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Broadband Experimental Validation of the Near Field Focusing Pattern of Frequency Selective Absorber based Kinetic Inductance Detectors

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Abstract— Passive imaging cameras at sub-millimeter wavelengths with large format focal plane arrays are being developed as the next generation of security screening systems. In this contribution, a dual-band focal plane array (FPA) at sub-millimeter wavelengths is presented. The detectors are based on bolometric kinetic inductance resonators, which allows the development of large format FPAs at medium cooled temperatures. Two frequency selective absorber (FSA) sets coupled to superconductive resonator lines were designed to implement a dual color security imager. The performance of the dual band imager was evaluated using a Fourier optics technique coupled to a Floquet mode analysis. The effective pattern of the imager coupled to a black body point source over a wide frequency band (1:6) was demonstrated experimentally with excellent agreement to the one estimated by using the proposed spectral technique.

Index Terms—THz absorbers, focal plane array, frequency selective absorber, Fourier optics.

I. INTRODUCTION

The next generation of security imagers at submillimeter wavelengths for stand-off detection of concealed weapons, [1], [2], will require the acquisition of images as large as a human body, over 100000 pixels, at quasi-video rate, higher than 10 Hz. The architecture of such imagers is typically composed of a quasi-optical system, a focal plane array (FPA) and a mechanical scanner. A large format FPA leads to longer integration time comparable to the frame rate. Therefore, the sensitivity requirement of such FPAs are relaxed. However, the design of large FPAs at sub-millimeter wavelengths remains a significant challenge.

Kinetic inductance detectors (KIDs) are a promising technology for implementing a large number of detectors in the order of several thousand at sub-millimeter wavelengths [3]. KIDs are composed of low frequency superconductive resonators. Bolometer based KIDs, provide the possibility of having large FPAs with medium cooled temperature and a reasonable cost for passive imaging. The NEP of these detectors are in the order of $10^{-15}W/Hz^{1/2}$ [4].

Exploiting this technology, in this work, a FPA suited for future security applications is designed. The outer diameter of the FPA has been set to $\Theta = 24 \text{ cm}$, corresponding to the maximum useful window of the available cryostat. In order to improve the probability of detection, one can use passive images taken at different frequency bands [5]. To this end, we propose here to modify the absorber design in [4] to be frequency selective [6] around a designed frequency. To realize images at two frequency bands, a FPA composed by two different and interleaved sets of detectors is proposed. The FPA will then consist of detectors for the lower bandwidth centered at 250 GHz, and the ones for the higher bandwidth centered at 500 GHz, as shown in Fig. 1. The proposed FPA can be operated with a linear scanner in order to generate fully sampled images in the two bands.

In order to optimize the performance of an imager based on a FPA made of FSAs, the spectral Fourier optics (FO)
technique as described in [7] is used. The quasi-optical system of the imager consists of the dual lens focusing in the near field described in [8]. The f-number, \( f_n \), (ratio between the focal distance and diameter of the optics) of the optical system is set to 2.

The paper is structured as follows. Section II describes the design of the FSAs for the two operational bandwidths. The architecture of the dual-band focal plane array is discussed in Sec. III. In section VI, the effective pattern of the imager coupled to a black body point source over a wide frequency band (1:6) was estimated theoretically, and demonstrated experimentally. Finally, Section V contains some concluding remarks.

II. FSA BASED KIDS

The functional elements of the detectors proposed in [4] are composed of two layers: a resistive mesh grid with a surface resistance of \( R_s = 5 \, \Omega \), and a superconducting meander strip below the grid. The layers are separated by a thin dielectric layer with the thickness of 150 nm and dielectric constant \( \varepsilon_r \approx 5.0 \). The entity is located on a silicon nitride membrane to thermally isolate it from the surroundings. The mesh grid absorbs the incoming radiation, and heats the elements on the membrane, which in the operating temperature range of 5 - 10 K are essentially in thermal equilibrium. The temperature dependence of the superconducting kinetic inductance is then used to read out the temperature change. The mesh grid was optimized for wide-band detection at \( f \approx 1 \) THz. The detector used a thick back short which introduced a frequency dependency, an angular variation significantly different from the Lambert’s cosine law. Because of this angular variation, electrically thick back-shorts will affect the coupling to optical systems [7], especially for off-focus detectors.

In this work, instead, the goal is to change the detector’s geometry into two different FSA layouts each with a limited bandwidth around 250 GHz and 500 GHz, respectively, with a nearly flat angular response up to 30°. To achieve this goal, the mesh grid can be loaded with a distributed capacitance using a geometry typically referred to as a Jerusalem Cross (JC) [9]. The absorption rate and out of band rejection of the resistive layer can be improved, by using a back short. The use of a quarter wavelength back short for the FSA1 will introduce a significant rejection in the 500 GHz band. The FSA2 is instead designed with a much smaller back short distance to short circuit the lower part of the frequency band. The capacitance behaviour in the FSA2 compensates the inductance introduced by such back short.

