Modulating Sub-THz Radiation with Current in Superconducting Metamaterial

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We show that subterahertz transmission of the superconducting metamaterial, an interlinked two-dimensional network of subwavelength resonators connected by a continuous superconducting wire loop, can be dynamically modulated by passing electrical current through it. We have identified the main mechanisms of modulation that correspond to the suppression of the superconductivity in the network by magnetic field and heat dissipation. Using the metamaterial fabricated from thin niobium film, we were able to demonstrate a transmission modulation depth of up to 45% and a bandwidth of at least 100 kHz. The demonstrated approach may be implemented with other superconducting materials at frequencies below the superconducting gap in the THz and subterahertz bands.

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Terahertz technology could have applications in security, biomedical imaging, atmospheric sensing, astrophysics, analytical chemistry, and communications, but its proliferation is hampered by a lack of switching and modulation solutions. In this Letter, we show how superconducting metamaterials can be used to create agile radiation modulators in the THz or sub-THz range, helping to close the so-called "terahertz gap."

Metamaterials are man-made arrays of subwavelength electromagnetic resonators designed to achieve new and improved electromagnetic functionalities. The main focus of metamaterial research today is in developing new switchable and active media, predominantly through hybridizing metamaterial arrays with other functional materials [1]. Compared to the conventional metamaterials made using metallic resonators [2], the metamaterials fabricated from superconductors possess unique advantages that are linked to low Joule losses in the microwave and terahertz spectral ranges [3–5]. However, the most important advantages of the superconducting metamaterials are related to the nature of superconductivity. For instance, the macroscopic quantum state of the superconducting charge carriers makes superconducting metamaterials extremely sensitive to many external stimuli allowing quantum level nonlinearities with arrays containing Josephson junctions [6–12] and with metamaterials exploiting the recently introduced quantum flux exclusion mechanism of nonlinearity [13]. Over the last decade, researchers have demonstrated that light [14], magnetic field [15–17], and temperature [5,16,18–26] can control the electromagnetic properties of the superconducting metamaterials. Here, we demonstrate the control of electromagnetic properties of the metamaterial by running current through its metallic framework.

Our metamaterial electro-optical modulator is an array of asymmetrically split rings exhibiting a high-Q Fano resonance that is highly sensitive to Joule losses [27,28]. The metamaterial has been fabricated by optical lithographic patterning of a 280 nm thick niobium film (critical transition temperature $\theta_c \approx 9$ K) deposited onto a sapphire substrate in the shape of a thin disk of thickness 0.5 mm and radius 15 mm [see Figs. 1(a) and 1(b); the metamaterial occupies an area of radius 11 mm].

The resonant electromagnetic response of the metamaterial is shown in Fig. 2(a) for a range of substrate temperatures. At temperature $\theta = 4$ K, the metamaterial displays a narrow asymmetrically shaped 50% transmission peak ($Q \sim 130$) that is centered at $\nu = 99.5$ GHz. The roll-off at the sharp edge of the Fano resonance is only 0.32 GHz. When the temperature is increased towards the superconductor-to-metal phase transition point ($\theta_c \approx 9$ K), the transmission peak broadens and its magnitude drops rapidly. In the normal state, where Joule losses in niobium are high [29,30], the resonance is completely suppressed and the transmission level of the array does not exceed 10%.

All the (asymmetric) split rings of our metamaterial network are sequentially connected by a wire, as illustrated in Fig. 1(a). This allows running the control current simultaneously through the entire metamaterial array. The control wire is perpendicular to the polarization state of the incident electromagnetic wave and does not affect the Fano resonance. The crossing point of the control wire with the split rings is deliberately chosen to be at the antinode of

