Wireless Josephson Junction Arrays as Tunable Metamaterials: Inducing Discrete Frequency Steps with Microwave Radiation

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Abstract

We report low temperature, microwave transmission measurements on a new switchable and tunable class of nonlinear metamaterials. A wireless two dimensional array of Josephson junctions (JJ) is probed as a metamaterial where each plaquette in the array is considered as a meta-atom. In the presence of microwaves, this compact metamaterial of 30,000 connected meta-atoms synchronizes the flow of Cooper pairs to yield a single robust resonant signal with a quality factor of 2800 at the lowest temperature for our measurements. The transmission signal is switched on and off and its amplitude and frequency are tuned with either temperature, incident rf power or dc magnetic field. Surprisingly, increasing the incident rf power above a threshold causes the resonance to split into multiple discrete resonances that extend over a range of 240 MHz for a wide temperature window. We posit that this effect is a new incarnation of the inverse ac Josephson effect where the Josephson plasma frequency locks to the rf drive frequency generating quantized frequency steps, instead of voltage steps, in the absence of a dc bias.

Prompted by theory [1],[2], extensive studies of carefully designed artificial materials, known as metamaterials, are underway to find new electromagnetic phenomena such as amplification of evanescent waves [3]-[9], extraordinary transmission [10], [11], negative index of refraction [12], [13], and classical analogues of electromagnetically-induced transparency [14]-[18]. However, in spite of recent advances using metallic metamaterials, requisites for practical applications such as switching on and off a signal and modulating a signal’s frequency and amplitude using external control parameters still need to be addressed. Since fulfilling these conditions with existing metallic structures is challenging, because of absorption losses, developing a new class of tunable metamaterials, such as superconducting metamaterials, is arguably warranted. [19]-[26]

In this Letter, we show that tunable metamaterials already exist in the form of superconducting Josephson junction, JJ, arrays. Most remarkable, however, isn’t their tunability per se, but discovering an unanticipated rf power and temperature dependent manifestation of discrete frequency steps that, to our knowledge, has not been previously reported. This physical phenomenon opens up new possibilities for signal processing if scaled to THz frequencies [27], new opportunities for high frequency detectors for radio telescopes [28], and raises new theoretical questions about the relevance of the inverse ac Josephson effect to microwave transmission experiments. The inverse ac Josephson effect is the reverse of the ac Josephson effect. In the ac Josephson effect, an applied dc voltage across a JJ generates a periodically oscillating supercurrent, pairs of electrons, that emits electromagnetic radiation whereas in the inverse ac Josephson effect, shining electromagnetic radiation onto an unbiased JJ induces a dc voltage difference across the tunneling barrier. Here we show that shining microwaves on a wireless Josephson junction array induces seven discrete frequency steps instead of voltage steps, and in between these resonances, there are narrow opaque windows in the transmission line. The inverse ac Josephson effect only applies for underdamped JJs [29] which also describes the JJs studied here.

Two dimensional Josephson junction arrays are macroscopic quantum materials with a highly tunable superconducting current. We consider a wireless two dimensional network of 30,000 connected Josephson junction
(JJ) plaquettes with each plaquette having a square loop geometry containing 4 equally spaced JJs; we consider these plaquettes as meta-atoms which form, in aggregate, a switchable and tunable metamaterial. In contrast to recent microwave transmission reports on discrete split ring JJ meta-atoms [30], [31], we find a sharp, robust resonance. As with our previous measurements on this sample, abet at evanescent frequencies [9], the resonance is clearly distinct from noise without processing the data or using any additional microwave components, such as amplifiers, attenuators, directional couplers or filters, which also differentiates our work from others.

The experimental apparatus, described in detail elsewhere [9], consists of a vector network analyzer connected to a X-band waveguide via phase-maintaining co-axial cables as seen in the schematic of Figure 1 a. The waveguide, enclosed in a vacuum can, is cooled to cryogenic temperatures; it is magnetically shielded by $\mu-$ metal to reduce the ambient field. The JJ metamaterial is positioned in the center of the waveguide and oriented such that the rf B-field is normal to the plane of the array as seen in the schematic in Figure 1 b.