The superconducting thermometer lines in the bolometric KIDs can be modeled, as two thin strip lines with a sheet impedance as estimated from the theory of Mattis and Bardeen [10]. Due to the presence of the superconducting lines, the absorption rate of the FSAs, in terms of frequency and polarization response, would be significantly altered in comparison to a free-standing design. These effects, however, can be compensated for by modifying the geometry of the JC FSAs differently for vertical and horizontal polarizations. In Fig. 2, the simulated, using CST MWS [11], absorption rates for the two FSA sets are shown. The proposed FSA unit cells combined with the resonators are also shown in the inset of Fig. 2. The absorption rate is comparable to the one of the free-standing design in the frequency and angular range of interest. Moreover, no significant variation was seen for incidence angles up to 30° for both polarizations.

![Fig. 2. The absorption rate of the optimized design: (a) FSA1, (b) FSA2.](image)

Since the FSA and the resonator lines are separated by an electrically thin membrane, the structures in Fig. 2 are difficult to model using lumped elements because of the coupling between the layers via higher order Floquet modes. Therefore, an equivalent circuit model based on an admittance matrix, \( Y_q(k) \), representing the scattering of the FSA unit cells [7] will be used in the next sections to evaluate the coupling of the FSA KIDs to the optical system. Such matrix was evaluated using CST MWS simulations with periodic boundary conditions.

III. DUAL BAND FOCAL PLANE ARRAY

In this section, the design of the KIDs based FPA for dual band operation is presented. The distribution of the FSA based KIDs over the focal plane is defined by a trade-off between the expected imager sensitivity, half power beam-width (HPBW), mechanical requirements and fabrication constrains of the detector.
For non-fully sampled FPAs, the optimum configuration in terms of sensitivity typically leads to a distribution of the detectors in the focal plane array over a hexagonal grid plus a two dimensional jiggling mechanism, [12] and [13], since this allows for the largest physical dimensions of the detectors. However, here a 45° scanning axis was chosen to be compatible with a single axis scanning mechanism. As a result, the FPA elements are allowed to be enlarged to a sampling rate of \(0.61\lambda_{of}\) [12]. Since the number of sampling points is frequency dependent, the FPA will then have double the number of FSA2 detectors compared to FSA1 ones. The mechanical scanner will acquire 6 and 12 image pixels per detector for the detectors at the lower and higher band, respectively. This layout has been chosen for three reasons: i) to maximize the physical area for the higher frequency pixels, ii) to use the same scanning mechanism for both frequencies, and iii) to optimize the silicon wafer use considering the fabrication tolerances. The physical dimensions of the two detector sets are then fixed to \(\omega_1 = 0.625\lambda_1\) and \(\omega_2 = 0.75\lambda_2\), respectively. Where \(\lambda_1\) and \(\lambda_2\) are the wavelengths at 250 GHz and 500 GHz, respectively. These values lead to a comparable utilization of the optics aperture to the one of an antenna based FPA [7]. The layout of a portion of the FPA is shown in Fig. 3, where FSA1 and FSA2 sets consist of arrays of 5x5 and 6x6 elements, respectively (As shown in Fig. 1).

![Fig. 3. Schematic representation of the dual band FPA. Scanning axis is indicated with the arrow.](image)

**IV. MEASURED PERFORMANCE**

In this section, the experimental performance of the imager in terms of effective angular pattern is reported. The quasi-optical system of the imager consists of an inversely magnified dual-lens structure as shown in Fig. 4(a), and described in [8]. In order to limit the out-of-band radiation, two band-pass filter windows are placed in the optical path between the lenses and the FPA.

In order to use the spectral analysis tool presented in [7] for the current geometry, the dual lens structure is analyzed using the commercial software GRASP [14] to derive the plane wave spectrum (PWS) generated by the optical system. As described in [7], the coupling mechanism between this PWS and the absorber can be represented via an equivalent Floquet circuit, Fig. 4(b). The periodic absorbing mesh response to a plane wave is included in the circuit via an equivalent admittance matrix, \(Y_{abs}(k_p)\), evaluated using CST MWS. The input voltage waves, \(V_{TE/TM}\), in the equivalent Floquet circuit can be related to the PWS.

