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Superconducting Metamaterial for Sub-Millimeter Wave Imaging: First Light

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Abstract – **We present results of first experiments with elementary cells for detection of sub-millimeter-wave radiation. The cells realize frequency-division multiplexing (FDM) readout of an antenna coupled superconducting hot electron bolometers (HEB) by means of integrated GHz-range superconducting resonators. Such cells can be coupled to a single transmission line for FDM readout, forming a large format imaging metasurface. The design of metasurface, consisting of hexagonal clusters, is discussed and experimental results for both the single cell and the 7-element hexagonal cluster are presented. The prototypes have been fabricated using thin film Nb technology with T_C of HEB bridges about 5 K and frequencies of resonators in 5 – 8 GHz range. Optical sensitivity measurements using a black body radiation source resulted in optical NEP of the cell about 3×10^{-14} W/√Hz at ambient temperature 1.4 K.**

I. INTRODUCTION

The imaging applications in radio astronomy require large arrays of ultrasensitive sub-millimeter wave detectors (more than 1000 pixels), which are cooled down to mK temperatures [1]. This raises the problem of reading out such matrixes with an acceptable number of connections which is very important for minimization of complexity and cost of such systems. A proven solution is the frequency-division multiplexing (FDM) [2] that means reading out of different pixels at different frequencies using only one signal line. There are at least two types of superconducting detectors employing the FDM: transition edge sensors (TES) [3] and microwave kinetic inductance detectors (MKID) [4]. The superconducting TES is known as the most sensitive device in a wider frequency range; it employs relatively low FDM frequency, since the output signal is boosted by a SQUID-amplifier usually below 1 MHz. The MKID can operate at much higher frequencies, up to 10 GHz, using compact integrated resonators [4]. This brings ease of using a cooled HEMT amplifier. We suggest using a fussy solution: an antenna-coupled superconducting hot electron bolometers (HEB) [5], embedded into a compact GHz-range resonators with different resonant frequencies. In an imaging array the resonators can be excited with a single coupled transmission line [6], similarly to MKID concept, which allows biasing and readout of the bolometers. The response of such an array then boosted by a single HEMT amplifier instead of array of a few SQUID amplifiers [1]. Thus, only two (input and output) coaxial lines are needed for operation.

The frequencies of high-Q resonators can be set by design as close as few MHz to each other being centered at about 10 GHz. This approach may lead to kilo-pixel HEB imaging arrays. To cover an arbitrary 2D surface, a set of hexagons looks a good choice. We suggest a 7-pixel hexagonal cluster (see Fig. 3a) combined with an immersion lens, forming a multi-beam integrated-lens antenna [7], as a building block of an imaging metasurface. Here we present our first attempt in fabrication and testing of such a cluster.

II. EXPERIMENTAL DETAILS

To verify our new concept, we have designed two different experimental chips: one containing the single pixel detector and another one bearing the hexagonal 7-pixel cluster. The chips have been fabricated on sapphire substrate using Nb thin-film technology.

Fig. 1a shows layout of the chip containing a single pixel. The HEB coupled to a double slot antenna is embedded into a quarter wave coplanar resonator near to its open end. The resonator is weakly coupled to a 50-Ohm CPW readout line. The resonator and the readout line are made of 300 nm Nb film with T_c about 8.5 K.

The HEB represents a narrow bridge made of 20 nm Nb film with T_c about 5K due to proximity effect; its area is 1 by 0.5 μm.

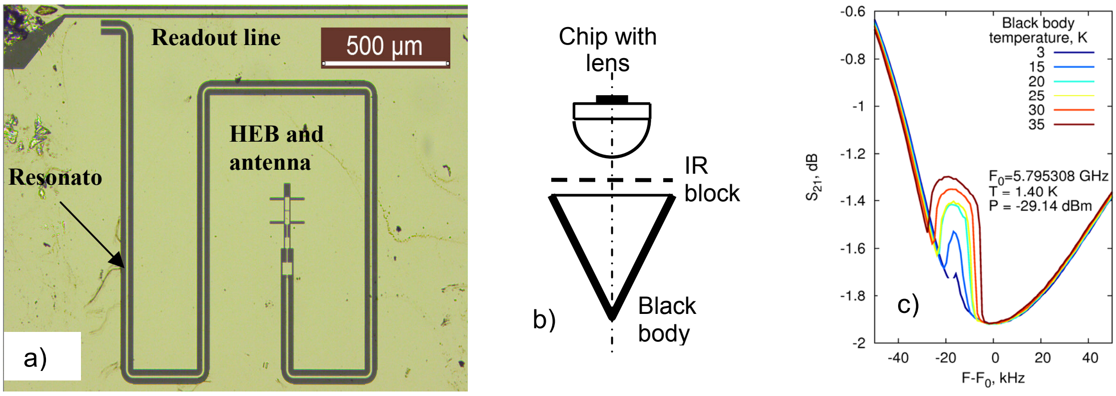

Fig. 1. Experimental details. a) A photograph of the chip containing HEB with a double slot antenna, embedded into a coplanar resonator. b) A sketch of the black body experiment for optical sensitivity. c) Optical response to a black body radiation near the resonant frequency F_0 at constant bias power feeding through readout line. Detector temperature is 1.4 K.

To perform optical measurements, the chip was glued directly on the flat back of the sapphire hemispherical lens mounted into a thermally controllable detector block. The scheme of an experimental setup installed inside a cryostat is shown in Fig. 1b. The black body was placed in front of the detector block to ensure that the main lobe of the antenna is completely covered by its aperture. The cryostat we used was equipped with a closed-cycle pulse tube precooled He^4 Joule-Thomson refrigerator, allowing temperatures down to 1.2 K.

