Effect of a hyperbolic metamaterial on radiation patterns of a single-photon source

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Abstract: We explore the effect of a planar hyperbolic metamaterial (a superlattice of TiN and $Al_{0.7}Sc_{0.3}N$ on MgO substrate) on the far-field radiation patterns of a single-photon source (a nitrogen-vacancy center in a nanodiamond).

OCIS codes: (270.0270) Quantum optics; (270.5565) Quantum communications; (160.3918) Metamaterials

1. Introduction

The problem of dipole radiation near planar interfaces has a long history of intensive studies since the beginning of the 20th century. We have performed investigations aimed at constructing an efficient on-chip, single-photon source, which would pave the way towards the development of quantum photonic technologies. The core element of the light source is a nitrogen-vacancy (NV) center, due to its stability, broadband, and anti-bunched emission at room temperature [1], [2]. Coupling NV centers to hyperbolic metamaterials (HMM) [3] enables non-resonant broadband enhancement due to high local photonic density of states within an HMM [4], [5]. Previously, HMMs were studied as a medium stimulating the radiative decay rate. Here, we investigate the influence of a planar multilayer metamaterial on far-field radiation pattern of a single-dipole emitter as the emitter approaches the surface of the metamaterial.

2. Methods and results

In this work, calculations were performed for the experimental setup shown in Fig. 1(a), which consisted of a 532-nm laser excitation source, oil immersion objective lens with NA 1.3 for focusing the excitation beam and collecting fluorescence signal, and detection system for measuring emission count rate, lifetime and photon statistics. NV centers are hosted in diamond nanocrystals with a median size of approximately 50 nm, i.e., the separation distance between the emitter and HMM surface h was assumed to be 25 nm. The NV center was modeled as an oscillating point dipole. The HMM was simulated as a multilayer stack consisting of 21 alternating layers of TiN and $Al_{0.7}Sc_{0.3}N$ grown on a MgO substrate [6] where each layer is 10-nm-thick. The top and bottom layers are made of TiN. Dielectric functions of the constituent materials were retrieved from spectroscopic ellipsometry measurements. The half-spaces above (superstrate) and below (substrate) the HMM were filled with immersion oil (ε_{sup} = 2.3) and MgO (ε_{sup} = 3), respectively. The radiation patterns of the dipole source near the HMM were calculated by utilizing dyadic Green's function formalism, angular spectrum representation, and far-field asymptotics. The influence of the metamaterial on the radiation pattern was exerted through the generalized Fresnel reflection coefficients, which were evaluated through the Thomas algorithm [7]. Figure 1(b) demonstrates the radiation patterns in the case of the NV center on top of the glass coverslip (upper row) and the HMM (lower row) for in-plane, perpendicular, and 45^0 dipole orientations (red arrows). Solid blue and dashed black lines correspond to the cross sections in xz and yz planes, respectively. In the case of the HMM, the radiation patterns become more directed and almost all of the radiation power is collected by the objective lens with the collection half-angle $\theta_c = 59.1^0$ (gray area). The spectrum of the normalized collected radiation power is shown in Fig. 1(c). The normalization factor is the collected radiation power emitted by the emitter on top of the glass coverslip. The spectral range of interest, 600-800 nm, is highlighted in red. Each line color corresponds to different dipole orientations: in-plane (‖, blue), perpendicular (⊥, red), and averaged (ave, black). The solid and dashed lines stand for the dipole on TiN/(Al,Sc)N HMM and 10-nm-thick TiN film. The thin metal film was added as another reference sample. The collected emission power of the emitter on top of HMM is increased about 2 times for in-plane orientation and decreased about 2 times for perpendicular dipole orientation in comparison to the reference sample with a bare coverslip substrate. In this work, we have also studied the dependence of the collected radiation power on the emitter-HMM separation distance h. The maximum and minimum of the collected power for in-plane and perpendicular dipole orientations, respectively, occurs at h about 70 nm.

3. Conclusions

A single quantum emitter coupled to a metamaterial is an important quantum system, which could potentially pave the way towards efficient on-chip integrated quantum devices. We theoretically studied the influence of a planar multilayer metamaterial on far-field radiation pattern of a single-dipole emitter as the emitter approaches the surface of the metamaterial. Specifically, a NV center in a nanodiamond was chosen as a quantum emitter and the metamaterial was implemented as a multilayer stack of TiN and (Al,Sc)N, which are both CMOS-compatible materials. We have demonstrated that the radiation patterns for both perpendicular and in-plane dipole orientations become more narrowly directed and the collected emission power is increased about 2 times and decreased about 2 times for in-plane and perpendicular dipole orientations, respectively, compared to the reference sample with a bare coverslip substrate. In the future, we plan to study the cases of HMM coated with pre-fabricated deterministic or randomly distributed nanostructures.

