7^{th} International Congress on Advanced Electromagnetic Materials in Microwaves and Optics – Metamaterials 2013
Bordeaux, France, 16-21 September 2013

Superconducting metamaterial for electronic imaging: Conceptual development

E.V. Erhan [1], S. V. Shitov [1,3] and A.V. Ustinov [1,2]

[1] National University of Science and Technology (MISIS), Leninsky prosp. 4, Moscow 119049, Russia
[2] Physikalisches Institut, Karlsruhe Institute of Technology (KIT), 76131 Karlsruhe, Germany
[3] Kotel'nikov Institute of Radio Engineering and Electronics (IREE RAS), Moscow 125009, Russia
e-mail of the presenter: sergey3e@gmail.com

Abstract **– We present conceptual design of a superconducting 2-D metasurface suitable for sensitive detection and imaging of small signals in frequency range 600-700 GHz. This 2-D medium contains compact planar antennas densely distributed over hexagonal spot and coupled to individual resonators, providing a possibility for simultaneous readout of the pixel-antennas using FDM technique. The layout and EM-simulations are presented; the numerical results demonstrate the feasibility of such devices for application at THz-range frequencies.**

I. INTRODUCTION

The electronic imaging devices usually suffer from two problems: limited sensitivity and slow/complicated readout from multiple pixels. These problems are related in parts due to need of longer integration time and numerous channels to be read at the same time. There is a known solution for simultaneous readout - the frequency-division multiplexing (FDM) Ref. [1] which means listening to response of different pixels at their individual carrier frequencies via single transmission line. There are at least two superconducting detector techniques employing the FDM: transition edge sensors (TES) Ref. [2] and microwave kinetic inductance detectors (MKID) Ref. [3]. The TES are known as the most sensitive devices in a wider frequency range; they employ relatively low FDM frequency, since their signal is boosted usually by SQUID-amplifiers, which feedback electronics is working well below 1 MHz. The MKIDs are working at much higher FDM frequencies, up to 10 GHz, using compact integrated resonators: either quarter-wave CPW or lumped element resonators Ref. [4]. These bring ease of using rf 50-Ohm amplifiers - semiconductor coolable amplifier. We suggest using a fussy solution: TES embedded into an integrated rf resonator, and the resonator response has to be read by a cooled rf amplifier that is similar to MKID technique Ref. [5]. No wires are needed neither for biasing nor for reading out such imaging array of TES; entire analysis has to be done using rf data only. The resonance carrier frequencies can be designed as close as few MHz at about 10 GHz central frequency that leads to a possibility of construction kilo-pixel imaging arrays for submillimeter wavelengths.

II. LAYOUT CONCEPT AND ELECTROMAGNETIC SIMULATION

To cover an arbitrary surface of an image projection with elementary pads (pixels), a set of hexagons, or honey comb, is rather good choice. The particular advantage of a hexagon is in its center symmetry. This symmetry is used in photography for adjustable lens aperture; the minimal distortion of the image processing is provided up to the corners of the aperture. To form an electronic film, the light sensitive "grains" are usually equipped with immersion lenses Ref. [6]. Let us imagine that each lens serves a hexagonal-shaped cluster of sensors as shown in Fig. 1a, i. e. carrying a chip with 7 bolometric RTD devices (Fig. 1b). This “multi-grain device” chip from Fig. 1b can be a sensing part of the imaging receiver (Fig. 1c). Assembling the chip with a single immersion lens forms the combination known as the multi-beam integrated-lens antenna Ref. [7]. To comply with FDM technique, the resistive sensors are integrated into individually tuned resonators, driven by a comb generator at their resonant (carrier) frequencies as shown in Fig. 1c. Adding more neighboring lenses in the hexagonal order, one can expand the "film" infinitely (Fig. 1a); each neighboring lens is integrated with similar 7-pixel chips following the principle “unique-frequency-resonator-for-a-pixel”.

