ISSN 0020-4412, Instruments and Experimental Techniques, 2013, Vol. 56, No. 4, pp. 485–490. © Pleiades Publishing, Ltd., 2013.
Original Russian Text © E.Yu. Gordiyenko, G.V. Shustakova, Yu.V. Fomenko, N.I. Glushchuk, 2013, published in Pribory i Tekhnika Eksperimenta, 2013, No. 4, pp. 125–131.

LABORATORY TECHNIQUES

Thermal Imaging System Based on a High-Temperature Superconductor

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Received July 7, 2012

Abstract—A laboratory prototype of an infrared imaging system is described. Its operating principle is based on the formation of an area on the surface of a patterned high-temperature superconducting (HTSC) film, which is sensitive to external radiation and its displacement by local heating. The basic parameters of the activated pixel zone were measured: dimensions $A \approx (95 \times 95)$ μm^2, detectivity $D^* = 1.3 \times 10^8$ cm Hz$^{1/2}$/W, and the time constant $\tau = 6$ ms. The considered pixel-by-pixel data readout procedure and the bolometric nature of the detector sensitivity open the possibility of utilizing the imaging system over a broad spectral range.

DOI: 10.1134/S0020441213030196

The problem of developing high-efficiency systems for large-format reception of thermal images with high temperature and spatial resolutions remains urgent despite a large number of studies that are aimed at the development and industrial production of such systems. This is due to the existence of a wide range of problems that require extension of the spectral range, whereas the majority of photodetectors (PDs) with high parameters are sensitive to wavelengths that are shorter than 20 μm.

The discovery of the high-temperature superconductivity (HTSC) phenomenon made it possible to develop fundamentally nonselective high-sensitivity bolometric PDs that are cooled with liquid nitrogen and intended for detecting radiation in the infrared (IR) and millimeter spectral regions. The achieved value of the noise-equivalent optical power NEP $\approx 6.3 \times 10^{-13}$ W/Hz$^{1/2}$ in a spectral range of 12–36 μm for HTSC bolometers is 100 times higher than the sensitivity of commercial uncooled pyroelectric detectors that are used in this wavelength range [1].

The analysis shows that the characteristics of IR systems can be considerably improved via an increase in the number of sensitive pixels in a PD [2]. When matrix detectors are developed, the problems of attaining a high sensitivity, response speed, and information readout from each pixel must be complexly solved. However, the development of HTSC-based multipixel devices is at present at the initial level. The development of a single bolometric pixel with the high sensitivity and response-speed parameters, which can become a basic element of matrix devices, is an actual problem [1], but the information readout from an array of such PDs is an unsolved problem.

In the known development works on integrally designed bolometric detectors on silicon-based membrane structures [3–5], it is suggested to solve the signal-switching problems in a conventional manner using charge-coupled devices (CCDs), which are formed on the common substrate with the detector array. However, no success was achieved so far in designing such IR image converters because of difficulties in providing the reliability and reproducibility of the characteristics of the array elements, which are typical of membrane structures, and a large number of the required technological operations that lead to degradation of the superconducting properties of HTSC films [6].

The possibility of using SQUID multiplexers for pixel-by-pixel information readout from HTSC detectors [7] is limited by the narrow dynamic operating range, nonlinearity of the transfer function, and presence of excessive $1/f$ noise in HTSC SQUID amplifiers [8]. In addition, the SQUID must be in close proximity to the PD, thus substantially reducing the matrix filling factor, and requires a large number of electrical connections to the electronics for subsequent signal processing.

The formation of a matrix of HTSC detectors and a multiplexer in separate layers with their subsequent electrical connection (hybrid technology) has certain difficulties. These are primarily the stringent requirements for the quality of electrical connections to HTSC structures on which the contact-noise level and the difficulty of stabilizing the temperature balance depend. The latter is determined by the contributions of all components of the system (including the multiplexer) at a very narrow temperature interval where the sensitivity of the HTSC bolometer is realized (<1 K).

