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Feasibility of Electrical-Contact Free Measurement of the Response of Superconductive Bolometer Arrays Using the Thermal Crosstalk

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Abstract. We utilized and investigated the unique dependence of the magnitude and phase of the response on the thermal crosstalk between bolometer pixels in an array to measure the response of the devices through fewer monitoring devices. In this study, we show the feasibility of the proposed read-out technique by use of two source pixels in an array, as the image-mapping devices, and one optically shielded pixel as the read-out device. While the sense pixels were electrical-contact free, the read-out device was current biased in 4-probe current-bias configuration. Both the phase and magnitude of the response due to the crosstalk in the array were found to be strongly dependent on the modulation frequency and the distance between the sense and read-out pixels. A series of measurements were designed to extract the response of each single sense-pixel. By combining the measured data, the response of individual pixels could be extracted through the interpolation of the mapped responses.

1. Introduction

We have already investigated and reported the parameters that affect the crosstalk between the neighbor pixels of the bolometer arrays elsewhere [1], [2]. There, we have defined the crosstalk-free modulation frequency (f_m) for the operation of the devices operating in the conventional configuration. That is, each pixel has electrical contacts and it is favorable that the pixels do not have any crosstalk. Since a very large area on most of the detector chips is occupied by the read-out electronics and/or the contact paths, it is favorable to decrease the electrical contact areas or contacts made to the sensor pixels. Decrease of the electrical contacts when possible, would lead to denser layout designs that enables increased spatial resolution, and decrease of the power consumption and the fabrication cost. In this study, we operate the devices below their crosstalk-free f_m to utilize the crosstalk between the devices in an array in detection of the response of the radiation sensing pixels with no electrical contacts. This is done by measuring the phase and magnitude of a read-out device in the array, which is biased using its electrical contacts. To the best of our knowledge, including semiconductor and superconductor detectors, this is the first time that such a read-out methodology is proposed and utilized. This approach would allow only one read-out pixel be used for a number of sense-pixels.

To investigate the feasibility of the proposed read-out methodology in this study, a design is implemented where a read-out pixel is used to read the response of two neighbor detector sense-pixels. We have experimentally found and formulated the unique dependencies of the phase and magnitude of

the thermal crosstalk based responses that enable the measurement of the response of the sense-pixels by fewer monitoring or read-out pixels. Here, we show the feasibility of the proposed method and present the design optimizations in terms of device dimensions and the operating frequency.

2. Sample Preparation and Experimental Setup

The crosstalk study was made possible through the illumination of the sense-devices and measuring the voltage response of the blocked read-out device in the same array. This was done using a gold coated shadow mask. In order to prevent thermal artifacts created by the mask, the mask was made in free standing configuration on top of the devices as shown in Fig. 1. The same experimental setup was used as in [3]. The devices were made of 200 nm thick pulsed laser deposited YBCO films on SrTiO₃ substrate material.

3. Results and Discussion

To test the feasibility of the proposed detection mechanism, we have implemented the device array configuration as shown in Fig. 1. The read-out pixel is chosen as device B, whereas devices A and C were chosen to be the sense-pixels being exposed to the incident radiation. The device B has contacts for 4-probe measurements, and devices A and C do not have any electrical contacts. The goal of this study is to find the methodology for extracting the response of the A and C pixels through the measured signal of the current biased device B.

3.1. Principle of Operation

The spatial and frequency dependence of the response at distance x away from a single pixel bolometer has already been formulated [3], [4].

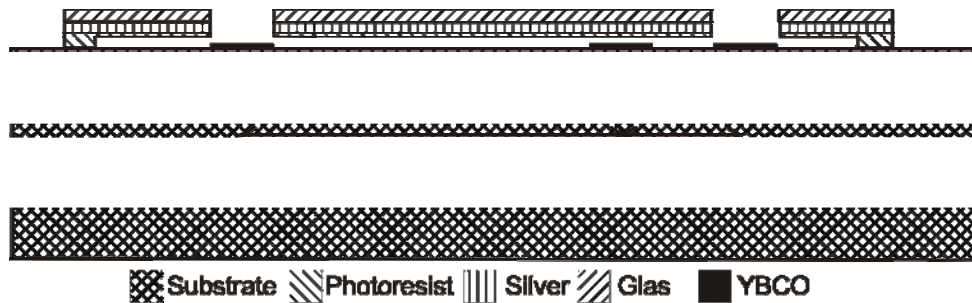
$$\frac{T(x, f)}{T_0} = \underbrace{\exp\left[-\sqrt{\frac{\pi f}{D}}x\right]}_{\text{Magnitude}} \underbrace{\exp\left[-j\sqrt{\frac{\pi f}{D}}x\right]}_{\text{Phase}} \quad (1)$$

Where, $T(x, f)/T_0$ is the normalized response under modulation frequency of f at x distance away from the source pixel, and D is the diffusivity of the substrate material. As shown in (1), with the increase of the distance x , the phase of the response, $-\sqrt{\pi f / D}x$, decreases resulting in further increase of the lag of the signal.

