Flux Exclusion Superconducting Quantum Metamaterial: Towards Quantum-level Switching

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Nonlinear and switchable metamaterials achieved by artificial structuring on the subwavelength scale have become a central topic in photonics research. Switching with only a few quanta of excitation per metamolecule, metamaterial’s elementary building block, is the ultimate goal, achieving which will open new opportunities for energy efficient signal handling and quantum information processing. Recently, arrays of Josephson junction devices have been proposed as a possible solution. However, they require extremely high levels of nanofabrication. Here we introduce a new quantum superconducting metamaterial which exploits the magnetic flux quantization for switching. It does not contain Josephson junctions, making it simple to fabricate and scale into large arrays. The metamaterial was manufactured from a high-temperature superconductor and characterized in the low intensity regime, providing the first observation of the quantum phenomenon of flux exclusion affecting the far-field electromagnetic properties of the metamaterial.

Superconducting electromagnetic metamaterials are attracting increasing attention due to low ohmic losses, high sensitivity to temperature and magnetic fields, as well as due to the exotic properties of the macroscopic quantum state of superconducting carriers¹, and essentially plasmonic nature of the electromagnetic response of superconductors²–⁴. Extraordinary transmission of superconducting hole arrays⁵–⁶ and EIT-like behavior of a superconducting meta-molecule⁷ have been observed. Moreover, temperature⁸–¹², magnetic field¹³ and current control¹⁴ of electromagnetic response of superconducting metamaterials have been demonstrated recently. Several groups have analyzed superconducting metamaterials with meta-atoms containing Josephson junctions¹⁵–¹⁹, experiments have been conducted on single superconducting qubit meta-atoms²⁰–²¹ and one-dimensional Josephson junction metamaterials²². The recently discovered class of iron-based superconductors²³ promises to extend the superconductivity range even further into the terahertz spectrum. The combination of low losses and strong non-linearities over the broad spectral range thus makes the superconducting metamaterials a central topic in the sub-optical metamaterial research.

Here we introduce a new type of superconducting metamaterial that we brand as the flux exclusion quantum metamaterial. It exploits magnetic flux quantization as a source of its switching functionality but does not require Josephson junctions in its construction, making it much simpler to fabricate and scale into large arrays. The metamaterial was manufactured from a high-Tc superconductor film and its electromagnetic properties were characterized in the low intensity regime at cryogenic temperatures. In this metamaterial we observed large changes in the electromagnetic response due to the quantum phenomenon of flux exclusion. We also manufactured and characterized two other types of metamaterial arrays, the electromagnetic properties of which model the low and high magnetic flux states of the new quantum metamaterial, thus illustrating its potential for switching performance.

Results

Basic design and modeling. The coherent nature of the macroscopic quantum state of carriers in a superconductor dictates that the magnetic flux through a closed superconducting loop will be an integer multiple of the flux quantum \( \Phi_0 = \hbar / 2e \approx 2.1 \times 10^{-15} \) Wb, where \( \hbar \) is the Plank’s constant and \( e \) is the charge of the electron²⁴. One may therefore deduce that in a much simplified picture, when resistive losses and kinetic inductance of the Cooper pairs are neglected, the response of the closed superconducting loop to ramped magnetic field \( (B_m) \) will be similar to that sketched in Fig. 1. At low magnitudes of the applied field the amplitude of the total magnetic flux...
of the incident wave does not penetrate the array and therefore is not directly engaged in the flux quantization. However, an incident electromagnetic wave polarized along the split-ring resonator gap will drive an oscillating current in the resonator that will produce oscillating magnetic field embraced by the split ring. The superconducting wire loop inside the split-ring will respond depending on the amplitude of the generated magnetic field and therefore depending on the incident wave intensity: or it will block the field penetration at low levels of magnetic flux, or it will allow penetration at high levels, thus ensuring the nonlinear nature of the response. As a result, in the flux penetration regime, the closed loop will be continuously driven by the oscillating magnetic field from one flux state to the next one, up and down the ladder (Fig. 1), in much the same way as superconducting loops driven by the slowly varying external magnetic field previously shown by Silver & Zimmermann.20