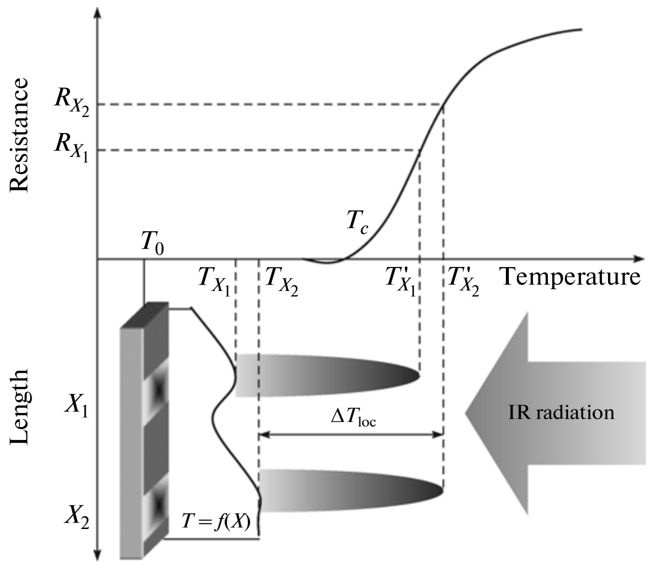

Fig. 1. Formation of sensitive areas on the surface of an HTSC strip.

A solution of the above problems can be found using new nonconventional methods for information readout from the array of bolometric elements. The approach to the recording of IR images that is considered in this study is based on displacements of a zone, which is formed on a continuous extended HTSC film by local heating and is sensitive to external radiation. The proposed approach may serve as a basis for creating highly efficient HTSC-based IR image converters.

The idea of this method [9–11] is explained in Fig. 1, where a bolometric structure in the form of a narrow HTSC strip on a substrate is presented.

When IR radiation is absorbed, a spatial temperature relief $T = f(X)$ that is formed on the strip surface represents the intensity distribution of detected radiation. In this case, the temperature increment ΔT_{X_i} in each conventionally taken region X_i is generally proportional to the fraction of the incident radiation power P_{X_i} and inversely proportional to the value of the thermal coupling G_{X_i} between each of these regions and the heat sink (cooling platform).

The initial temperature T_0 of the heat sink is chosen so that the entire strip is in the superconducting state and the spatial temperature relief does not exceed the critical temperature T_c anywhere. Thus, the electric resistance of the entire sample is zero. The next task is to read this temperature relief out and unambiguously lock the temperature increments ΔT_{X_i} to a position on the surface of the HTSC strip. For this purpose, laser radiation is focused at a local area of the strip and produces overheating of this area by ΔT_{loc}. The area changes to the resistive state in which a significant temperature dependence of the resistance appears.

In this case, the resistance of the entire strip is equal to the resistance of only this local area, which is heated by the laser beam, and the resistance value is proportional to the sum of the temperatures T_0 and ΔT_{loc} and the temperature increment ΔT_{X_i} of this area, which is caused by the absorption of the spatial fraction of radiation from a thermal object. Because the constancy of T_0 and ΔT_{loc} is assumed, when the laser probe moves along the strip, its resistance is modulated by the function of the spatial temperature relief $T = f(X)$, and if a bias voltage is fed to the ends of the strip, an alternating electric signal arises. Its envelope reproduces the spatial distribution of the intensity of detected radiation of the thermal object. This is equivalent to a successive interrogation of a chain of individual elementary detectors.

In contrast to conventional multielement receiving devices where sensitive pixels have sharp dimensions and are physically separated from one another, the concept of an "individual pixel" is conditional in this case. However, as was shown experimentally, the dimensions of the sensitive area that is selected on the surface of the HTSC strip using the laser probe can be determined and its sensitivity characteristics can be measured. Therefore, the term "multipixel detector" is valid as regards the considered HTSC structure. Such an HTSC strip can be obviously regarded as a one-dimensional (1D) chain detector and a meander-shaped structure, as a two-dimensional (2D) matrix detector.

