Detection of thermal radiation using lanthanum-strontium-iron oxide (LSFO) bolometers

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Received June 16, 2009; accepted June 27, 2009; published June 30, 2009

Abstract— Non-stoichiometric lanthanum-strontium-iron oxides (LSFO) are a promising class of materials for bolometers due to relatively high emissivity in the mid-IR and high temperature coefficient of resistance. We report, for the first time to the authors' knowledge, the detection of thermal radiation emitted by a blackbody calibration source whose temperature was 38°C (311 K) by an LSFO bolometer placed 500 mm from the source. The signal-to-noise ratio (SNR) of about 62 (i.e. 35.9 dB) was achieved using vector averaging of acquired spectra and by an increase in the measurement time. In the present paper we estimate the accuracy of temperature measurement and outline the directions of further research.

Temperature is one of the most frequently measured parameters during technological processes and in scientific research. When direct contact between the sensor and the measured object is not possible or undesirable, (e.g. for moving and contact-sensitive objects or objects inside vacuum equipment and vessels in hazardous locations [1]), temperature measurements ought to be performed using non-contact methods.

All non-contact radiometric temperature measurements are based on the detection of thermal radiation emitted by an object with temperature is above the absolute zero. Recent studies about non-contact temperature measurements concentrate mainly on new measurement techniques (e.g. emissivity independent techniques) [1],[2] and new types of infrared detectors (e.g. [3]-[5]). Thermal detectors have steadily gained importance in the science, industry, law enforcement and security. One of the most promising groups of thermal detectors are bolometers. Continuous research on bolometers is aimed at improving their performance, decreasing manufacturing cost and developing high-resolution bolometer arrays integrated with read-out and control electronics. Central to that research is the development of new materials, as it may result in the improved sensitivity, increased speed and reduced noise of bolometers.

The subject of research described in this paper was a promising group of materials known as non-stoichiometric lanthanum-strontium-iron oxides (LSFO). These materials are made of lanthanum iron oxide ($LaFeO_3$) by replacing some lanthanum (La) ions by strontium (Sr) ions. The resistance of such layers can be varied in a broad range by changing the La:Sr ion ratio and the thickness of the LSFO layer. These layers have a negative temperature coefficient of resistance α. Its magnitude reaches a few %/K at room temperature. They have comparatively high values of emissivity (ε>0.8) in the mid-infrared [6]. Moreover, these layers can be made using relatively simple technologies, e.g. low temperature co-fired ceramics (LTCC). These advantages make the LSFO layers a good candidate for application in bolometer infrared detectors.

A convenient way of detection of the thermal radiation involves modulating it by a mechanical chopper at a frequency f_0 followed by a detector (e.g. a bolometer) attached to a low-noise preamplifier. The output voltage of the preamplifier is subsequently filtered by a bandpass filter which central frequency is f_0. The voltage is measured by an RMS responding voltmeter. Its reading is proportional to the power incident on the detector. Such an approach eliminates most of the wideband noise of the detector and preamplifier, reduces the influence of the 1/f noise on the measurement and makes it immune to low frequency drifts and fluctuations. An FFT spectrum analyzer or a dynamic signal analyzer can perform the functions of a filter and a voltmeter.

The noise can be further reduced by averaging multiple measurements. When the measurement is conducted using an FFT spectrum analyser, the RMS averaging of multiple spectra is often used. Having a set of M spectra of N points (often called *lines*) each, the RMS averaged spectrum S is calculated as:

$$S_k = \sqrt{\frac{\sum_{j=1}^{M} \left(S_k^{\langle j \rangle}\right)\left(S_k^{\langle j \rangle}\right)^*}{M}} \tag{1}$$

where S_k – k-th line of the averaged spectrum, j – the number of averaged spectra, * - denotes a complex conjugate operator.

