The Multiplexing of Signals in Direct Detector Arrays using the Combination of Projections and Frequency Domain Biasing Methods

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Abstract—**A new method of signal multiplexing in submillimeter super low temperature direct detector arrays is proposed. This method makes it possible to sharply reduce the number of wires connected to direct detectors and SQUID's in the super low temperature area, significantly decrease the required number of SQUID based readout amplifiers, and substantially reduce the contribution of the SQUID and detectors noise and simplify connections of bolometers and SQUID's as compared to other known multiplexing methods.**

Keywords—M*illimeter- and submillimeter-wave direct detectors, super low temperature detectors, super high sensitive radiation detectors, signal and biasing multiplexing.*

I. Introduction

Arrays of super low temperature (T ≅ 0.3 - 0.1 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 lead-in the bias voltage to detectors and lead-out the 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 and realized [1, 2].

The Andreev reflection hot-electron bolometers with superconducting transition edge sensor or sensor 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 decrement $|\Delta I|$ (detected signal) in each moment in each bolometer of the array is connected with the absorbed radiation power P by expression [4]

$$|\Delta I| = (1/V)\cdot P, \qquad (1)$$

where V is fixed bias voltage applied to bolometer.

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

II. Signal Multiplexing Using Projection Method

We propose a novel 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 detected signals in rows are read out by one SQUID in each row (Fig. 1). The detected signals are integrated over readout time. The image of observed radiation and the array are rotated

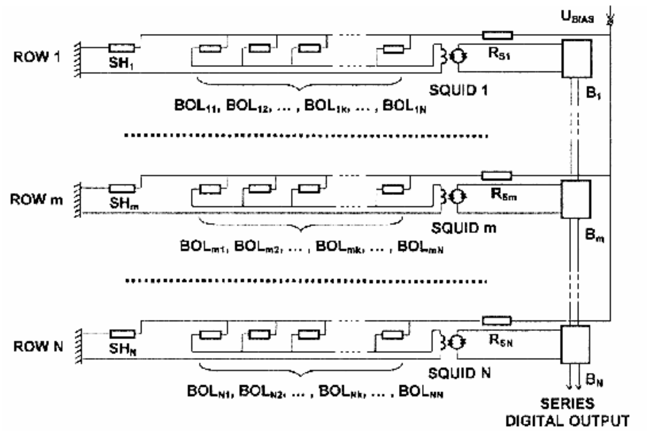

Fig. 1. Parallel electrical connection of bolometers with output to the SQUID-amplifier in each row: BOL_{mk} – bolometers with similar resistances R_{Bmk} and transition edge temperatures [4], SH_m – shunts feeding bolometers with fixed bias voltage V, R_{Sm} – series resistances of biasing circuits, $\{B_m\}$– 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 SQUID's are not shown.

Manuscript received May 2, 2005. This work was supported in part by the Russian Council on Leading Scientific Schools under Grant No. SSCH-1548.2003.2 and by the Department of Physical Sciences of Russian Academy of Sciences in frames of the Program "Problems of Radiophysics" – section "The Development of Terahertz Frequency Band".

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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 the detected signal sums gathered from all rows at all reciprocal angles using algorithms of the computer tomography [5]. We interpret the receiving element as the direct detector and the matching antenna into which the direct detector is incorporated (coupled) at microwave (in our case – submillimeter) frequency. The array of receiving elements based, for instance, on four-slot matching antennas with double polarization [6] 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 (Fig. 2) or electronic-optical, of rotation of image relatively to the array, what is equivalent to the rotation of the array relatively to the image.

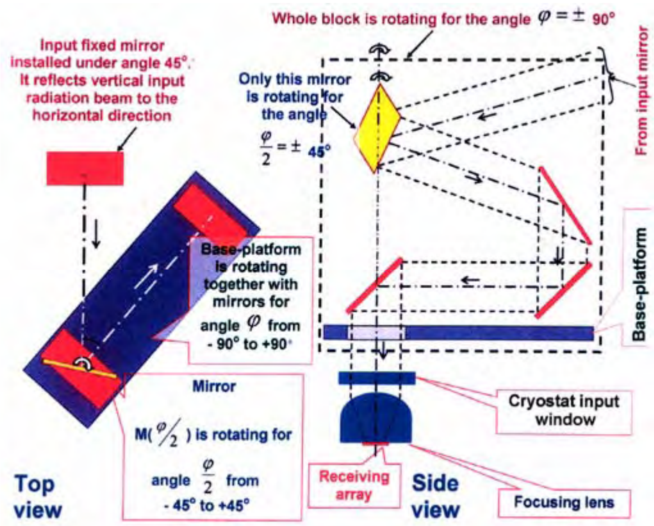

Fig. 2. A scheme of possible optical-mechanical rotating device providing the rotation of an image for angle from 0 to 180^0 relatively to the detector array in their common plane. It is possible to rotate the radiometer relatively its optical axis.