The authors acknowledge support by the AFOSR-MURI grant (FA9550-10-1-0264).

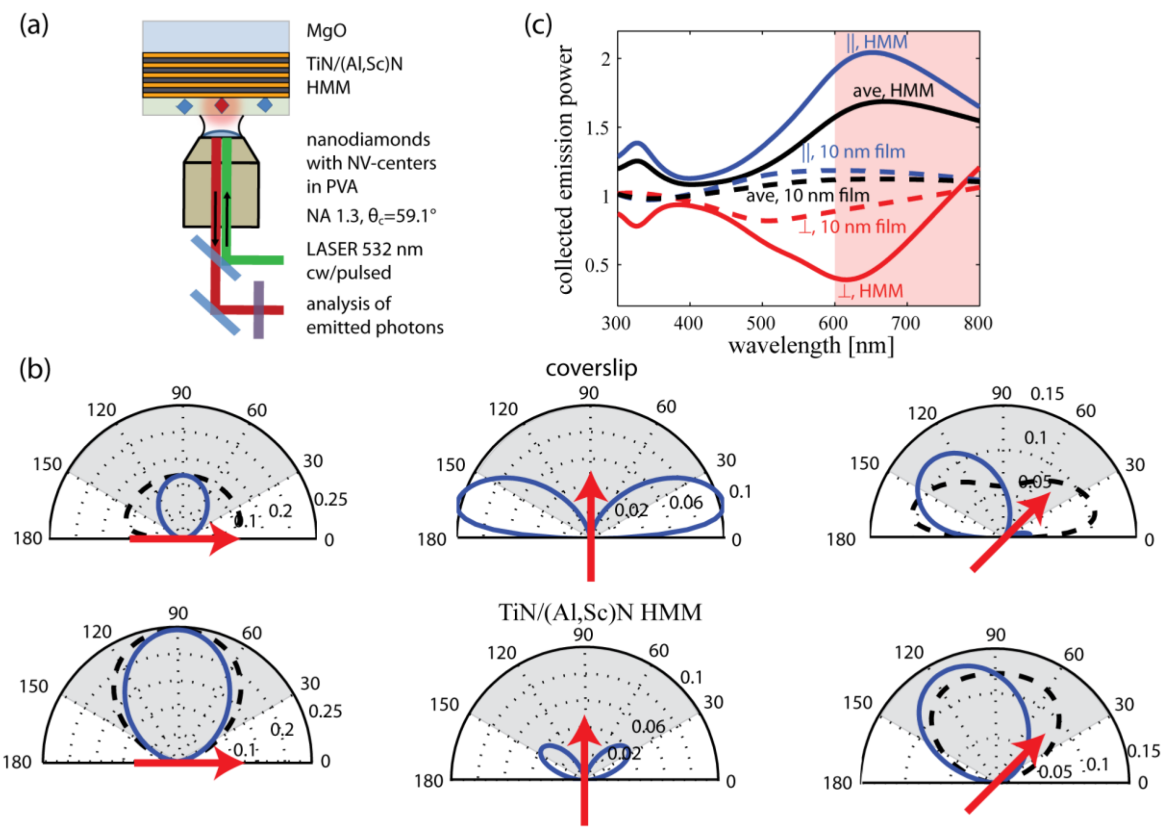

Fig. 1. (a) Schematic of the experimental setup. (b) Far-field radiation patterns of a single linearly polarized dipole on top of glass coverslip (upper row) and TiN/(Al,Sc)N HMM (lower row). The red arrows represent the dipole polarizations: in plane (||), perpendicular (⊥), and 45^0. The gray area indicates the collection angle of the objective lens with NA 1.3 (inclination angle of 59.1^0). (c) Spectral distribution of the collected emission power normalized to the power emitted by the dipole located on a coverslip. The spectral range of interest, 600-800 nm, is highlighted in red. Each line color corresponds to different dipole orientation: in plane (||, blue), perpendicular (⊥, red) and averaged (ave, black). The solid and dashed lines stand for the dipole on TiN/(Al,Sc)N HMM and 10-nm-thick TiN film.

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