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The multiplexing of signals in direct detector arrays using projections method

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Abstract

A new method of the signal multiplexing in low-temperature direct detector arrays is proposed. It is comprised of (1) the constructing the array in a form of parallel rows of the detectors connected in parallel in each row, (2) the reciprocal rotation of the observed radiation image and the array in their common plane, (3) the summation of the direct detectors signals in readout SQUID input coils in each row at each angle of the reciprocal rotation and the acquisition of sums forming thus the set named as projections and (4) the computer reconstruction of the initial image from the projections using the method of convolution and back-projections. The proposed method gives a possibility to reduce drastically amounts of wires connected to direct detectors and readout SQUIDs, to reduce sharply amounts of SQUIDs, to simplify the scheme of the connecting of direct detectors with SQUIDs, and to increase significantly a signal-to-noise ratio in the system.

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Arrays of low-temperature ($T \cong 0.3-0.1\,\mathrm{K}$) direct detectors of $N \times N$ dimension up to 100×100 and more are needed in radio astronomy for observations and measurements of distributed submillimeter radiation sources. Large amounts of wires (up to tens of thousands) have to be led into low-temperature area of the cryogenic system for the lead-in of bias voltage to detectors and lead-out detected signals from them. This will bring the influx of excessively large thermal power through wires to the low-temperature refrigerator which will not cope with it definitely. To solve this problem various methods of the multiplexing (commutation, concentration, group transmission and subsequent separation) of signals in direct detector arrays are proposed [1,2].

The Andreev reflection hot-electron bolometers with superconductive transition edge sensors or sensors based on SIN-junctions are examples of such direct detectors [3]. In the first said detector which is used in our subsequent consideration, the current increment ΔI (detected signal) in each moment in each bolometer of the array is connected with the absorbed radiation power P by expression [3]

$$|\Delta I| = (1/V)P \tag{1}$$

where V is fixed bias voltage applied to bolometer.

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The readout and amplifying of detected signals in direct detector array is realized using SQUIDs with ultimately high current sensitivity. On their level the multiplexing is based, for instance, on time division [1] or on frequency division [2].

We propose a method of the signal multiplexing in array of receiving elements with direct detectors which are connected for this purpose in parallel in set of rows and sums of signals in rows are readout by one SQUID in each row (Fig. 1). Signals are integrated over readout time. The image of observed radiation and the array are rotated reciprocally in their common plane fixing the array (or the image) at angle steps. The final procedure is the reconstruction of the initial image from the set of signal sums gathered from all rows at all reciprocal angles using algorithms of the computer tomography [4]. We interpret the receiving element as the direct detector and the matching antenna into which the direct detector is incorporated (coupled) at microwave frequency. The array of receiving elements based, for instance, on four-slot matching antennas with double polarization [5] is more adequate for proposed method in order not to lose the information on the difference in radiation intensity in two polarizations during reciprocal rotation of image and receiving elements array. The rotation of receiving elements relative to the image can be realized by means of the rotation of the telescope around its main optical axis. One may imagine some other methods, as optical–mechanical or electronic–optical, of rotation of image relatively to the array, what is equivalent to the rotation of the array relatively to the image.

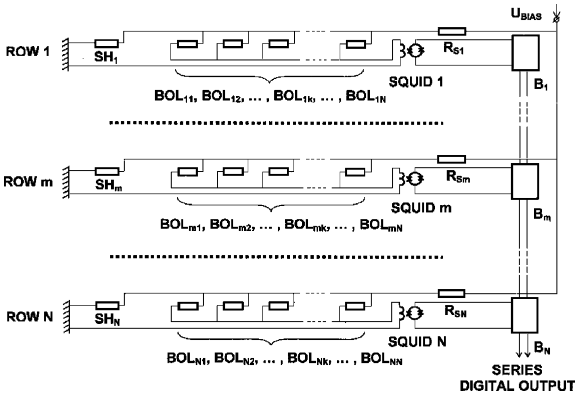

Fig. 1. Parallel electrical connection of bolometers with output to the SQUID-amplifier in each row: BOL$_{mk}$—bolometers with similar resistances R_{Bmk} and transition edge temperatures [3], SH_{m}—shunts feeding bolometers with fixed bias voltage V, R_{Sm}—series resistances of biasing circuits, $\{B_{\mathrm{m}}\}$—projections acquisition system (block of SQUID-electronics, analog-to-digital converter and data parallel-to-series digital converter in each row for data transmission bus). Feedback circuits of SQUIDs are not shown.

The fixed bias voltage for all bolometers in row is supplied from one shunt resistance (Fig. 1) like in case of single TES bolometer [6] and its value is determined by the expression $1/R_{\mathrm{SH}} \gg \sum 1/R_{\mathrm{BOLk}}$ in each row. The system stability is providing by choice of this resistance in accordance with an expression $1/R_{\mathrm{SH}} + \sum 1/(R_{\mathrm{dif}})_{\mathrm{BOLk}} > 0$, where $(R_{\mathrm{dif}})_{\mathrm{BOLk}}$ is the negative differential resistance of each bolometer connected into fixed-voltage bias circuits in each row. The summing of all detected signals in each row is realizing in input coil of SQUID readout-amplifier, one in each row for N bolometers. By this reason the drastic reducing of amounts of wires leading in, the bias to bolometers and feed-back signals to SQUIDs, and leading out, detected signals, is achieved. The amount of SQUIDs themselves is reducing as well.

The sets of signal (detected current) sums in rows at different angles θ of reciprocal positions of array and image can be named projections in a similar as in the computer tomography. Exactly by this reason we have given the name of proposed multiplexing method.