We shall note that electromagnetic functionality of the flux exclusion quantum metamaterial described here is distinctively different from the artificial atoms based on Josephson junctions, where the transition between the quantum energy levels of the meta-atom is achieved by absorption of single energy quanta of the incident wave21. In our case the resonant properties of the metamaterial are derived from the outer split-ring resonator of the meta-molecule which, at high frequency, acts as an LC circuit. Nonlinearity here is a result of inductance being a function of intensity: higher intensity levels of incident waves creates a larger magnetic flux through the ring. At a certain level of excitation the applied flux can drive transitions between the different quantum flux states of the inner ring, thus dynamically modifying the inductance and the resonant properties of the LC circuit (meta-molecule).

We illustrated the switching in the flux quantization metamaterial by modeling its response using two different metamaterial structures. One of them modelled the flux penetration regime. It was an array of split ring resonators without the superconducting wire loop inside. Another metamaterial modelled the flux exclusion regime. It was also an array of split ring resonators, but in addition, each resonator embraced a superconducting disk blocking the flux penetration through its center. We assumed in our modeling that the metamaterial structures were manufactured from thin films of high-temperature superconductor yttrium-barium-copper-oxide (YBCO). The full 3-dimensional Maxwell calculation of metamaterial transmission, using the two-fluid model of superconductivity of YBCO,21 illustrates the switching (see Fig. 2). Blocking the flux penetration through the array embraced by the split ring results in a 2.7 GHz shift of the transmission resonance. Such a shift would correspond to switching from the flux penetration state to the flux exclusion state in the flux quantization metamaterial with meta-molecules consisting of a superconducting rings embraced by split rings. Figure 2 also shows the redistribution of the magnetic field in the meta-molecule that arises due to switching.

To observe the switching, the incident field shall drive the flux quantization metamaterial to such a level that applied flux through the disk exceeds $\Phi_0$. Simultaneously, the electrical current density in the outer perimeter of the disk shall reach the critical value that destroys superconductivity thus allowing the magnetic field to penetrate inside. From the models in Fig. 2 we estimated that, at resonance, the amplitude of the flux applied to the nested disks in the metamaterial (at temperature $T = 77 K$) would reach a few $\Phi_0$ for the incident radiation intensity levels below ~ 50 $\mu W/cm^2$. At such intensity the current density in the outer perimeter of the disk will be of the order of $10^5$ A/cm$^2$. This is much smaller than the critical current density of the wire, which is approximately $10^6$ A/cm$^2$ at $T = 77 K$.

Woodcut metamaterial design. To approach the regime where flux quantization will be observable ($LI \approx \Phi_0$) one could operate the metamaterial very close to superconductor’s critical temperature,
A profound effect on the resonant response of metamaterials. To understand this, we consider the high-frequency conductivity of high-Tc superconductors, which leads to suppressed switching as Joule losses dampen the current. Thus, increasing the temperature leads to an up-shift in the resonance frequency of the metamaterial. This shift is well replicated by the free-space electromagnetic response of the metamaterial.

Electromagnetic characterization. The level of intensity of ~1 W/cm² required to demonstrate switching was not achievable in our experimental setup and we characterized electromagnetic properties of the woodcut metamaterial in the flux exclusion regime only. To evaluate the potential switching of electromagnetic properties from the flux exclusion to the flux penetration regimes, we experimentally modeled the two regimes by comparing the measured transmission of the split-ring metamaterial and the metamaterial with split-ring resonators containing the field-blocking nested disks (inside the split rings). These two reference metamaterials represent the two extreme modes of the woodcut metamaterial operation: the flux exclusion and the flux penetration mode.

All three metamaterials shared the same unit cell and split-ring dimensions and were manufactured by the same technological process (see Methods). The free-space electromagnetic response of the three metamaterials in the 75 GHz-110 GHz frequency range was characterized using a network analyzer and focusing horn antennas. The metamaterial samples were placed in a closed-cycle cryostat with transparent windows. The interference microscope picture of a fragment of the woodcut metamaterial (colour expresses height). The metamaterial is created by patterning 300 nm thick YBCO film deposited onto a 1 mm thick sapphire substrate and covers an area of 30 mm in diameter.