The fixed bias voltage for all bolometers in row is supplied from one shunt resistance (Fig. 1) like in case of single TES bolometer [7] and its value is determined by the expression $1/R_{SH} >> \sum 1/R_{BOLk}$ in each row. The system stability is providing by choice of this resistance in accordance with an expression $1/R_{SH} + \sum 1/(R_{dif})_{BOLk} > 0$, where $(R_{dif})_{BOLk}$ is the negative differential resistance of each bolometer connected into fixed-voltage bias circuits in each row [7]. 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 SQUID's, and leading out, detected signals, is achieved. The amount of SQUID's themselves is reducing strongly as well.

The sets of current decrements (detected signals) 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 [5]. 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 $\{P_{mk}\}_\Theta$ 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 current decrements $\{\Delta I_{mk}\}_\Theta$ calculated through (1) is obtained. A detector noise current of approximately similar value is added to each current decrement ΔI_{mk}. By the reason of large sum (N~100) of current decrements ΔI_{mk} (detected signals) flowing to the input coil of one SQUID its noise can be neglected. The result of the summing detected signals and corresponding noise currents is the following table:

$$\left\{ \sum_k \Delta I_{1k} + \sqrt{N I_n^2}, \ldots \sum_k \Delta I_{mk} + \sqrt{N I_n^2}, \ldots \sum_k \Delta I_{Nk} + \sqrt{N I_n^2} \right\}_\Theta . \qquad (2)$$

(direction of ξ coordinate →)

The set of sums (2) like in the computer tomography are projections in (ξ, θ) coordinates [5]: 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. Besides we see from (2) that the signal-to-noise ratio at the output of row is $\sim\sqrt{N}$ times higher than at the output of single bolometer what is one more advantage of the proposed multiplexing method.

The reconstruction of images is realized by the method of convolution and back-projections. Algorithms of this procedure are well developed and described [5]. 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 $\{P_{mk}\}$ 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 decrements sums values in the table (2) also have to be approximated with distributions of detected $\iota(\theta,\xi)$ and noise currents $\varsigma(\theta,\xi)$ where ι is linear density of current decrements 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:

$$\iota(\theta,\xi) = (1/V) \int_{L(\theta,\xi)} p(x,y)ds. \qquad (3)$$

The factor $1/V$ takes into account the relation between ι and p following from (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 regularizing method can be proposed for its solution in accordance with which the derivation of equation (3) can be obtained as [8]

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

where the convolution kernel is introduced through its Fourier image as

$$\left.\begin{aligned}K(\xi)&=\int_{-\infty}^{+\infty}K_\alpha(\omega)\cdot e^{-i\omega\xi}\,d\omega\\ K_\alpha(\omega)&=|\omega|/(1+|\omega|^{2r})\end{aligned}\right\}$$

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

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

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

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 components of the projection linearly into noise components of the reconstructed image in the same way as signal components. This means 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×N = 100×100 receiving elements by described method. We have used image of M33 Galaxy obtained at wavelength 100 μm (Fig. 3,a) [11] as primary one. Omitting simulation details, its results are given at Fig.3,b. One may see that the signal multiplexing procedure using projections method is working normally.

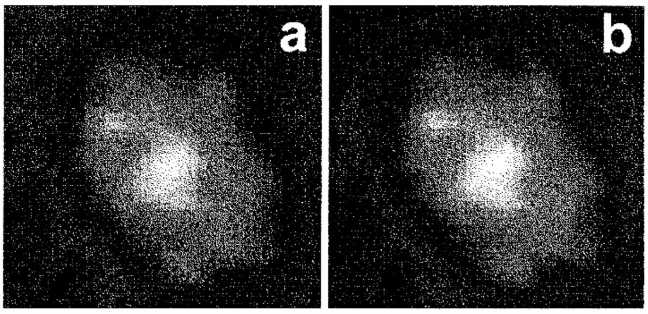

Fig. 3. (a) Primary image of M33 Galaxy, obtained at λ=100 μm [10]; (b) Simulation results of the projections multiplexing procedure using the image of M33 Galaxy as initial one.