The sample is a portion of a much larger array [32], [33]; its transport properties, before removing electrical contact pads and reducing its size, have been extensively studied elsewhere. [34] Scanning electron microscope, SEM, images of a single tunneling junction, Nb-amorphous silicon-Nb, and of a single meta-atom are seen in the upper and lower left images, respectively, of Fig. 1 c. The 500 nm niobium thick square loop is $29 \mu m \times 29 \mu m$ with a linewidth of $5 \mu m$. Each of the 4 JJs in the loop has an area of $2.5 \mu m^2$ with an insulating barrier of 10 nm. A colored optical microscope image of a single meta-atom showing niobium coverage is seen in the lower right image of Fig. 1 c; the non-continuous coverage of niobium indicates that resonance occurs because charged particles must tunnel across capacitive tunneling barriers to circulate throughout the network. A portion of the JJ metamaterial is seen in the SEM image of Fig. 1 d. The individual JJ meta-atoms are about 1500 times smaller than the microwave wavelength, which is approximately 40 mm, placing them in the deep sub-wavelength limit.[35] The superconducting transition temperature, $T_c$, of the individual niobium islands is 9.2 K. [36]

If we consider that each JJ contributes a capacitance, C, estimated to be 0.9 pF, a normal state resistance, R, estimated to be 510 $\Omega$, and a critical current, $I_c$, which is estimated to be 0.165 $\mu A$, [37], we can estimate the degree of damping in a junction, using the dimensionless McCumber parameter, $\beta_c$, which is $\beta_c = \frac{2eI_c}{\hbar C}$ $\sim$ 118, where $e$ is the electron charge and $\hbar$ is Planck's constant divided by $2\pi$. Since $\beta_c > 1$, the junction is said to be underdamped meaning that there are inertial effects of the "phase" particle [38] which satisfy one of the conditions required for the inverse ac Josephson effect [29]. A second condition that needs to be met is that the driving rf frequency should be significantly larger than the natural Josephson plasma frequency, $f = \frac{1}{2\pi} \sqrt{\frac{2eI_c}{\hbar C}} \sim 15$ GHz. [39] The resonant frequency, which is the plasma frequency [9], also depends, in part, on the sample’s location in the waveguide indicating the need for additional capacitive terms [40], which would lower the resonant frequency but not by enough to satisfy this second condition. Nevertheless, we will show that the mechanism responsible for the transmission features seen here are due to the inverse ac Josephson effect.

Cooling the sample to temperatures below the su-
perconducting transition temperature and applying low power microwaves to the JJ array results in a sharp resonance at \( f = 8.08 \text{ GHz} \) appearing in transmission as seen in the plots of Fig. 2. Extinguishing the resonance is achieved by either increasing the temperature above the superconducting transition temperature as seen in Fig. 2 a, or by increasing input power as seen in Fig. 2 b.

Increasing temperature, at fixed rf power, shifts the resonance to lower frequencies and broadens the resonance. This is seen in the transmission vs frequency plots for different temperatures in Fig 3 a-d. As temperature increases, Cooper pairs break lowering the critical current, \( I_c \), and thus shifting the resonance to lower frequencies. While the density of Cooper pairs decreases, the density of normal conduction electrons increases, leading to more dissipation and insertion loss; for instance, a jump of \(-5 \text{ dB} \) in insertion loss is measured when the temperature reaches \( 7 \text{ K} \) as seen at 7.2 GHz in Fig. 3a and 3b. While these behaviors are reminiscent of those seen with superconducting metamaterials \cite{22, 42}, they are not identical. Here, the resonances are more sensitive to temperature increases due to Cooper pairs tunneling across barriers as described by the Ambegaokar-Baratoff current-temperature relation. \cite{43}

Similar temperature dependent resonant responses persist when comparing responses at two different rf powers, \(-55 \text{ dBm} \) as seen in Fig. 3 a, and \(-49 \text{ dBm} \), as seen in Fig. 3b. At \(-49 \text{ dBm} \), the higher rf power, the resonance also shifts to lower frequencies while broadening with increasing temperature; however, the overall amplitude decreases and the resonance dip splits into two for \( T < 6 \text{ K} \).

