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Effects of Strong Capacitive and Inductive Coupling on Hysteretic rf SQUID Metamaterials

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Abstract–Radio frequency Superconducting Quantum Interference Devices (rf SQUIDs) have been designed as self-resonant objects that interact strongly with electromagnetic fields. As such, one can utilize an array of such self-resonant rf SQUIDs as a metamaterial, both in the quantum and classical limits [1-3]. The original concept was to cover a plane with rf SQUIDs to act as a nonlinear [4] and highly tunable metasurface, and this is how the metamaterials were initially realized. In early theoretical and experimental work, the rf SQUIDS were packed together side-by-side in a single plane to enjoy substantial long-range (dipole-dipole) mutual inductance of the SQUID loops due to their close lateral proximity in the plane. This coupling gives rise to remarkable collective behaviors of the metasurface, such as Chimera states [5], disorder dominated states [6], and coherent modes of oscillation [7]. Such states have been directly imaged by laser scanning microscopy in the superconducting state under microwave magnetic flux driving illumination [8].

We consider the effect of strong *capacitive* and inductive coupling between radio frequency rf SQUIDs in a metamaterial geometry when driven by rf flux at and near their self-resonant frequencies [9]. Capacitive coupling between rf SQUIDs, in any context, is considered for the first time, to our knowledge. We set up and solve the equations of motion for the gauge-invariant phase on the Josephson junctions in each SQUID, and include the ability of SQUID loops to share currents through capacitive overlap of their loop wiring. The capacitive coupling gives rise to qualitatively new self-resonant response of rf SQUID metamaterials, and is demonstrated through theory, numerical modeling and experiment on strongly coupled rf SQUID metamaterials [9].

Keywords (Index Terms)–Superconducting metamaterials, rf SQUIDs, laser scanning microscopy, capacitive coupling, SQUID self-resonance.

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