Considering the crosstalk for a two-pixel case, the crosstalk response at point x_b , caused by devices A and C, are the superposition of the responses of individual pixels A and C at x_b . Eq. (2) shows this superposition relation:

$$\frac{T(x_b, f)}{T_0} = \exp\left[-\sqrt{\frac{\pi f}{D}}d_a\right]\exp\left[-j\sqrt{\frac{\pi f}{D}}d_a\right] + \exp\left[-\sqrt{\frac{\pi f}{D}}d_c\right]\exp\left[-j\sqrt{\frac{\pi f}{D}}d_c\right] \quad (2)$$

Fig. 1 shows the implemented design and the structure of the array with the shadow mask. In Fig. 2, the superposition relation is shown together with experimental data confirming the validity of the above superposition (due to the interference) assumption for $x_a = 40 \mu\text{m}$ and $x_c = 170 \mu\text{m}$.



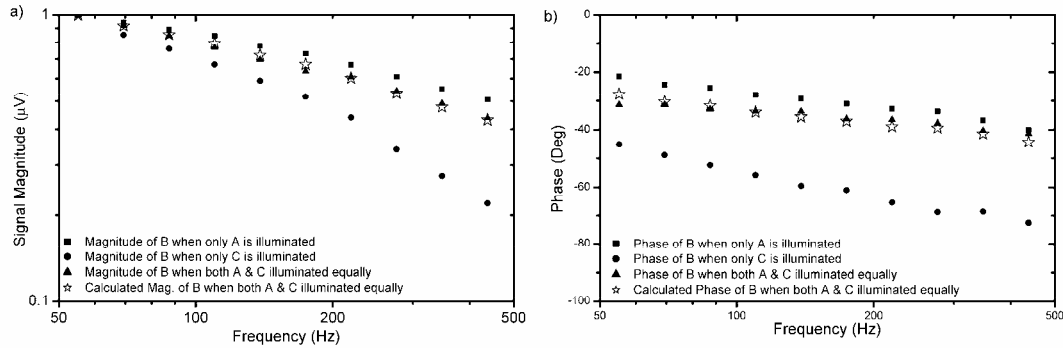


Fig. 2. The response magnitudes (a) and phases (b) of A, B and C (■, ▲ and ●). In the figures (a) and (b), ☆ points shows that the magnitude and phase of the sum of the responses of A and C fit to that of the phase and magnitude of B (▲).

The read-out pixel B, will have a response due to sense-pixels A and C with $x = 40 \mu\text{m}$ and $170 \mu\text{m}$, respectively. If we add these two responses in vector form to include both their phase and magnitude contributions, we get the curves denoted by (▲) in Fig 2. The three experimental curves in Fig 2 are obtained by three illumination configurations as; i) only A, ii) only C, iii) both A and C. The calculated curves in the figures 2a and 2b are obtained by vectorial sum of individual responses of A and C. As shown in the figure, the vector sum of these responses fit closely to the case of simultaneously illumination of A and C devices, and while the phases fit well, the magnitudes do not. This is because the measurements were done at different times and due to the difficulty of the laser alignments, the magnitudes could not be perfectly aligned to the former state. However, one should note that the normalized response in the experimental curves and the calculated curve, fit very well. In the following section, we investigate the calculations in the inverse approach. That is, given the simultaneous illumination data, we extract the individual contributions of the devices A and C by using the measured phase and magnitude of superposition of the two responses.

