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Meta-bolometer based on toroidal response

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In this letter, we propose a meta-bolometer based on high Q-factor microwave toroidal metamaterial with integrated absorbing superconducting pad. The resistance of superconducting elements can be varied by absorption of terahertz (THz) radiation (heating), which drastically changes the metamaterial microwave response. We study numerically the dependence of metamaterial resonance characteristics over the resistance (R) of the absorber pad. To explain the nonlinear spectral feature, we perform multipole expansion of the response at the resonance frequency for different values of R. We also estimate theoretically how characteristics of the resonance change over the pad temperature in the case of the square-shaped absorber made from a superconducting hafnium film.

Metamaterials are artificial periodic structures with exceptional properties, unachievable in conventional electronic materials. Metamaterials with easy-to-engineer properties have been of significant use in the development of bolometers. Metamaterials are usually integrated into bolometers as absorbers [1, 2]. As a result, one can broaden [3], narrow [4] or move the bandwidth, increase sensitivity, and control the speed of operation [5]. Toroidal metamaterials stand out by extremely high-Q resonances. Their radiation losses are suppressed, and fields in the metamolecules origin are extremely high and sensitive to the additional losses. In this letter, we introduce a novel concept of meta-bolometer. It is based on the combination of a microwave high-Q factor toroidal metamaterial as readout device with embedded micro-pad superconductor as an absorber of THz radiation. We establish that a pad with 20 kOhm/sq sheet resistance reduces metamaterial Q-factor and changes the stop-band level by as much as −50 dB at 1.5 GHz. Importantly, this sensitivity to the additional losses requires no galvanic connection to the absorber. This allows one to detect THz heating of superconducting pad via the change in metamaterial transmission spectrum.

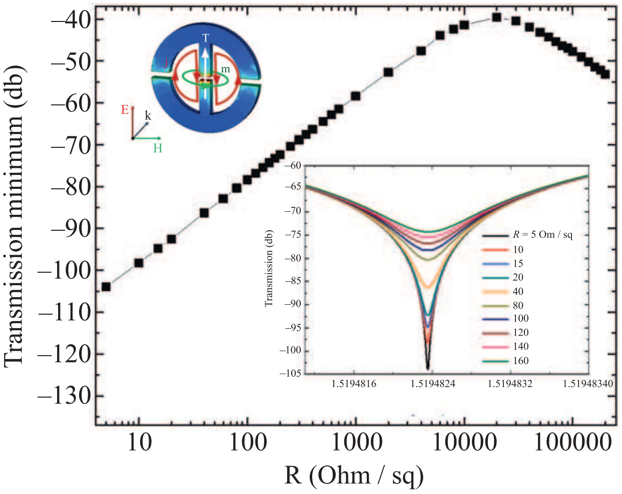

Fig. 1. (Color online) Dependence of the transmission minimum over resistance of the inserted absorber. In the insets – metamaterial model and simulated transmission spectra for different resistance of the insertion

The metamaterial we choose to play the role of the high Q-factor resonator is anapole metamaterial proposed by Basharin et al. [6]. Among the properties of chosen metamaterial, we highlight the negligible impact of the losses in real conductors on the metamaterial Q-factor: just two orders of magnitude less [6]. The array of metamolecules was simulated with periodic boundary conditions. Each of the periodically arranged metamolecules consists of two mirrored epsilon letters as shown in the inset in Fig. 1. In the simulation, an incident microwave radiation, polarized along the central wires, penetrates the single PEC metamolecule accounting for the periodic boundary conditions of their array. It excites two counter-directed currents in the metamolecule voids, which results in magnetic fields vectors being rotated around the central strips. Such field con-

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figuration resembles a torus cross-section, which enables excitation of the toroidal dipole moment along with the electric dipole moment.

We consider the absorber as a superconducting hafnium film because of its nonlinear response at 1.5 GHz below $T_c = 400\,\mathrm{mK}$. Respectively, we estimate the losses in hafnium over temperature at the metamaterial resonant frequency using Mattis–Bardeen theory. This approach can significantly improve the future design of the terahertz/millimeter-wave detectors. We incorporate an absorbing (Hf) pad between the central strips, 1.85 mm away from each. We study, then, how the metamaterial resonance changes with the increasing resistance of the pad.

The role of the absorber plays a $0.5 \times 0.5\,\mathrm{mm}$ pad with variable surface resistance. Physically, this means that bolometer based on our metamaterial is illuminated with two electromagnetic waves at the same time. The wide microwave beam is the plane wave at the resonance frequency of the metamaterial. The second beam is THz radiation which is absorbed by a lossy element (Hf pad) in the center of each metamolecule.

While simulating nonlinear Hf absorber, we consider the model of its high-frequency-induced transition from superconducting to the normal state. We plot its resonance minimum over the surface resistance of the pad in Fig. 1. The actual transmission spectra for small resistance varying from $R = 5\,\mathrm{Ohm/sq}$ to $R = 160\,\mathrm{Ohm/sq}$ are presented in the inset in Fig. 1.

In conclusion, we proposed a model of a superconducting meta-bolometer. We demonstrated that toroidal metamaterials are very promising candidates for bolometers applications due to strongly localized electric fields and extremely high Q-factor transmission spectra. This allows toroidal metamaterials to detect the slightest change of incorporated absorbers resistance. The proposed bolometer is based on the superconducting transition. To show this, we used Mattis–Bardeen theory to evaluate the dependence of the metamaterial resonance characteristics over the temperature of Hf pad. In the practical implementation, a focused THz beam would heat the absorber, while a plane GHz wave would be used for reading the absorber's temperature at the resonant frequency of the toroidal metamaterial. The depth of the resonance on the transmission spectrum of the GHz wave would reveal the temperature of the pad, and, correspondingly, the frequency of the detected THz radiation. Practical realization of the proposed bolometer has potential applications in astronomy as detectors of extremely low THz signal levels available from the Cosmic Microwave Background Radiation [7, 8] and other objects of the Deep Space [9].

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