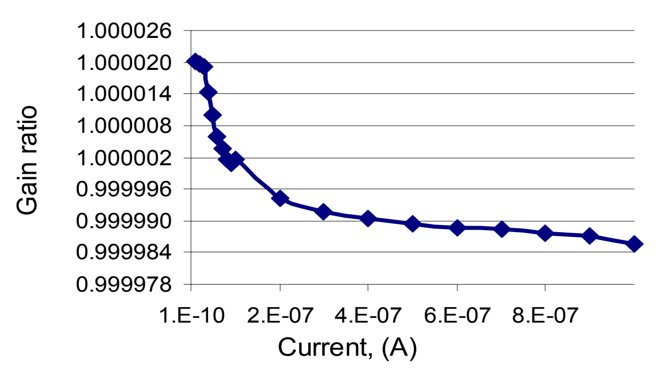

Fig.4. Nonlinearity of 10^6 gain versus input current.

gain range 10^6 versus input current for the second pyrometer. In corresponding photocurrent range (calibration at Sn fixed point-231.928°C) the NET is around 0.77 mK. For the gain ranges 10^9 and 10^{10}, the deviation from average was around 0.01%, which corresponded to the temperature about 6mK. These gains used in temperature range 150°C – 200°C, where the pyrometer calibrated against the In fixed point (156.6°C) and the best NET is around 8 mK.

In Fig.5. is shown a typical short time stability of preamplifier output voltage. At lower gain ranges the value of standard deviation of output voltage is decreased sufficiently.

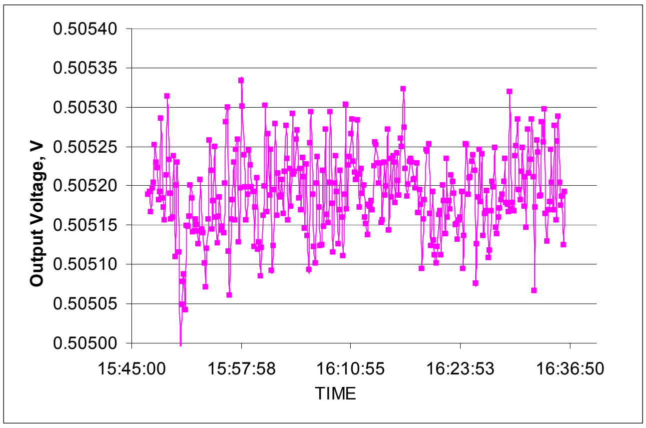

Fig.5. Short time stabilityof output voltage at 10^{10} gain (standard deviation $5.21 \cdot 10^{-5}$ V).

Both pyrometers were tested for influence of the ambient temperature to the dark signal. Detector's temperature of both pyrometers was controlled by the separate thermocontroller, however the temperature of preamplifiers was not controlled. The pyrometers were placed into chamber, internal temperature of which increased during the measurements. The temperature was measured by the Pt-100 thermometer, which was placed near the preamplifier. Practically in all cases were obtained typically increasing of dark signal with increasing the ambient temperature dependence (see Fig. 6.).

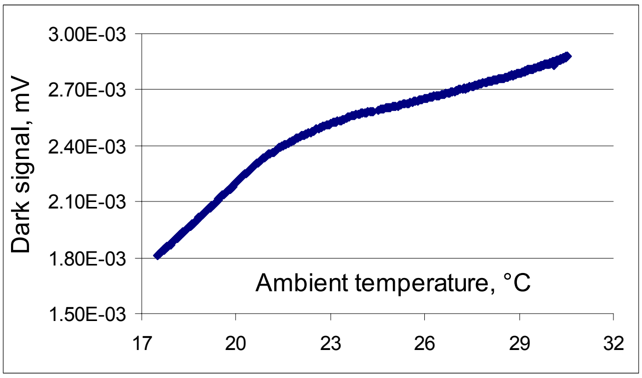

Fig.6. Dark signal versus ambient temperature.

CONCLUSION.

Two preamplifiers, which are used in radiation termometers, were tested for the nonlinearity of the converting and gain of input current to the output voltage. It was found that, the relative uncertainty originated from the uncertainty in gain ratios measurements for both pyrometers was negligible as in calibration at fixed points, as well in scale dissemination. The temperature errors, originated from the nonlinearity of the converting and gain of input photocurrent to the output voltage in well designed preamplifiers are less than the pyrometers noise equivalent temperature.

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