The graph in Fig. 1c demonstrates an optical response of the experimental detector. The readout line transmission S_{21} is found being changed near the resonant frequency if we vary the black-body temperature. The operating point near the transition temperature of the HEB was set via adjustment of the bias power. The S_{21} response versus black-body temperature, shown in Fig. 2a, has been measured at fixed frequency corresponding to the center of the optical response "crater" in Fig. 1c. The incident optical power is calculated using Plank's formula for diffraction limited antenna beam ($A\Omega=\lambda^2$) and for the antenna bandwidth ≈ 100 GHz centered at 645 GHz.

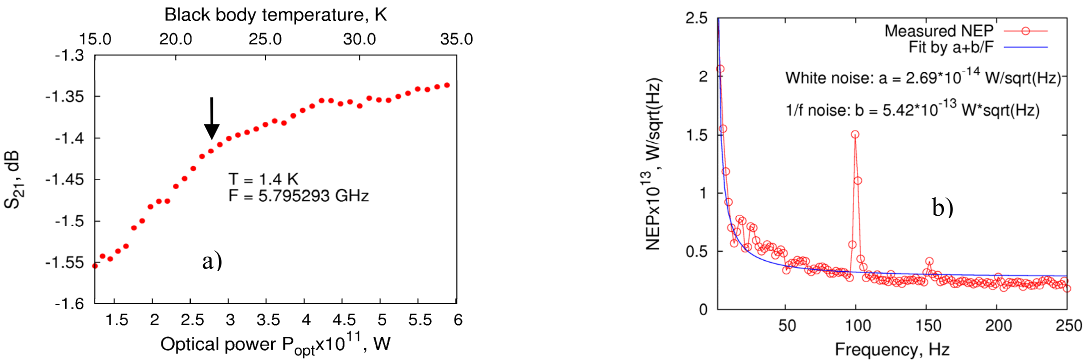

Fig. 2. a) Detector response versus optical power and black body temperature. Detector temperature is 1.4 K; b) NEP for the optimal operating point (market with the arrow in figure a))

These data allow us to calculate an optical responsivity and convert measured noise spectrum into the optical NEP, shown in Fig 2b. One can see that the particular noise spectrum contains 1/F component along with the white noise component accompanied with 100 Hz and 150 Hz mains interferences; calculated spectral density of the white noise component yields the optical NEP of $2.7\cdot10^{-14}$ W/√Hz.

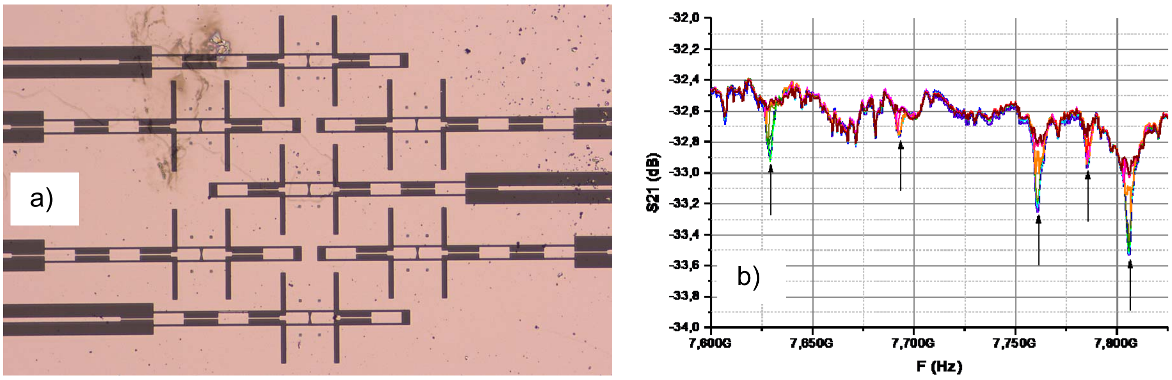

Fig. 3. Elementary hexagonal cluster: a) layout of an experimental chip containing 7 pixels (resonators and readout line not shown); b) resonant dips in readout line transmission S_{21} of the experimental chip measured at 4.2 K. The dips are tunable with variation of RF power (different colors correspond to different power levels).

The hexagonal cluster is designed on the base of an improved antenna-coupled HEB. The layout of the 7-pixel cluster is shown in Fig. 3a. The result of measurement at temperature of 4.5 K is shown in Fig. 3b. Unfortunately, only 5 resonant dips in the transmission $|S_{21}|$ appears within the frequency range 7.6-7.9 GHz. Most probably, there are two pixel defected at about 7.67 GHz and at 7.73 GHz. It is encouraging that all the working dips are tunable with microwave power. It is important to note that even the first chip performance is acceptable for further experiments on optical sensitivity.

III. Conclusion

The elementary cell of a sub-millimeter wave imaging metasurface exploiting microwave readout of HEB detector at 5.8 GHz is fabricated and tested successfully. The potential of the new readout principle is clearly demonstrated with measuring of optical sensitivity at NEP of about $3{\cdot}10^{-14}$ W/√Hz for a Nb superconducting HEB with T_c of 5 K.

The main building block of an imaging metasurface, the 7-pixel cluster, exploiting FDM readout of HEB detectors in frequency range 7.6-7.9 GHz, is fabricated and tested experimentally, demonstrating most of the pixels being sensitive for the readout power. Since even the first tested hexagonal cluster can be accepted for further optical measurements.

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