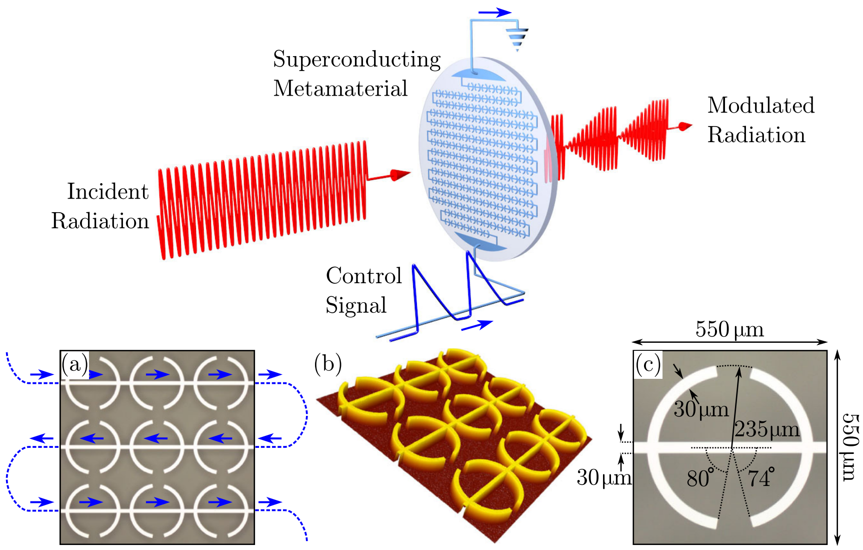

FIG. 1 (color online). Electro-optical modulator based on superconducting metamaterial. Main diagram: Sub-THz radiation is modulated by passing current through a planar metamaterial array, fabricated lithographically from superconducting niobium. (a) Optical microscope and (b) interference microscope profile images of the metamaterial's unit cells. Bright parts on the optical image and profile show a patterned niobium film on the sapphire substrate. The horizontal (blue) arrows in (a) indicate the path of the electric current through the network of metamolecules. (c) Details of the metamolecule are annotated on the microscope image.

the oscillating currents driven by the sub-THz radiation. This maximizes the influence of the control current on the transmission of the metamaterial by changing the conductivity inside the metamolecules where it matters most.

The metamaterial has been housed in the optical helium-cooled cryostat for wide temperature control. The transmission and the transient dynamic response have been measured in a free-space setup in the range of 75–110 GHz using a microwave network analyzer (Agilent N5242A, Agilent, USA), mm-wave adaptors (OML V10VNA2, OML Inc., USA) and horn antennas equipped with lenses (Flann Microwave Ltd.) that focused radiation into the cryostat.

Figure 2(b) shows the electrical current established in the metamaterial at substrate temperature $\theta = 4$ K, in response to a 50 μs long ramped control voltage pulse [see the inset of Fig. 2(b)]. Depending on the magnitude of the current driven through the metamaterial, two distinct regimes of operation can be identified. In what we will call the subcritical, low excitation regime, the current grows linearly with voltage. This regime is observed for currents up to the critical value of $\sim$500 mA. Exceeding the critical current leads to the increase of metamaterial resistance, resulting in a sharp drop in current, despite the rising voltage. We term this second regime as supercritical. We studied the modulation of metamaterial transmission in both regimes while keeping the metamaterial temperature at $\theta = 4$ K.

In the subcritical regime of operation, the transmission modulation of the metamaterial was measured at the Fano resonance ($\nu_0 = 99.5$ GHz). Applied control currents were sinusoidal with amplitudes of up to 250 mA and frequencies ranging between 0.5 and 100 kHz. The electrical response of the metamaterial was linear and equivalent to the resistor $R = 3.1\ \Omega$ connected in series with the inductor $L = 3.2\ \mu$H. Figure 3 shows the amplitude of the metamaterial's transmission change at the peak of the Fano resonance. The plot reveals two mechanisms of transmission modulation in the subcritical regime: the slow mechanism with the roll-off at $\sim$4 kHz and a fast, frequency-independent mechanism.

The supercritical regime of modulation has also been characterized at the peak of the Fano resonance ($\nu_0 =$ 99.5 GHz). The applied control signal was in the form of voltage ramps of duration from 10 to 1000 μs and peak voltage of up to 40 V. The ramp repetition rate was kept low ($\sim$ 25 Hz) to prevent the metamaterial from overheating. Figure 4(a) illustrates the dynamics of the transmission change for the case of a 200 μs long ramp pulse: the transmission decreases progressively with the applied voltage dropping by 45% towards the end of the ramp. The kinks in the transmission and voltage curves mark the transition from the subcritical regime to the supercritical regime. Voltage ramps of the same magnitude but different pulse durations produce peak transmission changes, growing from -10% for a 10 μs ramp duration to almost -50% for millisecond-long ramp pulses [see Fig. 4(b)]. The transmission suppression could also be controlled with the amplitude of the ramp pulse, as illustrated in the inset to Fig. 4(b). The dependence of the maximum transmission change on the voltage ramp amplitude was fairly linear, revealing the onset of saturation at about 30 V. In all cases, the relaxation of the ramp-induced transmission change had an exponential-like (thermal) dynamics with decay time shorter than 25 μs.