Discussion
Expected change in the woodcut metamaterial’s transmission upon flux switching is illustrated in Fig. 4a. The Maxwell calculations (Fig. 4a) and the experiment (Fig. 4b) show that flux penetration leads to an up-shift in the resonance frequency of the metamaterial array. The experimentally observed value of the shift is about 7 GHz for temperatures below 60 K, decreasing towards critical temperature of superconductivity. This shift is well replicated by calculations (Fig. 4a,b). Some minor discrepancies between experimen...
mentally measured and calculated characteristics of the metamaterial response are explainable by tolerance of the fabrication process (widths of lines and gaps in the designs) and simplifications of the two-fluid model of superconductivity that does not account for any anisotropy of the material’s response.

We expect that upon reaching the excitation level of $\sim 1$ W/cm$^2$ the woodcut metamaterial will exhibit a similar $\sim 7$ GHz shift in transmission resulting in $\sim 20$ dB of transmission change. However, the exact dynamics of this shift which is likely to take the form of a hysteretic nonlinear response, is difficult to predict and it has to be investigated both theoretically and experimentally in the future.

At this stage we should note, that experimentally observed transmission spectra for the woodcut metamaterial (Fig. 4d) are closely matched by the transmission spectrum of the empty split ring metamaterial with field-blocking disk, as would be expected for the flux exclusion regime. We therefore conclude that at intensity level of 50 $\mu$W/cm$^2$ the woodcut metamaterial remains in the flux exclusion state. As far as we are aware this is the first observation of the quantum phenomenon of flux exclusion affecting the macroscopic properties of a metamaterial. Here one can see a nearly perfect corroboration between the computed (Fig. 4c) and experimentally measured values (Fig. 4d) of woodcut metamaterial transmission. The good agreement between the full 3-dimensional Maxwell calculations and experimental spectra indicates a high quality of the samples and thus a non-destructive nature of the fabrication process (superconducting properties of remaining YBCO are not diminished). This gives us confidence that a quantum-level flux penetration switching will be observable in these structures at the higher intensity levels.

In conclusion, a new type of superconducting metamaterial capable of quantum level nonlinear response underpinned by flux quantization has been designed, modeled, manufactured from a high-temperature superconductor and characterized in low-intensity, flux exclusion regime. Measurements on model metamaterial samples have demonstrated the extent of the expected change in the metamaterial’s transmission upon switching. Quantum metamaterials based on the proposed principle could find applications in active devices for controlling THz and sub-THz radiation.

Methods
Metamaterial fabrication. The metamaterials have been created by patterning the 300 nm-thick YBCO film (critical temperature 83 K, critical current density $10^6$ A/cm$^2$ at temperature 77 K) on 1 mm-thick sapphire substrate which was deposited by commercial supplier (Theva, Germany). Substrate was a disk of diameter 30 mm. The patterning was carried out using UV-photolithography followed by ion beam milling (dry etching).

Housing of metamaterial. The metamaterials have been placed inside an closed-cycle helium-cooled optical cryostat. The cryostat was equipped with a temperature sensor and an electric resistance heater. This allowed to control the metamaterial temperature within the range $T = 5 \ldots 300$ K.

Transmission data acquisition. The transmission of sub-terahertz radiation has been measured in range 75 – 110 GHz using microwave vector network analyzer (Agilent) with sub-terahertz adapter antennas. The output power of the adapter antennas has been measured with a commercially supplied power meter. The frequency-dependent attenuation of the cryostat has been measured (typically 50% of radiation intensity was lost on the way from antenna to metamaterial) in a separate experiment and used to calculate the exact radiation intensity incident on the metamaterial.

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**Author contributions**
The principle of flux exclusion metamaterial was proposed by NIZ, VAF, AT and VS. VS supervised the project. VS, NIZ, ARB, AT and VAF have designed the metamaterial structures. VS performed numerical analysis and manufactured samples jointly with ARB. Characterization experiments were performed by VS with assistance from ARB, AT and VAF. All co-authors contributed to the analysis and interpretation of results. The manuscript was written by VS and NIZ in consultation with all other co-authors. NIZ supervised the project.

**Additional information**

**Competing financial interests:** The authors declare no competing financial interests.

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