Superconducting artificial atoms as building blocks for quantum metamaterials

A. V. Ustinov

Physikalisches Institut, Karlsruhe Institute of Technology
Wolfgang-Gaede-Str. 1, D-76131 Karlsruhe, Germany
Fax +49-721-608-46103; e-mail: ustinov@kit.edu

Abstract

This presentation will review ideas and first experiments to develop quantum metamaterials comprised of networks of superconducting elements. The design flexibility of superconducting meta-atoms with Josephson junctions allows for utilizing small sizes down to the nanoscale while maintaining very low losses and frequency tunability. Superconductors offer an intriguing and unique possibility of exploring the quantum effects in metamaterials. Superconducting quantum bits (qubits) based on Josephson junctions have all characteristic properties of macroscopic artificial ‘atoms’ that behave as quantum two-level systems and evolve quantum-coherently with the external field. Quantum metamaterials can be designed using arrays of Josephson qubits embedded into superconducting waveguides.

Using superconductors as replacement for normal metals in metamaterials allows reducing losses by several orders of magnitude, shrinking the size of artificial meta-atoms, and achieving tunable frequency of operation. The losses in superconductors remain extremely small at photon energies below the superconducting energy gap, which corresponds to frequencies ranging from several 100 GHz to several THz, depending on the choice of the superconducting material. Superconducting metamaterials can be composed of superconducting thin films, transmission lines and resonators. Embedding Josephson junctions in superconducting thin-film structures make it extremely easy to tune the resonance frequency in a broad range by applying an external magnetic field. Josephson junction acts as a parametric inductor that is tunable by superconducting screening current flowing through it. Thus, arrays of Josephson junctions enclosed in superconducting loops are very attractive candidates for frequency-tunable low-loss metamaterials.

Atoms of materials found in nature interact with electromagnetic field as two-level quantum systems. Recently, artificially made quantum system have been reported in many experiments with superconducting nonlinear resonators cooled down to their ground state. At ultra-low temperatures, superconducting loops containing Josephson junctions behave as macroscopic two-level quantum systems (qubits). The energy level separation of these quantum meta-atoms can be easily tuned and designed at wish in a frequency range between of few GHz and several 100 GHz, which translates into electromagnetic field wavelengths ranging between centimetres and millimetres. In contrast to the case of natural atoms or molecules, superconducting qubits allow for a very strong effective dipole coupling to the external electromagnetic field. This opens unique opportunities of designing periodic structures made of meta-atoms that are ultra-strongly and coherently coupled to the electromagnetic fields in a transmission line or a cavity. The major technical challenge for artificially made quantum superconducting metamaterials will be in matching as close as possible the energy level separation of many physically different and, therefore, not exactly identical meta-atoms. This problem can, nevertheless, be circumvented by utilizing very strong coupling of the meta-atoms to the electromagnetic field, similar to the way of overcoming the effects of inhomogeneous broadening in lasers made of natural atoms. This should allow for novel ways of generating and controlling non-classical electromagnetic waves (light squeezing, coherent down- and up-conversion, etc.). I believe that this emerging field will get driven by very interesting experiments in the near future.