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A primary disadvantage of the RMS averaging is its inability to reduce noise present in the bandwidth occupied by the acquired signal. Such reduction is possible when a vector averaging is used. Employing it:

$$S_k = \frac{\sum_{j=1}^{M} \mathrm{Re}\left(S_k^{\langle j \rangle}\right)}{M} + i \frac{\sum_{j=1}^{M} \mathrm{Im}\left(S_k^{\langle j \rangle}\right)}{M} \tag{2}$$

where S_k – k-th line of the averaged spectrum, j – the number of averaged spectra, $i = \sqrt{-1}$, we obtain an average where the amplitudes of signal components are averaged while the amplitudes of noise components are reduced. The reduction of noise components amplitudes is proportional to the square root of the number of averaged spectra $\sqrt{M}$. Since the presented measurements required a good signal–to-noise ratio, the vector averaging was used in the processing of the signal.

A laboratory set-up was developed to perform all the necessary measurements. Similarly to our previous systems developed for the bolometer noise measurement [7], [8], it consists of a carefully shielded and grounded low-noise pre-amplifier and a bias current source, an FFT spectrum analyzer SR785 and a low-noise high-voltage power supply. Moreover, it contains a blackbody calibration source Mikron M315 and a mechanical chopper MC1000 operating at f_0=2 Hz. The block diagram of the setup is presented in Fig.2 and its view in Fig. 3.

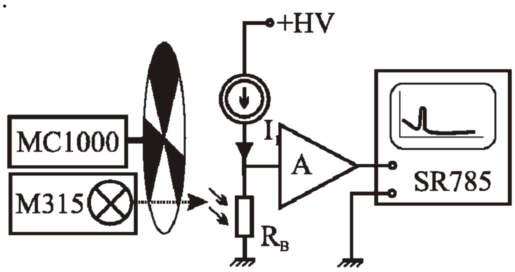


Fig. 1. Block diagram of the measurement setup. R_B – bolometer, A – amplifier

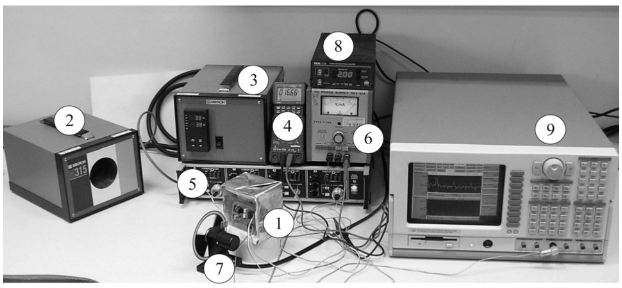


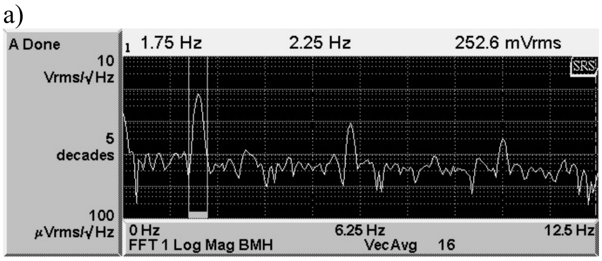
Fig. 2. View of the measurement setup: 1 – pre-amplifier, 2 – blackbody cavity, 3 – blackbody controller, 4 – current meter, 5 – power supply, 6 – low-noise high-voltage power supply, 7 – chopper, 8 – chopper controller, 9 – FFT analyzer

An LSFO bolometer, consisting of an LSFO layer deposited on an AlN substrate using the LTCC technology, was used in the experiment. The active area of the layer was about four square millimetres (2x2 mm) and its resistance was 2,2 MΩ at 20°C. The temperature of blackbody calibration source M315 was set to 38°C (close to that of the human body). The distance between the calibration source and the detector was 500 mm.

Two measurement sets were taken. A spectrum of the signal was acquired and is presented in Fig. 4a. The peak corresponding to the frequency of 2 Hz is clearly visible. The RMS voltage of the signal, measured in the bandwidth from 1.75 Hz to 2.25 Hz, is given in the upper right corner of Fig. 4a.