Portions of radiation power coming to each of receiving elements of array can be described by the table $\{P_{\mathrm{mk}}\}_{\Theta}$, where k is number of detector in row and m is number of row. The subindex Θ means that we have the number of radiation power parts sets corresponding to different reciprocal angles between the array and the image. A corresponding table of detected currents $\{\Delta I_{\mathrm{mk}}\}_{\Theta}$ calculated through Eq. (1) is obtained. To each current ΔI_{mk} a detector noise current of approximately similar value is added. By the reason of large sum ($N \sim 100$) of currents ΔI_{mk} (detected signals) flowing to the input coil of one SQUID its noise can be neglected. The result of the summing detected currents and their noise currents is the following table:

$$\left\{\sum_{\mathrm{k}} \Delta I_{1\mathrm{k}} + \sqrt{N\overline{I_n^2}}, \ldots, \sum_{\mathrm{k}} \Delta I_{\mathrm{mk}} + \sqrt{N\overline{I_n^2}}, \ldots, \sum_{\mathrm{k}} \Delta I_{\mathrm{Nk}} + \sqrt{N\overline{I_n^2}}\right\}_{\Theta}. \quad \text{(direction of } \xi \text{ coordinate} \rightarrow\text{)} \tag{2}$$

The set of sums (2) like in the computer tomography are projections in (ξ, θ) coordinates [4]: θ is current value of the rotation angle of the receiving element array relatively to the image, ξ is current coordinate along given projection set. We see from Eq. (2) that the signal-to-noise ratio at the output of row is $\sqrt{N}$ times higher than at the output of single bolometer.

The reconstruction of images is realized by the method of convolution and back-projections. Algorithms of this procedure are well developed and described [4,7]. They may be applied for our case without extra efforts when to express the searching for unknown (reconstructing) radiation power field not by discrete data field of parts $\{P_{\mathrm{mk}}\}$ but by continuous power density field $p(x, y)$, where x and y are coordinates in the common plane of the image and receiving elements. Sets of discrete functions being current sums values in the Table (2) also have to be approximated with distributions of detected $\imath(\theta, \xi)$ and noise currents $\varsigma(\theta, \xi)$ where $\imath$ is linear density of signal currents and ς is linear density of noise currents. We define the projection from function $p(x, y)$ to the family of lines $L(\theta, \xi)$ as

$$\imath(\theta, \xi) = \frac{1}{V}\int_{L(\theta,\xi)} p(x, y)\, \mathrm{d}s. \tag{3}$$

The factor $1/V$ takes into account the relation between $\imath$ and p following from Eq. (1). The derivation of the radiation power density distribution $p(x,y)$ from the projections set (3) is the ill-conditioned inverse problem of mathematical physics and Tikhonov regularization method can be proposed for its solution in accordance with which the derivation of Eq. (3) can be obtained as [8,9]

$$p(x, y) = \frac{1}{\pi} V \int_{\theta=0}^{\theta=0+\pi} \mathrm{d}\theta \times \int_{-\infty}^{+\infty} K_\alpha(\xi - \xi')\imath(\theta, \xi')\, \mathrm{d}\xi' \tag{4}$$

where the convolution kernel is introduced through its Fourier image as

$$K(\xi) = \int_{-\infty}^{+\infty} K_\alpha(\omega) \cdot \mathrm{e}^{-\mathrm{i}\omega\xi}\, \mathrm{d}\omega$$

$$K_\alpha(\omega) = |\omega|/(1 + |\omega|^{2r})$$

where α is the regularization parameter and r is the regularization rate.

The additive random current noise expressed like total signal current in form of linear current density has to be added into the reconstruction algorithm (4)

$$p(x, y) = \frac{1}{\pi} V \int_{\theta=0}^{\theta=0+\pi} \mathrm{d}\theta \int_{-\infty}^{+\infty} K_\alpha(\xi - \xi')\imath(\theta, \xi')\, \mathrm{d}\xi' + \frac{1}{\pi} V \int_{\theta=0}^{\theta=0+\pi} \mathrm{d}\theta \times \int_{-\infty}^{+\infty} K_\alpha(\xi - \xi')\varsigma(\theta, \xi')\, \mathrm{d}\xi' \tag{4'}$$

where $\varsigma(\theta, \xi')$ is the noise component of projection under the current angle in given direction. In this way the algorithm transforms the noise component of the projection linearly into noise component of the reconstructed image in the same way as signal components. This means

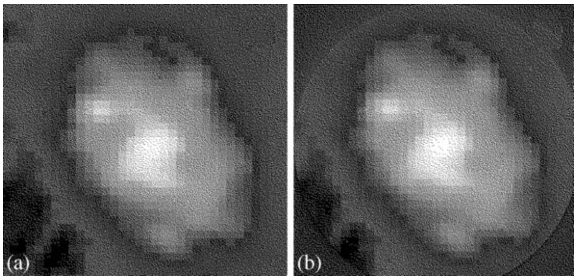

Fig. 2. (a) Primary image of M33 Galaxy, obtained at $\lambda = 100\,\mu\mathrm{m}$ [10]; (b) Simulation results of the multiplexing procedure using the image of M33 Galaxy as initial one.

that the signal-to-noise ratio in the reconstructed image will be the same as in projections and consequently the mentioned above advantage in signal-to-noise ratio will remain.

We have computer simulated the procedure of signal multiplexing in the array of $N \times N = 100 \times 100$ receiving elements by described method. We have used image of M33 Galaxy obtained at wavelength 100 μm (Fig. 2a) [10] as primary one. Omitting simulation details, its results are given at Fig. 2b. One may see that the signal multiplexing procedure using projections method is working normally.

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