Presented here prototyping approach is using relatively bulky resonators tuned between 4.5 GHz and 6 GHz

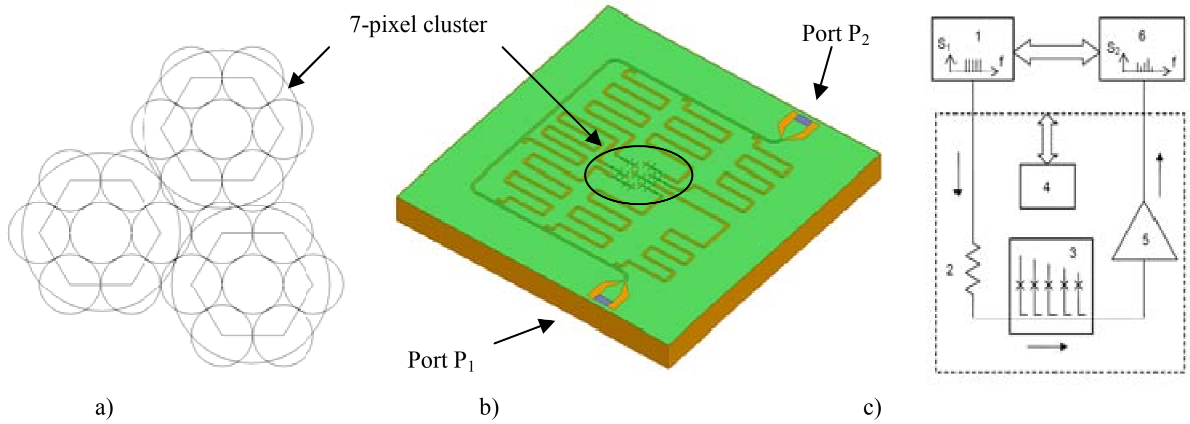


Fig. 1. Concept for electronic film cluster. a) Hexagon-shaped 7-pixel expandable arrangement. b) Layout of practicable 7-pixel sensor with folded quarter-wave resonators. c) Equivalent electrical scheme of the imaging receiver (concept). The master generator *1* of comb spectrum $S1(f)$ supplied pumping signal via attenuator *2* (40–50 dB) to array *3* of *n* resonators (here, n =5). Crosses indicate detectors that control the *Q* values of resonators. Dashed contour shows the volume cooled by refrigerator *4*. Post-amplifier *5*, registrator *6* compares the amplitude of signal $S2(f)$ at individual frequencies of each resonator to those in the initial signal $S1(f)$ and then calculates a thermal power of the incident signals. The system has no wire connectors except for two coaxial cables.

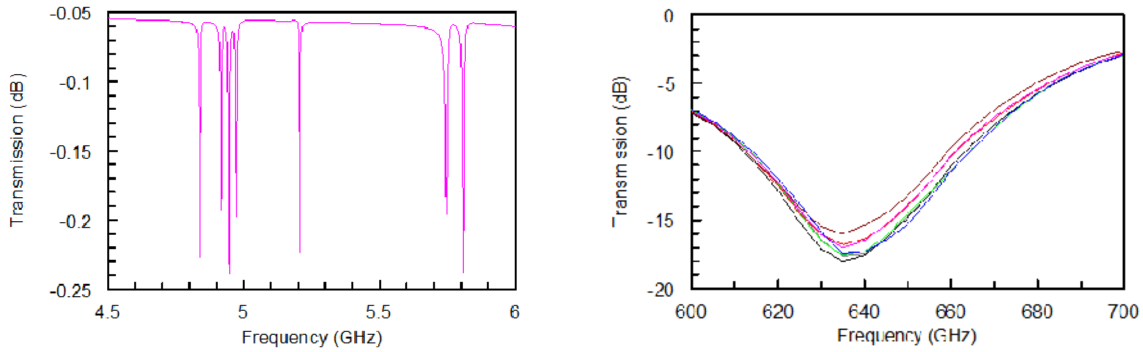
that left no possibility to concentrate more than one hexagonal cluster at the chip 4 mm by 4 mm

The particular design (EM-model) of the electronic film cluster (the chip) from Fig. 1b contains 3 electromagnetic ports: P_1 and P_2 for input and output the comb carrier. The port P_3 is located inside each of the 7 identical double-slot antennas. The antennas are designed for the frequency range 600-680 GHz as shown with scattering parameter S_{33} (Fig. 2b). Each antenna covers a pixel of the common image and provides interception of the signal energy from the object, converting the signal into THz current and directing the current to a tiny TES sensor located in the geometrical center of the antenna. The good match of the antenna and the sensor (low S_{33}) is achieved due to careful design of the impedance transformer placed inside the antenna. The TES sensor is pre-heated with carrier applied to the port P_1 so the sensor is relatively strong-coupled with the resonator at rf. To conserve the THz signal, the special filters prevent the escape of the THz current to the carrier path. Since the TES sensor is a kind of RTD with low heat capacity, Ref. [8], it assumed to be extra warmed by the THz current from the antenna. Finally, the growth of the resistance of TES will reduce Q-factor of its carrier resonator that will be registered via measuring S_{21} parameter of the chip.