An important feature of the proposed approach is the substantial simplification of the inquiry of individual pixels because the receiving structure can be matched to the multiplexer using only two electric connections. It should be also noted that the manufacturing technology is substantially simplified and, as a result, the reliability improves.

In order to study the possibility of the practical implementation of the proposed method, a laboratory prototype of an HTSC IR imaging system was developed and manufactured. Its block diagram is shown in Fig. 2.

HTSC photodetector structure *3* was placed on a cooled platform in the vacuum part of an optical nitrogen cryostat. The temperature of the cooled platform was controlled in a range of 80–90 K and stabilized with an accuracy of 0.005 K using temperature stabilizer *4*. The entrance window on the optical cryostat was produced of ZnS, thus allowing the effect of both IR radiation from a detected thermal object and switching visible radiation on the studied receiving structure.

Semiconductor laser diode *9* with a radiation wavelength of 0.63 μm and a fixed power of 5 mW was used as the local heating source. Using germanium filter *2*, which was positioned at an angle of 45° to the system's optical axis and simultaneously performed the function of a rotary mirror for switching radiation, the laser

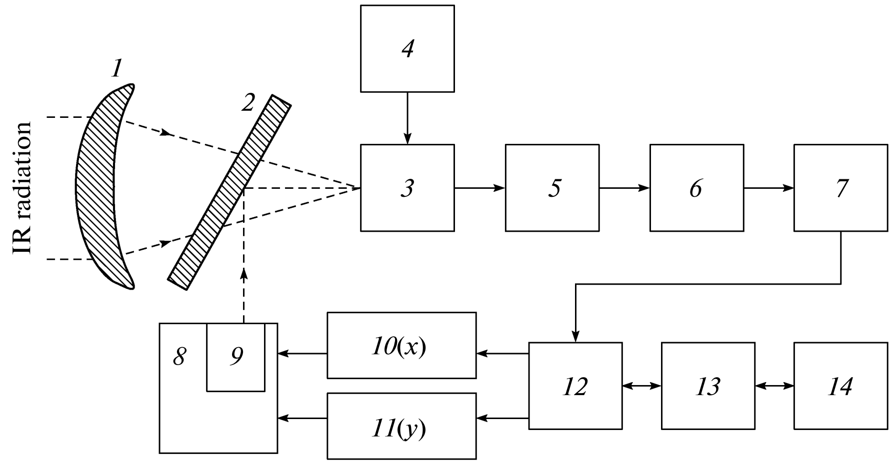

Fig. 2. Block diagram of the HTSC converter: (*1*) IR objective lens, (*2*) germanium filter, (*3*) HTSC detector in the optical cryostat, (*4*) temperature stabilizer, (*5*) preamplifier, (*6*) lock-in detector, (*7*) analog-to-digital converter, (*8*) movable platform, (*9*) local heating source, (*10*) horizontal-scanning stepping motor, (*11*) vertical-scanning stepping motor, (*12*) control microprocessor, (*13*) parallel interface, and (*14*) personal computer.

beam entered the optical cryostat through its entrance window and was precisely focused to the receiving plane of the HTSC structure; the length of the laser-irradiated area on the surface of the HTSC strip was 10 μm. To reduce the heat spreading over the receiving area, the laser radiation was modulated at a preliminarily calculated frequency of 20 kHz at which the diameter of the heat spot from the laser probe did not exceed the diameter of the scattering circle of the IR objective lens, and the mutual thermal influence of neighboring interrogated pixels was minimized.

The laser diode that served as the local heating source was placed on movable platform *8*. The platform could be displaced in vertical and horizontal directions so that the laser beam also moved over the receiving surface of the HTSC structure, thus selecting local sensitive areas in its different parts. The platform moved in two mutually perpendicular directions using ПБМГ-200-265 stepping motors (SMs) (*10* and *11*) with an instantaneous rotation angle (step) of the axis of 1.8°, which corresponded to a 8-μm displacement. The SMs were controlled with an electronic unit on the basis of an ADSP-2181KS133 processor (*12*), which is a 16-bit microprocessor with high-speed execution of commands and a developed interface for connecting peripherals.