3.2. Example of extraction of the response of two sense-pixels with one read-out pixel

In Section 3.1, it was shown that the response of device B, due to simultaneous illumination of the two sense-pixels, is the superposition of separately illuminated A and C pixels. In this regard, one can solve the problem with the reverse approach of the above. Having the data for simultaneous illumination of sense pixels A and C, we extract the information of the response contribution from each pixel. Fig. 3 shows the phases of the response curves vs. $\text{Mag(A)}/\text{Mag(C)}$ at different modulation frequencies. For example, the 5 points of the curve at 174 Hz, which have been numbered in Fig. 3, has been obtained by 5 different measurements: 1- only device A was illuminated (taking into account the leaking laser beam, $\text{Mag(A)}/\text{Mag(C)}=100$); 2- The laser was aligned so that $\text{Mag(A)}/\text{Mag(C)}=2$; 3- The laser was aligned at the middle of A and C ($\text{Mag(A)}/\text{Mag(C)}=1$); 4- The laser was aligned so that $\text{Mag(A)}/\text{Mag(C)}=0.5$; 5- only device B was illuminated (taking into account the leaking laser beam,

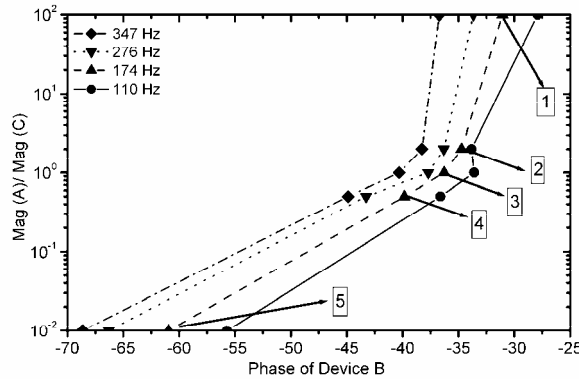


Fig. 3. $\text{Mag(A)}/\text{Mag(C)}$ vs. Phase of read-out device B. By measuring the phase of device B, $\text{Mag(A)}/\text{Mag(C)}$ can be obtained. The numbers in squares show the calibration data points.

$\text{Mag(A)}/\text{Mag(C)}=0.01$). Thus, once the phase of read-out pixel is known, $\text{Mag(A)}/\text{Mag(C)}$ in the whole range can be found with proper interpolation as proposed and shown in Fig. 3. Once the $\text{Mag(A)}/\text{Mag(C)}$ is found, their values can be derived by using the single pixel response curves reported in [1].

3.3. Determination of Optimum Modulation Frequency Based on the Device Dimensions

For uniquely determination of the response of A and C devices, the $\text{Mag(A)}/\text{Mag(C)}$ vs. phase plots should have one-to-one correspondence. e. g., the curve of 110 Hz in Fig. 3 cannot be used for this purpose. In the lower end of the frequencies, since L_f is greater than the device separations, the devices A and C are coupled to each other as well. Based on the thermal diffusion length relation $L_f=(D/\pi f)^{1/2}$ and using the thermal diffusivity of $0.027 \text{ cm}^2/\text{s}$, the crosstalk-free f_m between the devices A and C would be 19.4 Hz. Below this frequency, we cannot differentiate the response of device A from device C. Above the crosstalk-free f_m of device C and B, which is around 500 Hz, the response measured by the read-out pixel B would only be due to the device A. Thus we should keep the f_m above 20 Hz and below 500 Hz. The most optimum operating frequencies for this given configuration is the frequencies that are just below the crosstalk-free f_m between B and C. In Fig. 2, we see that the optimal operating frequency is around 250 Hz where the maximum phase difference between A and C pixels is obtained, which well fits our estimations.

3.4. Determination of Optimum Device Layout Dimensions Based on the Modulation Frequency

The studied bolometer array in this work was mainly designed for investigation of the inter-pixel crosstalk of the neighbour devices, rather than the non-contact measurement of the IR response. Hence the extraction of the individual signals cannot be done efficiently for the studied devices. In this case the error margins are large and the useable range of the modulation frequencies is narrow.

As a design consideration, two main issues should be taken into account. First, the phases of the response caused by the individual sense-pixels should be as different as possible. This is while the crosstalk magnitudes of the responses should be as close to each other as possible. To be able to achieve both of these preferences at the same time, apart from the device separations, the sizes of the sense-pixels should also be chosen different accordingly. For example, if the distant devices are made larger in area, then the magnitude of the crosstalk response on the read-out pixel would be greater. Though the phase of the response is dependent on the distance and it would not change considerably. In some applications, different sizes of sense-pixels might not be desired. In this case, the read-out pixel shape would need to be adjusted so that the desired responses from the sense-pixels are obtained.

4. Conclusion

By utilizing the unique dependence of the phase of the response vs. device separation in an array, measuring the response magnitude of electrical contact free pixels was shown to be possible using fewer read-out pixels. Based on the results of this study, one can derive the theoretical limit of the minimum required read-out pixels for any number of the source pixels in such read-out configuration. This can also be done for designs with very high number of source pixels, by utilizing the signal processing algorithms. In addition, optimum array designs for this specific purpose should be made.

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