We argue that the supercritical regime of modulation involves a superconducting-to-normal phase transition triggered in the metamaterial by ramping up the current. Indeed, switching from the subcritical to the supercritical

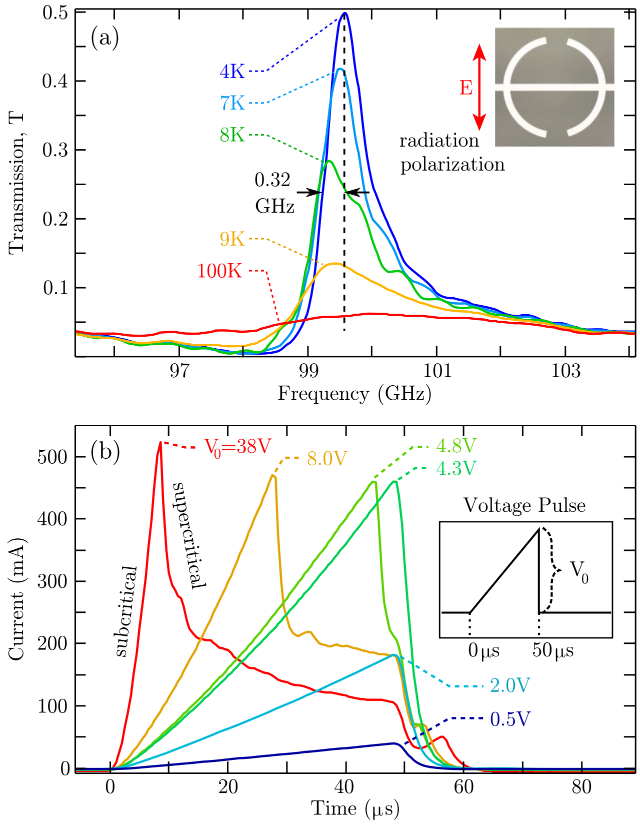

FIG. 2 (color online). Properties of the superconducting metamaterial. (a) The transmission spectra below and above the critical temperature of the phase transition in niobium, $\theta_c \approx 9$ K. (b) Transient electrical current through the metamaterial (at temperature $\theta = 4$ K) when the control loop is driven by ramped voltage pulses (as shown on the schematic in the inset).

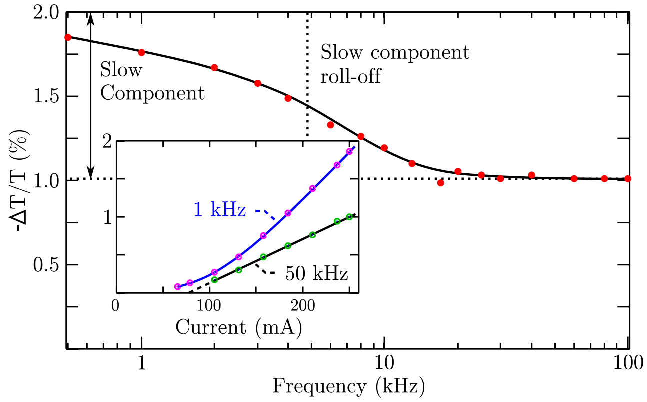

FIG. 3 (color online). Subcritical regime of electro-optical control. Main graph: Amplitude of the transmission change as a function of frequency of the sinusoidal control signal. The horizontal dashed line separates the contributions from the fast and slow mechanisms of response. The vertical dashed line marks the roll-off of the slow modulation component at ~4 kHz. Inset: Amplitude of the transmission change as a function of the peak modulation current for sinusoidal modulation with frequencies of 1 and 50 kHz.