The thus organized control of the local heating source made it possible to precisely perform the spatial selection of individual sensitive areas on the receiving plane of a studied HTSC structure and to flexibly program any scanning law. The laser beam of the local heating source performed line-by-line displacements over the receiving plane with an identical step of 8 μm in the vertical and horizontal directions, forming a rectangular raster with a format of up to 256 × 256 points.

As heating sources, we used an etalon of an absolutely black body (ABB), radiation from which was focused to the HTSC structure using IR objective lens *1*, and a second laser diode with a wavelength of 0.63 μm, radiation from which, being defocused to a cross-sectional diameter of ≈100 μm and attenuated with a polarization filter, was injected into the cryostat similarly to the radiation from the switching laser. Radiation from the ABB was modulated using a mechanical shutter in the form of rotating disk with holes. The disk rotation frequency was stabilized with an electronic stabilizer.

Infrared germanium objective *1* was a three-lens optical system with a focal length of 50 mm, a lens speed of 1 : 0.85, an IR radiation transmission coefficient of ≈0.95 in a spectral range of 1–18 μm, and a minimum circle of confusion in the focal plane of ≈50 μm (which is close to the theoretical value for this spectral range).

Low-noise preamplifier *5*, which is based on an AD797 integrated operational amplifier with a gain of 200 in a frequency band from 200 Hz to 100 kHz, was used to amplify photoresponse signals. The intrinsic-noise voltage of the preamplifier reduced to its input was within 1 nV/Hz$^{1/2}$. A photoresponse signal was subsequently amplified and processed using lock-in nanovoltmeter *6*. Using 12-bit analog-to-digital converter (ADC) *7*, which is based on an ADS7862 integrated circuit, a detected signal was converted into a digital code and was further processed using signal processor *12*. The signal processor also recorded data into the internal buffer and transferred information to personal computer (PC) *14*.

The software that was developed for further signal processing had a wide range of functions that allowed displaying a 2D image of the studied HTSC structure in a convenient graphical form on a monitor using a color palette for representing the intensity of recorded signals. The software also allowed digital filtering of images, image brightness and contrast variations, subtraction of a constant background level, construction

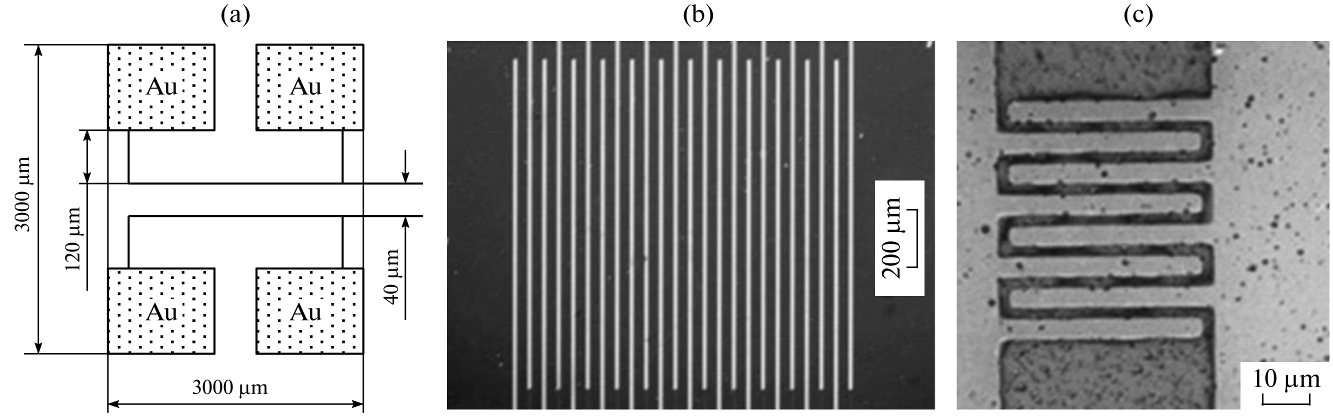

Fig. 3. Photosensitive elements: (a) a sketch of the geometry of the HTSC structure that is equivalent to a 1D chain detector; (b) a meander that is equivalent to a matrix detector; and (c) the test meander.