![Fig. 4. (a) Schematic representation of the imaging system, including the dual lens optics and the band-pass filter stages. The point source is placed at \(\hat{p}_s\) in the FoV which corresponds to a detector placed at \(\hat{p}_{det}\) in the focal plane. (b) Equivalent transmission line model of a periodic absorber with period smaller than half wavelength above a ground plane at distance \(h_{abs}\).](image)

One can follow the similar steps than described in [7] to obtain the spatial fields representing the response of the absorber to the optical system, \(\hat{e}i(\hat{p}_f, \hat{p}_s)\) and \(\hat{h}i(\hat{p}_f, \hat{p}_s)\), where the position of the source is explicitly indicated by \(\hat{p}_s\). Finally, for small displacements of the source position around \(\hat{p}_s\), the power received by the detector can be approximated as [7]:

\[
P_{abs}(f, \theta_s, \phi_s) \approx 0.5 \left| \int_{W_{1/2}} e^{i(\hat{p}_f - \hat{p}_i, \hat{p}_s)} \times h^i(\hat{p}_f - \hat{p}_i, \hat{p}_s) \right|^2 \, d\hat{p}_f
\]
where $\theta_s = \tan^{-1}\left(\frac{\hat{\rho}_z + \frac{\Delta \rho_{fov}}{R}}{\hat{\rho}_x + \frac{\Delta \rho_{fov}}{R}}\right)$ and $\phi_s = \cos^{-1}\left(\frac{\hat{\rho}_z + \frac{\Delta \rho_{fov}}{R}}{\hat{\rho}_x + \frac{\Delta \rho_{fov}}{R}}\right)$ are the angular positions of the source, $\hat{e}_s(\hat{\rho}_x - \Delta \rho_1, \hat{\rho}_z)$ and $\hat{h}_s(\hat{\rho}_x - \Delta \rho_1, \hat{\rho}_z)$ are the fields translated by the flash point, $\Delta \rho_i = -\Delta \rho_{fov}/M$. Fig. 4(a), $M$ is the optical magnification, $w$ is the side length of the absorber.

In this work the detector is positioned at a distance from the center of the FPA, $\rho_{det} = 31 \, \text{mm}$, corresponding to a pixel in the field of view (FoV) located 25.82 cm away from the center of the image plane ($\hat{\rho}_z$ in Fig. 4(a)). This particular configuration is the same used in the measurements. The Floquet model proposed in [7] characterizes the absorber response to an optical system assuming local periodicity, i.e. neglecting edge effects. The power absorbed includes the spillover associated to the diffracted fields in the focal plane, the ohmic and reflection losses of the dual-lens, the response of the two filter stages, and the frequency response of the FSAs.

The quality of an image is dictated by the power received by the imager, when illuminated by a black body point source radiating over the whole frequency band ($BW = 100$ to $625 \, \text{GHz}$). This effective pattern, in the Rayleigh Jean’s limit, can be expressed as:

$$p_{\text{FPA}}^{\text{effective}}(\theta_s, \phi_s) = \int_{\omega \in \omega_{\text{BW}}} \frac{p_{\text{abs}}(f, \theta_s, \phi_s)}{\lambda^2} \, df$$

(2)

where the term $1/\lambda^2$ indicates the frequency behavior of the brightness for a black body source in Rayleigh Jean’s limit.

The effective pattern was measured for two detectors (one per each bandwidth). The measurement was performed by displacing the black body point source in the FoV. The results are shown in Fig. 5 for both FSA1 and FSA2 and compared to the theoretical computation based on the spectral model of [7]. The theory and the experiments are in excellent agreement until $-10 \, \text{dB}$. Below this value, the noise due to the measurement setup is dominant. The pattern shows good symmetry. Its HPBW is $1.59 \, \text{cm}$ and $1.11 \, \text{cm}$ for FSA1 and FSA2, respectively. These values are then compared to the diffraction limited HPBWs. The latter can be calculated as the HPBW of an Airy pattern corresponding to the design f-number, $f_n = 2$ at the central frequencies of FSA1 and FSA2. The results show that the HPBW performance of the designed imager is comparable to the diffraction limited case.

V. CONCLUSION

In this contribution, a dual-band focal plane array for security imagers at submillimeter wave frequencies was presented. The detectors are based on a bolometric superconducting KID configuration since it allows to design large FPA at medium cooled temperature. Two FSA sets coupled to superconductive resonator lines were designed to implement a dual color security imager. The geometry of the unit cells is based on a Jerusalem cross configuration and the designed FSAs show a stable angular response. The detectors in the dual band FPA are distributed over a hexagonal grid to maximize their physical size and then improve their sensitivity. The performance of the dual band imager was evaluated using a Fourier optics technique coupled to a Floquet mode analysis. The effective pattern of the imager coupled to a black body point source over a wide frequency band (1:6) was estimated, and successfully demonstrated experimentally. The HPBW of this pattern is comparable to the one of a diffraction limited quasi-optical system.

![Fig. 5. The effective pattern compared between the proposed method and the measurement for (a) FSA1, (b) FSA2 sets, for a vertical polarized source.](image)

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