To elucidate the effect of the resonances splitting at \(-49 \text{ dBm} \), we compare two large sets of temperature data, one at \(-55 \text{ dBm} \) and the other at \(-49 \text{ dBm} \) as seen in Fig. 3 c and 3 d. The aggregate temperature data at \(-49 \text{ dBm} \) and for \( T < 5.2 \text{ K} \) clearly show a simple "egg crate" pattern in transmission that is not present at \(-55 \text{ dBm} \). With increasing rf power, screening currents begin to slosh back and forth generating an ac magnetic field which cancels the applied RF field. Furthermore, when these induced ac supercurrents, driven by external microwave radiation, lock to the natural oscillations of the array there is a range of DC currents for which there are constant frequency steps. This current range is depicted in the number of resonances, with different amplitudes, appearing at the same frequency.

Frequency locking is also manifested when increasing the RF power at fixed temperature, \( T= 1.1 \text{ K} \), as seen in the transmission vs frequency plot in Fig. 4. As the RF power increases, the number of dips also increase. While an increase in the current decreases the depth of the dip, it does not explain multiple dips. We surmise that the increase in the number of dips is analogous to Shapiro steps observed in dc current-biased experiments.
FIG. 5: (Color online) a.) Resonant frequency versus temperature at -49 dBm. Seven steps are clearly visible for \( T < 5 \text{ K} \). Each of the different colors correspond to separate dips containing multiple resonances. A line is drawn to show the linear dependence at temperatures close to the transition temperature of the array. Inset: Comparison between -49 dBm (red) and -55 dBm (blue). b.) Transmission Amplitude, \( S_{21} \), versus temperature at -49 dBm (red and green) and -55 dBm (blue).

We also analyze these results by studying how the resonant frequency and transmission amplitude change with temperature and rf power. These results are shown in the plots of Fig. 5. There are seven steps in resonant frequency below 5 K that are clearly observed, with each step represented by a different color, in Fig. 5 a. Considering the temperature to be proportional to the dc current and the frequency proportional to dc voltage, by the Josephson relation, \( V_{DC} = n(\hbar \omega_{RF})/2e \), then these steps look similar to those found in I(V) curves for spontaneous emission in biased, underdamped JJ arrays. The range of phase locking and DC currents in our experiments is indicated by the plateaus for each frequency; the width of the plateau becomes smaller with higher order steps because the current is expressed in terms of a Bessel function. Between resonant frequencies, the phase is unlocked leaving narrow electromagnetically opaque regions. A diagonal line is drawn in the plot to show the linear behavior between frequency and temperature at temperatures close to \( T_{co} \), the transition temperature of the array, \( \sim 6.5 \text{ K} \). Comparing resonant frequencies for -55 dBm and -49 dBm reveals two main differences: first is the appearance of steps at -49 dBm and second, is the systematic higher shift in the frequency vs temperature at -55 dBm below the transition temperature as shown in the lower inset of Fig. 5 a. This shift is due to the induced rf currents being lower.

The strength of the resonance, transmission amplitude of \( S_{21} \), is dependent on rf power as seen in Fig. 5 b. However, we find that it also varies with temperature, in contrast to split ring resonators with JJs, except at temperatures between \( \sim 5 \text{ K} \) and 6 K which coincides to temperatures where frequency steps no longer prevail. Since the resonance splits at -49 dBm, we label the two resonances either left as seen in green in Fig. 5 b or right as seen in red in Fig. 5 b. The -55 dBm and -49 dBm curves crossover at \( \sim 6.5 \text{ K} \) which is the same temperature that the resonant frequency flattens out as seen in Fig. 5 a. This is indicated by a vertical dash line in Fig. 5. There is still a resonance beyond 6.5 K that doesn’t change in frequency suggesting superconducting quasiparticles tunneling until \( T \sim 8.5 \text{ K} \).

In conclusion, our results demonstrate that a wireless JJ array in a waveguide can controllably switch on and off a microwave signal with temperature and input power. The array can also modulate the signal over a range of frequencies and amplitudes by varying either input power, temperature, or dc magnetic field (not shown here). Modulating signals with temperature is traditionally considered to be quite slow; however, for JJ arrays, the response occurs rapidly and without noticeable delay. The signal is sharp and robust without processing the data and does not require the aid of amplifiers and filters in the experimental configuration. Moreover, our results reveal qualitatively new phenomena for tunable metamaterials that occur as the input power increases, breaking the central resonance down to discrete frequencies. Finally, this alternative perspective on metamaterials may provide new strategies for future metamaterial design and tunability.

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