of the intensity profiles of a recorded signal in any direction, data recording in graphical formats that are compatible with standard packages for processing digital images, etc.

Two variants of planar HTSC structures were used as photosensitive elements. Their topography and dimensions are shown in Figs. 3a and 3b, respectively: a 3-mm-long strip with a width of 40 μm is an analogue of a 1D chain detector, and a meander with an area of 1.5 × 1.5 mm^2 (23 HTSC strips with a width of 50 μm, a length of 1500 μm, and a gap between them of 10 μm) is an analogue of a 2D matrix detector. Both geometries of HTSC microstructures were formed using the electron-beam lithography and chemical-etching techniques [12] on the basis of epitaxial films with the C axis perpendicular to the substrate: 200-nm-thick $YBa_2Cu_3O_{7-x}$ films on 500-μm-thick $SrTiO_3$ or $LaAlO_3$ substrates.

In order to refine and optimize the technological processes that are used to produce films and form geometrical structures, a set of test HTSC samples was preliminarily manufactured. The samples had the form of a 3-μm-wide strip that was folded into a meander with an area of 50 × 50 μm^2 (Fig. 3c). Measurements of the characteristics of the test samples showed that the applied technological processes may serve as the basis for developing multipixel bolometric detectors, because they do not lead to degradation of the superconducting properties of films and provide both a high accuracy in the geometry formation and the reproducibility of the parameters of the manufactured structures.

Because the radiation power from the local heating source in our prototype had a fixed value, the maximum value of the photoresponse signal from the selected area was achieved by choosing the initial temperature T_0 of the entire sample. This temperature was preliminarily determined experimentally from the value of the photoresponse to radiation from the external source.

Figure 4 shows images of the HTSC strip on which a defocused attenuated beam from the second laser diode is incident. It is seen that when local heating moves along the HTSC strip, its areas successively change to the resistive state and, as a result, a temperature relief produced by external radiation appears.

A high-quality image (the maximum photoresponse of the sampled area when the remaining part of the strip is in the superconducting state) is obtained at specified parameters of the laser probe, when the optimal temperature of the considered HTSC structure is 86.6 K. As the temperature further increases, the entire strip changes to the resistive state, and the response of the sampled area drops (the slope of the temperature derivative dR/dT reaches a maximum and then decreases).

To measure the parameters of individual pixels of the analogue of a matrix detector, we evaluated the dimensions of the formed local sensitive areas. For the specified parameters of the laser probe (the beam diameter, power, and modulation frequency), these dimensions are determined by the processes of spreading of the temperature relief, which is formed upon radiation absorption over the receiving area of the HTSC structure, and depend on the thermal properties of the film and substrate materials (thermal conductivity, specific heat, absorption coefficient, etc.) and on thermal design of the HTSC structures.

The area of a single sensitive element was determined experimentally from the spatial distribution of the photoresponse voltage during detection of modulated radiation from the heating source with the known dimensions (ABB with a calibrated diaphragm at the cavity output). Because the used IR objective lens provided the smallest circle of confusion with a diameter of 50 μm, the chosen diameter of the diaphragm aperture was also equal to 50 μm.

The ABB diaphragm was positioned on the optical axis in front of the IR objective at a distance of the back focal length of the objective. In this case, the size of the diaphragm image that was focused to an arbitrary area of one of the strips of the HTSC meander was also equal to 50 μm. The HTSC structure was scanned by the local heating source with a pitch of 8 μm. As a result of the lock-in detection of a photoresponse at the modulation frequency of switching radiation, the measured diameter of a heated spot from ABB radiation was $L \approx 95$ μm (at a level of 0.37).

