Metamaterials and Transformation Optics for Single-photon Emitters

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Abstract— We have experimentally demonstrated the broadband enhancement of single-photon emission from nanodiamond NV centers coupled to planar multilayer metamaterial with hyperbolic dispersion. A tapered metamaterial waveguide for efficient outcoupling of high-k metamaterial modes has been numerically studied and fabricated.

Introduction: The major thrust of research in quantum photonics is to build quantum computing and networking technologies [1]. The simplest and most fundamental quantum photonic states to be employed are single photons. Many techniques based on nonlinear phenomena and atom-like systems have been demonstrated to generate single photons. Nitrogen vacancy (NV) color centers in diamond have attracted widespread attention due to their stable, broadband, and anti-bunched emission at room temperature [2], however, the efficiency of such emission is naturally low. Massive research efforts to solve this problem have utilized resonant based structures, which are typically narrowband and have a relatively slow response.

Enhancement of Single-photon Emission by Hyperbolic Metamaterials: An unorthodox approach is to use metamaterials with hyperbolic dispersion (HMM) [3], which enables one to implement highly efficient, broadband, and fast single-photon sources. In our recent work, we have experimentally studied the broadband enhancement of single-photon emission from nanodiamond NV centers coupled to a planar multilayer metamaterials with hyperbolic dispersion [4]. The metamaterial is fabricated as an epitaxial metal/dielectric superlattice consisting of CMOS-compatible ceramics: titanium nitride (TiN) and aluminum scandium nitride ($Al_xSc_{1-x}N$). It has been demonstrated that employing the metamaterial results in significant enhancement of collected single-photon emission and reduction of the excited-state lifetime.

Tapered HMM as an Efficient Method for Outcoupling High-k Modes: The emission enhancement mechanism is based on the HMM ability to support extra radiative channels. These channels are surface and bulk high-k metamaterials modes. Hence, the emission rate of NV center coupled to HMM can be further increased by proper outcoupling of these high-k HMM modes into free-space modes. As a next step, we suggest a modification of both the HMM structure and the detection scheme to enable more efficient photon collection. In this new approach, adiabatically tapered HMM waveguides which transition from high filling fraction for maximal emitter enhancement to a lower filling fraction for optimal outcoupling were designed and fabricated using shadowed angle deposition technique. The total outcoupling efficiency of the high-k modes in the in-plane direction is expected to be two to three orders of magnitude better than standard out-of-plane outcoupling methods.

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