The 7-pixel image can be recovered via continuous monitoring of amplitudes of the dips of the individual carriers (Fig. 2a). Since the dips from Fig. 2a are not equidistant in frequency scale, this particular layout (Fig. 1b) has to be improved. This discrepancy can be explained with influence of the exact position and shape of the right-angle turns of the folded resonators. The turns are made for compactness of the whole structure within the chip 4 mm by 4 mm. Any turn produces a small irregularity following by appearance of extra impedance that unavoidably influences the resonant frequency.

III. Conclusion

The electronic imaging metasurface exploiting RTD sensors is developed. The basic element is a chip sized 4 mm by 4 mm and containing 7 pixels. The pixels are compacted within the hexagonal area and illuminated with the immersion lens. The neighboring lenses are, in their turn, also arranged into a hexagonal structure. This combination is forming a metasurface suitable for infinite extension over an arbitrary image. The particular circuit does not contain details smaller than 2.5 µm that allow for fabrication process using optical lithography. We plan to implement micron-size TES sensors that should allow in the future achieving the low-noise operation at the NEP down to 10^{-17} W/Hz$^{1/2}$ at ambient temperatures about 250 mK.



a) b)

Fig. 2. Tuning parameters of the 7-pixel electronic "image". a) Dips in transmission (S_{21} parameters) mean reflections in the throughput (carrier) transmission line. The dips are varying with change of heat applied to the corresponding pixels due to change in Q-factor of their resonators. b). Dip in reflection (S_{33} parameter) means low reflection (good coupling) of THz-range antenna to its load (TES bolometer, R = 1 Ohm).

Acknowledgement

The authors acknowledge support from the Ministry of Education and Science of the Russian Federation via contract №11.G34.31.0062.

References

[1] T.M. Lantinga, Hsiao-Mei Choa, John Clarkea, Matt Dobbsc, Adrian T. Leea, M. Luekera, P.L. Richardsa, A.D. Smithe, H.G. Spielerc, "Frequency Domain Multiplexing for Large-Scale Bolometer Arrays", *Millimeter and Submillimeter Detectors for Astronomy*, vol. 4855, pp. 172-181, 2003.
[2] K. D. Irwin, G. C. Hilton, "Transition-Edge Sensors", *Topics Appl. Phys*. vol. 99, pp.63-149, 2005.
[3] B. A. Mazin, "Microwave Kinetic Inductance Detectors: The First Decade", *The Thirteenth International Workshop on Low Temperature Detectors - LTD 13 AIP Conference Proceedings,* vol. 1185, pp. 135-142 2009.
[4] J. P. Silver, "Oscillator Resonator Design", *GEO Quarterly No 17*, 2008.
[5] S.V.Shitov, "Bolometer with High-Frequency Readout for Array Applications", Technical Physics Letters, Vol. 37, No. 10, pp. 932–934, 2011.
[6] K. A. Serrels, E.P. Ramsay, P. A. Dalgarno, B. D. Gerardot, J. A. O'Connor, R.H. Hadfield, R. J. Warburtonc and D. T. Reid, "Solid immersion lens applications for nanophotonic devices", *Journal of Nanophotonics*, vol.2, issue 1, pp. 3, 2008.
[7] A.V. Uvarov, S.V.Shitov and A.N. Vystavkin, "Analysis of Multi-Beam Immersion Lens Antenna for High-Sensitive Submilimeter Wave Transition-Edge Sensor", *Uspehi sovremennoj radiojelektroniki,*vol.8, pp. 43-50, 2010.
[8] P. F. Dunn, *Fundamentals of Sensors for Engineering and Science*, CRC Press Taylor & Francis US, 2011.