Thus, it can be considered that, in this case, the area of a pixel, which is determined by the parameters of the laser probe, the thermal diffusion length, and aberrations and diffraction of the optical system, is $A \approx 95 \times 95$ μm^2 (for simplification, it is considered that the pixel has the shape of a square). Because the distance between the receiving pixels must be at least L, it can be inferred that the considered meander-shaped HTSC bolometric structure (Fig. 3b) is equivalent to a matrix detector with a format of 12 × 14 pixels.

When the volt–watt sensitivity of individual pixels of the matrix-detector analogue is measured, the ABB radiation intensity was modulated at a frequency of 300 Hz. The entire HTSC structure was in the superconducting state at the temperature that corresponded to the maximum photoresponse amplitude from individual pixels. The laser beam from the local heating source was positioned on the surface of the HTSC meander strips with a pitch of ≈100 μm. The lock-in detection of signals was performed at the ABB modulation frequency.

The photoresponse signal voltage was measured at each point and the volt–watt sensitivity of the sampled pixel was determined. For a size of a unit sensitive pixel of 95 × 95 μm^2, the average (over the pixels) volt–watt sensitivity was $S = 20$ V/W.

Measurements of the noise voltage of the investigated HTSC structure within a frequency band from 200 Hz to 20 kHz and its individual spectral components at frequencies of 200, 500, 1000 Hz, and 20 kHz were performed in order to determine the detectability and noise-equivalent power for individual pixels of the matrix. It was revealed that voltage fluctuations that correspond to excessive noise and determine the minimum detectable power of detected radiation prevail in the studied structure. In addition, the pixel-to-pixel detectability spread (≈22%), which is due to film defects and a nonuniform heat removal to the heat sink, was evaluated.

The following average parameters of a pixel of the HTSC matrix analog were obtained for a sensitive pixel with an area of 95 × 95 μm^2: volt–watt sensitivity $S = 20$ V/W, the noise-equivalent power NEP $= 7.5 \times 10^{-11}$ W/Hz$^{1/2}$, the detectability $D^* = 1.3 \times 10^8$ cm Hz$^{1/2}$/W, and the time constant $\tau = 6$ ms.

Using a set of germanium dispersion filters, studies of the sensitivity of one of the meander elements in spectral ranges of 3–5, 8–12, and 1–18 μm were also studied [13]. Changes in the sensitivity that were within 20% were revealed in the above spectral regions,

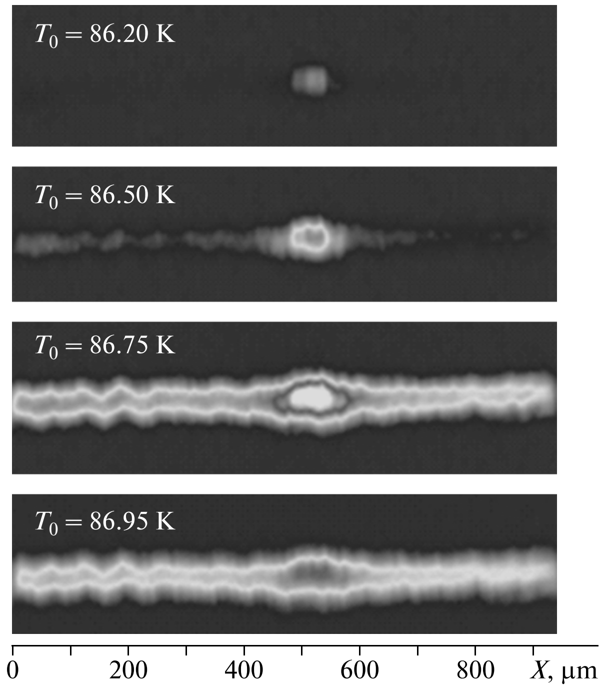

Fig. 4. The photoresponse amplitude from the selected sensitive area as a function of the temperature of the HTSC structure.

thus confirming the bolometric nature of the response and the fundamental possibility of creating HTSC-based nonselective bolometric detectors.