regime takes place at about 500 mA, corresponding to a critical current density of 6×10^6 A/cm^2 for a wire cross section of 280 nm $\times$ 30 μm. This agrees with the directly measured critical current density of 3×10^6 A/cm^2 reported by Zhuravel *et al.* for niobium metamaterials [31]. The transition to the normal state typically starts at a small defect in the wire and rapidly spreads until it reaches the final size, which is a function of the applied bias voltage [32,33]. The dc resistance of niobium in the normal state changes very little with temperature below 20 K. Since the dc resistance of the superconducting niobium is zero, we can estimate the proportion of the metamaterial in the normal state at any time by comparing its resistance with the normal-state value measured at temperature 10 K. Even for the longest ramp pulses (with peak amplitude of 38 V), no more than 20% of metamaterial went into a normal state. Based on numerical modeling of the metamaterial's transient thermal response (see the Supplemental Material [34]), we conclude that, during a supercritical ramp pulse, the mean temperature of the sapphire substrate increased by less than 1 K. Such a change can account for no more than a 5% change in metamaterial transmission [see Fig. 2(a)].

The transmission modulation in the supercritical regime can be explained as follows. The experimentally observed transmission modulation is a result of the collective response of the entire metamaterial array. Its high-Q resonance corresponds to the excitation of antisymmetric current modes in all the split-ring metamolecules [27], which trap the radiation in the plane of the metamaterial array in the form of magnetoinductive surface waves (trapped mode). Such waves were shown to mediate interactions between the metamolecules, making the metamaterial response very sensitive to any changes in the array [35,36]. Consequently, when only a few metamolecules undergo the transition to the normal state, the locally increased Joule losses draw energy from the entire metamaterial array and therefore affect its transmission by a far greater proportion than one would expect from purely geometrical considerations. After the control pulse ends, the heat from the niobium escapes into the sapphire substrate through the contact thermal resistance (R_b) formed between the two materials. As a result, the transmission of the metamaterial is restored to the original value. The observed transmission relaxation time of 25 μs [see Fig. 4(a)] allows us to estimate $R_b = 2 \times 10^{-3}$ K $\cdot$ m^2/W (see the Supplemental Material [34]). It is significantly larger than some of the values reported for other low-T_c superconductors on sapphire substrates [37], indicating possible improvements for the future implementations. Assuming that heat can be withdrawn sufficiently fast from the sapphire substrate and ignoring the time it takes to induce a superconducting-to-normal phase change (this process can occur at subnanosecond rates [38–40]), the 25 μs cooling time sets the maximum possible modulation bandwidth in the supercritical regime at 40 kHz.

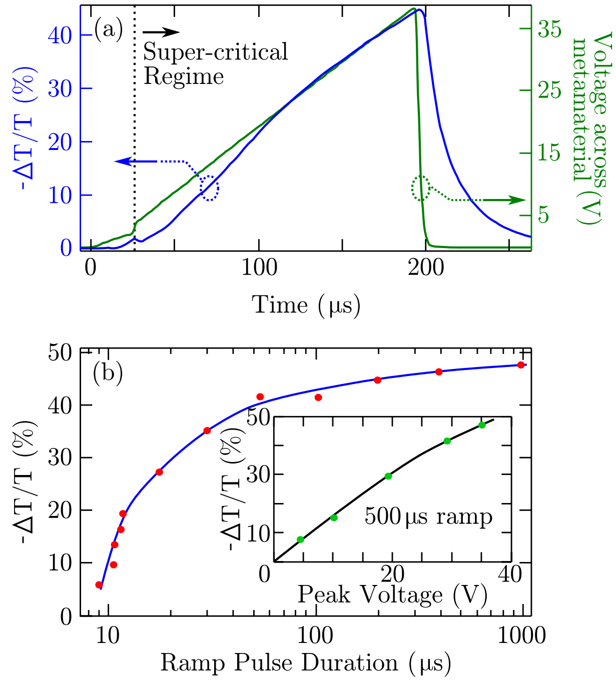

FIG. 4 (color online). Supercritical regime of electro-optical control: high currents. (a) Dynamics of the metamaterial transmission change (left hand side axis; blue) corresponding to a 200 μs long control voltage ramp applied across the metamaterial (right hand side axis; green). The kinks in both curves at 26 μs signify the onset of the supercritical regime. (b) Amplitude of the transmission change as a function of the voltage ramp duration at a 38 V peak value. The inset shows the change of the transmission achieved with a 500 μs long control voltage ramp for different peak voltages.

