Arrays of electrically small antennas with SINIS detectors for SubTHz astronomy and atmosphere propagation research

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Abstract. An overview of different arrays of electrically small annular antennas of 350 GHz band with integrated superconductor-insulator-normal metal-insulator-superconductor (SINIS) detectors is presented in this paper. Arrays developed for both astronomical observations on the BTA 6 m telescope and measurements there of test sources for investigation of atmospheric turbulence to estimate its influence on the data rate of subTHz telecommunication channels. It is shown both numerically and experimentally that to simulate the electrodynamics of such non-phased antenna arrays it is necessary to investigate the whole array, not a single cell with Floquet ports. The first results of studying of superconducting antennas are also presented in this paper.

INTRODUCTION

The main field of application of SINIS detector arrays in the subTHz frequency range is radio astronomy [1, 2]. However, the limitations by significant atmospheric absorption of subTHz waves hinder the development of terrestrial radio astronomy in this band, which is important for astrophysics, and restrict it by space [3, 4] and high-altitude [5, 6] observatories, which is not a mass consumer of receiver developments. At the same time, the development of space and ground 7G [7] communications is also actively moving into this frequency range [8, 9]. Therefore, the task of creating highly efficient receiving systems and studying the features of the propagation in atmosphere of subTHz waves in various conditions are becoming increasingly. There are lots of works [10, 11] devoted to propagation of sub THz waves in the atmosphere or the microwave astroclimate.
astroclimate is differ from the usual astroclimate in the optical range. There are not only the effect of water [11] but other atmospheric gases, oxygen first of all.

In optics, on the other hand, an essential effect on the astroclimate is not only absorption, but also scattering by turbulences of the atmosphere has. Atmospheric turbulence can dramatically spoil the image of objects in astronomy and radically increase communication errors. Study of atmospheric turbulence in optics is carried out on the basis of an assessment of the image quality of known astronomical sources (well-known objects on the sky like Venus, Orion, Crab nebula etc.). Taking into account the proximity of subTHz to optics, which actually represent the far-IR range, it can be assumed that turbulence in the atmosphere will also affect subTHz waves. The paper presents the results of the development of an array of antennas with SINIS detectors of subTHz waves, suitable for both astronomical observations and measurements of test sources to assess the effect of atmospheric turbulence on the data transmission rate of subTHz telecommunication channels.

MODELING

In this section we present the results of development of electrically small antenna array operating in 200-400 GHz frequency band. The first step in modeling of antennas array is choice of a unit element of the array. As it was show in our previous work [12] for arrays without polarization selectivity the best variant is to use ring antenna. The radiation pattern of such an antenna (see [12]) is pointed across the substrate and does not create substrate modes. The modeled radiation pattern of full array of 25 annular antennas on silicon lens is presented in Fig. 1. A typical metamaterial consists of a periodic array of subwavelength metallic resonators that are collectively coupled to the free-space excitation. With small antennas, the array can be designed to accommodate a wider bandwidth and occupy a much smaller physical space which allows it to be placed in the waist of a single-mode horn or in the focus of immersion lens. In the simplest case, an analytical model of lumped elements can be used to estimate parameters of such array [13-15]. Another way is to use modern software (for example, CST STUDIO SUITE or HFSS) for modeling to obtain more accurate results, an estimation of the spectral response and a radiation pattern. In our previous publications on arrays of electrically small antennas [13], [15], the calculation of a unit cell with Floquet ports that were placed at the boundaries corresponding to the minimum and the maximum of z-coordinate was used. This method allows you to quickly obtain the results, however this results are far from the real electrodynamics picture of such array (see results of modeling in ref. [13], [15]). This is due to the fact that this method can only be applied for phased antennas arrays. As an example, Fig. 2 shows the radiation patterns of non-phased array of weakly coupled to each other antennas located in different parts of the array. According this, the modeling was carried out for a full (9*9 elements) array with open boundaries and irradiation by a source from the far zone Fig. 3a, [14]. Typical dimensions of the modeled structure: diameter of antenna is 60 μm, a period is 70 μm, thickness of gold film is 200 nm, and thickness of substrate is 65 μm. Measured spectral response from [14] is presented in Fig. 3b. As a model of SINIS detector, a seriesl connection of a discrete port (50 Ω) and a lumped element (capacitance, 25 fF) was used.

SINIS detector at a glance: The sensitive element of such detector is the absorber made of normal metal. Two NIS (Normal metal – Insulator - Superconductor) junctions connected in series with an absorber serve as thermometers. Radiation absorption in the SINIS structure leads to heating of the absorber, which can be measured as the tunnel current increase in the NIS thermometers. The sensitivity of such detectors can be estimated using non-equilibrium distribution functions of electrons and phonons and the theory of quantum absorption of radiation [16]. A SINIS detector with a suspended absorber seems to be promising way for increasing of the sensitivity compared to conventional structure with absorber on the substrate [17].

Figure 1 - The modeled radiation pattern of array of 25 annular half-wave antennas on Si lens
Figure 2 - Radiation patterns of antennas located in different parts of the array.

Figure 3 – Electrically small antenna array: a) Modeling of 9*9 array of electrically small antennas: image of project (left) and modeled spectral response (right), mode 1 and 2 are two orthogonal polarizations of TE_{11} of circular waveguide, [14], b) results of measurements.

SUPERCONDUCTING ELECTRICALLY SMALL ANTENNAS

Besides normal-metal antennas we also study antenna arrays made of superconducting material. The use of a superconductor antenna as prolongation of superconducting electrodes of SINIS allows both to reduce losses in the antennas and avoid overheating of the superconducting electrode of the SINIS detector by hot quasiparticles. For the first tests, we repeated the design of the array of gold electrically small antennas, replacing gold by superconducting aluminum. The advantages are presented in the measurements of the current-voltage characteristics at 300 mK. Here, the criteria are the value of the energy gap and the ratio of the resistances at zero bias and far beyond the gap. At a temperature of 300 mK and a small area of superconducting electrodes, the ratio of the resistances of the detector array did not exceed 100, whereas for a similar array with superconducting antennas, the ratio was close to 1000. And at a temperature of 100 mK, the resistance ratio exceeded of 10000 Fig. 4.

Figure 4 – Superconducting antenna array with SINIS detector: a) SEM image of a part of single antenna with detector; b) – Measured dynamic resistance at bath temperature of 100 and 300 mK.
CONCLUSION

Different arrays (made from gold and superconducting aluminum) of electrically small annular antennas of 350 GHz band with integrated SINIS detectors are presented in this paper. It is shown that for modeling of such arrays it is necessary to simulate the whole array with open boundaries. Such arrays are matched to incoming radiation in a wide frequency range and can work in conditions of high background power (tens of pw). The spectral response was measured in frequency band from 200 to 400 GHz and we obtained relatively uniform spectral characteristic (see Fig. 3b). The first tests of superconducting aluminum electrically small antennas showed their efficiency - the measured resistance ratio exceeded 10000 at bath temperature of 100 mK. Further development of large superconducting arrays of electrically small antennas that is intended for approaching a distributed absorber model. The proposed technology of magnetron sputtering with separate lithography allows one to create tunnel structures of any shape and size and can be used in industrial production with conventional technological equipment.

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