As an illustration, Fig. 5b shows a fragment of a meander thermogram with an image of a 50-μm-diameter thermal object (ABB diaphragm) that was obtained for the converter prototype. As is seen from the background meander thermogram (Fig. 5a), the used HTSC film has point and extended technological defects and a nonuniform thermal contact between the substrate and cooling platform (a lower temperature in the upper central part). The thermogram in Fig. 5c was obtained via the background subtraction.

The obtained experimental data point to the fundamental possibility of using the proposed approach for organizing pixel-by-pixel information readout during development of HTSC-based multipixel IR detectors. In view of the fact that it is exactly the problem of multiplexing individual pixels that currently remains the main constraint in the development of HTSC-based photoelectronics, the considered method can become the basis for building large-format HTSC-based receiving systems.

The comparatively low obtained parameters—the size of the formed pixel $L \approx 95$ μm, the detectability $D^* = 1.3 \times 10^8$ cm Hz$^{1/2}$/W, and the pixel-to-pixel sensitivity spread ≈22% —are not caused by the fundamental limitations of the method, but are associated with the quality of the used films (presence of excessive noise, etc.) and the geometry of the manufactured

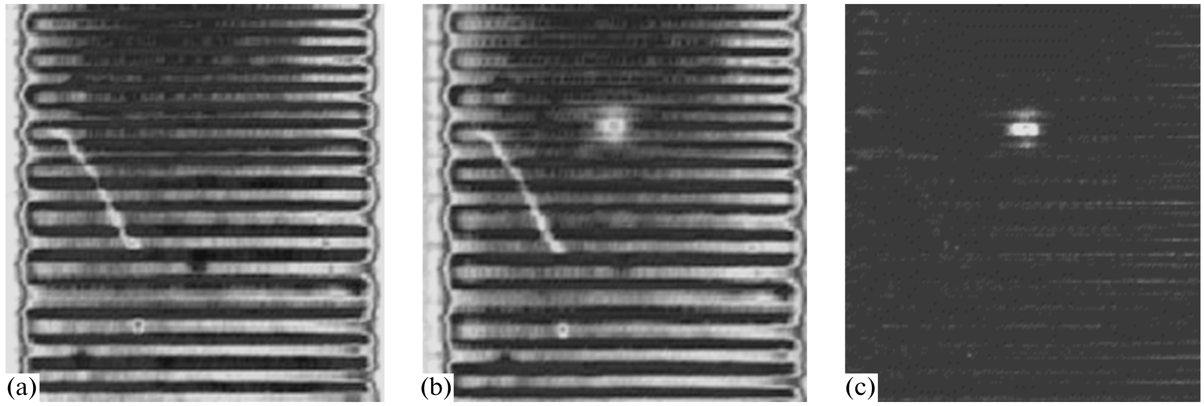

Fig. 5. An image of a heating source obtained using the HTSC detector (meander) with interrogation of pixels by local heating: (a) background (defects and HTSC-structure sensitivity spread are seen); (b) IR image of the heating source; and (c) IR image of the heating source with the subtracted background.

structures. The converter parameters can be improved via the perfection of the manufacturing technology of receiving HTSC structures and optimization of the thermal design of the receiver (optimization of the dimensions of the film structures and substrate, the use of absorbing coatings, separation of the functions of sensitive and receiving elements [14], adding of microantennas, etc.).

ACKNOWLEDGMENTS

This study was supported by the budget of the National Academy of Sciences of Ukraine and continues the studies that are being performed at the Institute for Low Temperature Physics and Engineering of the National Academy of Sciences of Ukraine and Argonne National Laboratory (United States).

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Translated by A. Seferov