In order to ensure that the electrical interference pickup did not contribute to the measurement, it was repeated with a M315 blackbody source set to the room temperature of about 20°C. The spectrum of the acquired signal is presented in Fig. 4b.

a)



b)

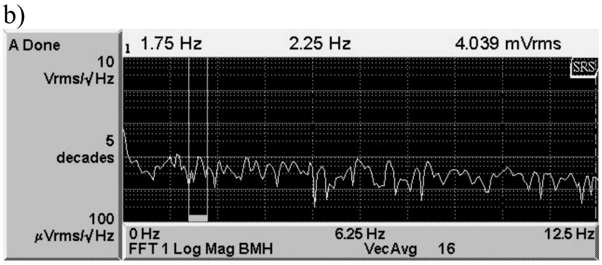


Figure 4. Acquired spectra of the object at 311 K (38°C) (a) and 293 K (20°C) (b).

In this case the signal value for 2 Hz is not greater than for the other frequencies, therefore the peak registered previously must correspond only to the radiation of the blackbody. The RMS voltage of the noise (and possibly some interfering signals), measured in the bandwidth from 1.75 Hz to 2.25 Hz, is given in the upper right corner of Fig. 4b. Based on the RMS voltages from Fig. 4a and Fig. 4b, we can calculate the signal-to-noise ratio (SNR) to be about 62 (i.e. 35.9 dB). Attaining such a high SNR value was possible by using the vector averaging of acquired spectra and by an increase in the measurement time.

Let us assess the possible temperature measurement accuracy using an LSFO bolometer. In the measurement system described above, the output voltage signal U corresponds to the bolometer resistance change that is proportional to the difference between the radiant flux emitted by the blackbody cavity and the radiant flux emitted by a chopper blade [9]. Applying Stefan-Boltzman law [1], we can obtain:

$$U = K\sigma T_{ob}^4 - K\sigma T_{ch}^4 = K\sigma\, T_{ob}^4 \left(1-\left(\frac{T_{ch}}{T_{ob}}\right)^4\right) \tag{3}$$

where: T_{ob} – object temperature, T_{ch} – chopper blade (ambient) temperature, σ – Stefan-Boltzman constant, K – coefficient including system amplification and system geometry.

In the case when T_{ob} = 311 K, T_{ch} = 293 K, the factor $(T_{ch}/T_{ob})^4$ is equal to 0.78 and cannot be omitted. Let us assume the measurement for T_{ref} = 311 K resulting in U_{ref}=252.6mVrms to be the reference measurement. We can write:

$$K\sigma = \frac{U_{ref}}{0{,}22\, T_{ob}^4} \tag{4}$$

Given the measured signal-to-noise ratio of about 62, we can assume that the output voltage can vary by about 1,5%. From (3) and (4) we have:

$$\frac{T_{ob}}{T_{ref}} = \sqrt[4]{\frac{U \pm \Delta U}{U_{ref}}} \tag{5}$$

From (5) we can calculate the temperature measurement error assuming that the only error source is the output voltage noise. Other sources of errors (e.g. influence of difference of emissivity, calibration and reference errors) were omitted in our analysis. However, they could be partially represented in the resulting output signal (considered as noise) for fitting the blackbody cavity to the environment temperature.

In this way the estimated temperature measurement error, for the operating point T=311 K (38°C), is about 1.2°C.

Such accuracy is relatively high, especially given the fact that the detector used in the experiment had a relatively simple structure and the measurement frequency was relatively low. This calculation does not take into account two important factors – long-term stability of relevant parameters of the detector and possible effects of its thermal cycling.

Due to the 1/f noise and the excess noise of the LSFO layer, relatively long measurement time, reaching eight minutes, was used. Hence the further research will primarily focus on improving of the manufacturing technology of LSFO layers. It can be expected that this will substantially reduce the noise of these layers. Moreover, a more comprehensive research into the long-term stability of these devices will be carried out

Finally, the optimization of the detector design will extend its operating frequency bandwidth, enabling further improvement in the accuracy and reduction of measurement time.

The research was partially supported by funding from the Faculty of Electronics, Telecommunications and Informatics of the Gdansk University of Technology.

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