Next, we consider the transmission modulation in the subcritical regime. Here, the whole of the metamaterial is in the superconducting state and therefore exhibits no Ohmic losses. However, the external wires feeding the control signal into the metamaterial have nonzero resistance and therefore heat up when current flows through them. We can estimate the time it takes for the heat generated in the contact pads to diffuse from the edge of the metamaterial to its center. Given the distance from the contact pads to the metamaterial center $r = 11$ mm and assuming the thermal diffusivity of sapphire $\kappa = 0.12\ \mathrm{m^2/s}$ [41], the diffusion time is $\tau_d = r^2/4\kappa = 250\ \mu$s. In the case of a continuously oscillating control signal, τ_d corresponds to 4 kHz, which agrees well with the roll-off of the slow subcritical modulation mechanism (see Fig. 3). We therefore conclude that the slow component of the transmission modulation in the subcritical regime is due to heating of the metamaterial by the power dissipated in the contact pads.

We argue that the fast subcritical transmission modulation mechanism (see Fig. 3) is due to the suppression of superconductivity by the magnetic field generated in the niobium by the control current. In the case of weak magnetic field, the change in niobium sub-THz conductivity will be proportional to the magnitude of the applied field and therefore to the amplitude of the control current. We can assume that the metamaterial transmission modulation will be proportional to small changes in niobium conductivity. Consequently, in the absence of heating (i.e., at modulation frequencies above 10 kHz), the transmission modulation of metamaterial will be proportional to the amplitude of the control current. By contrast, at low modulation frequencies where the heating mechanism prevails, the relation between transmission modulation and control current amplitude should become at least quadratic, as dictated by Joule's law. This is exactly what we observed in the experiments (see the inset of Fig. 3). Using the literature data for high-frequency conductivity of niobium [30] and its response to applied magnetic field [42], we estimate (see the Supplemental Material [34]) the subcritical transmission modulation, due to fast modulation mechanism, to be 3%, which compares well to the experimentally observed 1% (see Fig. 3).

The transmission change of the metamaterial in response to the control current at 50 kHz reveals a nonzero threshold of about $I_{\mathrm{th}} = 80$ mA (see the inset of Fig. 3). We attribute this to the appearance of the Abrikosov vortices (small domains of niobium in the normal state), which enter the path of the resonantly induced sub-THz currents at the junctions between the control wire and the arcs of the split-ring metamolecules. Given the dimensions of the control wire and using the published data for niobium [43,44], we arrived at the threshold value of $I_w = 17$ mA (see the Supplemental Material [34]). Since the width of the wire effectively increases at the junctions, this value (I_w) serves as the lower limit estimate of the observed threshold current (I_{th}).

In conclusion, we showed that, by running current though a network of metamolecules in a superconducting metamaterial, one could achieve a strong and fast modulation of sub-THz radiation. We provided an experimental proof-of-principle demonstration of such a modulation and identified the underlying physical mechanisms of the effect. Our approach can also be used for modulating THz radiation in high-T_c superconducting metamaterials [19,20]. Compared to recently demonstrated semiconductor-based metamaterial modulators [45–48], our system achieved a similar rate and depth of modulation with a much larger active area (and therefore much lower control power per active metamaterial area) due to the virtual absence of a capacitive response. The same property makes our approach uniquely suited in the situation where spatial resolution is required (such as imaging and spatially multiplexed communications) and offers an advantage over the existing schemes of THz-range electro-optical modulation based on optical and microwave mixing [49]. We were unable to demonstrate modulation rates beyond 100 kHz due to the limited bandwidth of our equipment, but we argue that the mechanism of conductivity modulation exploiting the self-induced magnetic field is extremely fast. Indeed, the Abrikosov vortices in niobium have been reported to propagate as fast as 2000 m/s [50], which brings the rate of the transmission modulation in the superconducting metamaterial into the VHF frequency band.

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