II. COMBINATION OF PROJECTIONS AND FREQUENCY DOMAIN BIASING METHODS

Further development of the multiplexing scheme using the projection method is its combination with the frequency domain biasing method proposed by Berkeley group [2]. In said method each single bolometer is biased with its own frequency (Fig. 4). The frequency comb is amplifying by one or very small amount of SQUID. Signals are separated by lock-ins.

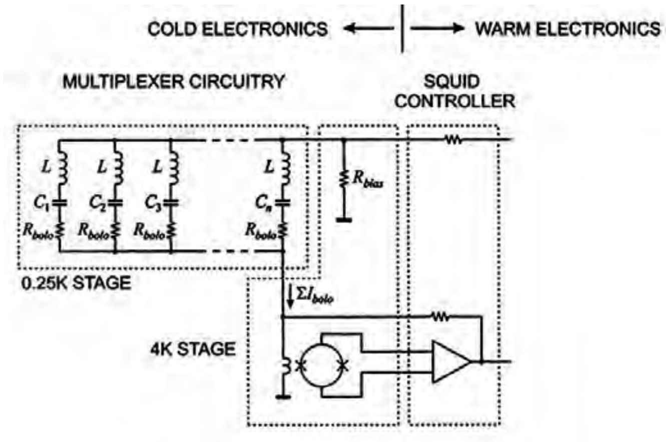

Fig. 4. Scheme of frequency domain multiplexing method.

We propose to put a row of N bolometers (Fig. 5) connected in parallel instead of each single bolometer R_{bolo} in accordance with previous method. This gives combination of advantages of both methods.

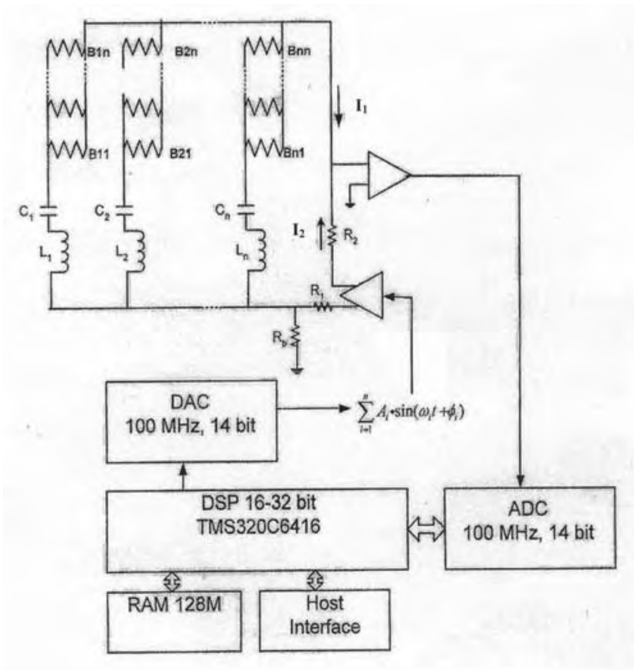

Fig. 5. Scheme of the bolometer connection and biasing in the combined multiplexing method.

In this scheme the separation of signals from rows is realized in the digital signal processor (DSP) in multifrequency lock-in mode. The frequency current comb I_2 compensates the pedestal of the current comb I_1 containing signals. Computer simulation results of operation of 29-channel lock-in amplifier (scheme is given above) having one SQUID` and frequency

of discretization 150 MHz are shown at Fig. 6.

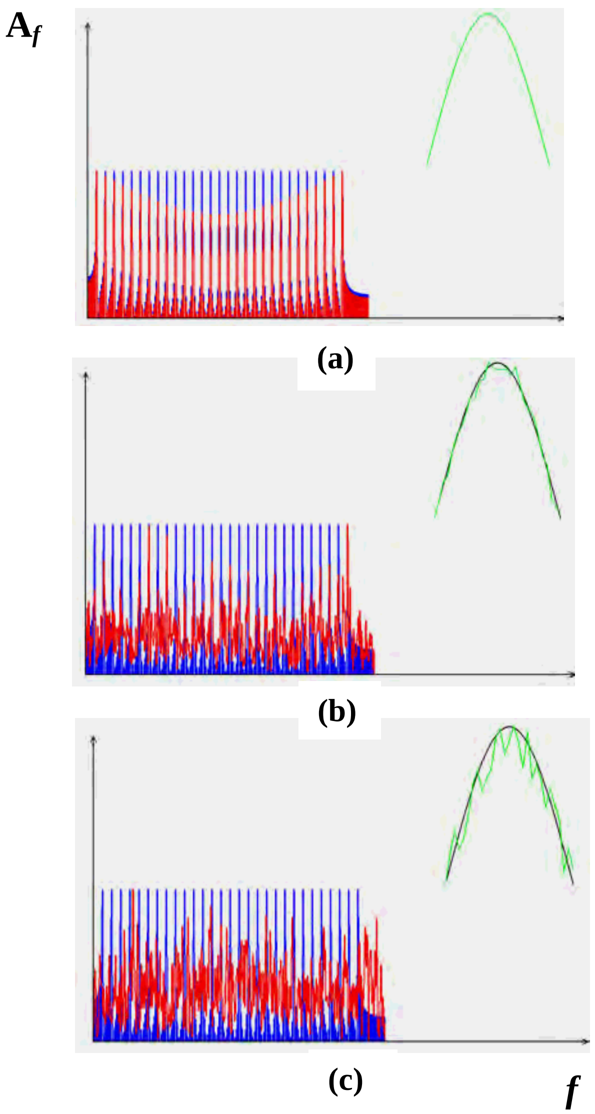

Fig. 6. Results of operation computer simulation of the scheme shown at Fig. 5. At the left of each picture – input and outout frequency combs; at the right-top – initial and processed signal distributions along a bolometers row without noise (a) and in the presence of noise with noise-to-signal ratio N/S = 1 (b) and N/S = 50 (c).

One may see from Fig. 6 that that the multifrequency lock-in amplifier operation is efficient. Existing DSP's permit an operation up at 128 frequency channels: array, i.e. in our case for array of 128 x 128 detectors. However by the reason of SQUID bandwidth restriction (~ 1 MHz) the scheme has to be divided for 4 sections with one SQUID in each section.

It is possible to conclude that the projection method and the frequency domain biasing method complement one another.

ACKNOWLEDGMENT

Authors thank S. V. Shitov and P. L. Richards for useful discussions.

REFERENCES

[1] K. D. Irwin, M. D. Audley, J. A. Beall, J. Beyer, S. Deiker, W. Doriese, et al., "In-focal-plane SQUID multiplexer", *Nuclear Instruments and Methods in Physics Research,* A 520, 2004 (Proc. of the 10th Intern. Workshop on Low Temperature Detectors – LTD-10, Genoa, Italy, July 7-11, 2003), pp. 387-389.

[2] J. E. Ruhl, P. A. R. Ade, J. E. Carlstrom, H. M. Cho, T. Crawford, M. Dobbs, et al., "The South Pole Telescope", *Proc. SPIE (Intern. Symp. on Astronomical Telescopes)*, 2004. www.spt.uchicago.edu/extweb/spt_spie_2004.pdf.

[3] A. N. Vystavkin, "Supersensiting hot-electron microbolometer with Andreev electron reflection phenomenon for submillimeter radio astronomy", *Radiotekhnika i Elektronika* (in Russian), 2001, v. 46, # 7, pp. 806-815.

[4] A. N. Vystavkin, A. G. Kovalenko, S. A. Kovtonyuk. "Study of superconducting transition in a Mo/Cu thin film structure and estimation of sensitivity of SUBMM waveband region TES bolometers on the basis of such a structure, *This Symposium*.

[5] W. Swindel and S. Webb, "X-ray transmission computer tomography", in "The Physics of Medical Imaging", Ed. by S. Webb, *Adam Hillier Publ. House,* Bristol and Philadelphia, 1988.

[6] G. Chattopadhyay and J. Zmuidzinas, "A dual-polarized slot antenna for millimeter waves," *IEEE Trans. Antennas Propagat.*, May 1998, v.. 46, pp. 737–737.

[7] K. D. Irwin, "An application of electrothermal feedback for high resolution cryogenic particle detection", *Appl. Phys. Lett.,* 1995, 10 April, 66 (15), pp. 1998-2000.

[8] A.N. Tikhonov, V.Ya. Arsenin, Methods of solution of ill-conditioned problems (in Russian), Moscow, "Nauka", 1986.

[10] I.B. Rubashov, A.A. Timonov, A.V. Pestriakov, Doklady Akademii Nauk SSSR (in Russian), 1981, v.258, №4, pp.846-850.

[9] IPAC-NASA, M33-Spiral Galaxy, http://sirtf.caltech.edu/Education/Messier/m33.html.