Metalloelectric optical antennas for ultrabright single-photon sources

Xue-Wen Chen, Mario Agio, and Vahid Sandoghdar

Citation: *AIP Conf. Proc.* **1475**, 44 (2012); doi: 10.1063/1.4750090

View online: <http://dx.doi.org/10.1063/1.4750090>

View Table of Contents: <http://proceedings.aip.org/dbt/dbt.jsp?KEY=APCPCS&Volume=1475&Issue=1>

Published by the [American Institute of Physics](#).

Related Articles

41 GHz and 10.6 GHz low threshold and low noise InAs/InP quantum dash two-section mode-locked lasers in L band

J. Appl. Phys. **111**, 023102 (2012)

Kinetic analysis of two dimensional metallic grating Cerenkov maser

Phys. Plasmas **18**, 084508 (2011)

The self-consistent nonlinear theory of electron cyclotron maser based on anomalous Doppler effect

Appl. Phys. Lett. **98**, 261502 (2011)

Cavity quantum electrodynamics for photon mediated transfer of quantum states

J. Appl. Phys. **109**, 113110 (2011)

A method of suppressing mode competition in a coaxial localized-defect Bragg resonator operating in a higher-order mode

Phys. Plasmas **18**, 064506 (2011)

Additional information on AIP Conf. Proc.

Journal Homepage: <http://proceedings.aip.org/>

Journal Information: http://proceedings.aip.org/about/about_the_proceedings

Top downloads: http://proceedings.aip.org/dbt/most_downloaded.jsp?KEY=APCPCS

Information for Authors: http://proceedings.aip.org/authors/information_for_authors

ADVERTISEMENT

Submit Now

Explore AIP's new open-access journal

- **Article-level metrics now available**
- **Join the conversation! Rate & comment on articles**

Metalldielectric Optical Antennas for Ultrabright Single-Photon Sources

Xue-Wen Chen,^{1,2} Mario Agio,³ and Vahid Sandoghdar^{1,2}

¹Max Planck Institute for the Science of Light, 91058 Erlangen, Germany

²Department of Physics, Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany

³National Institute of Optics (INO-CNR) and European Laboratory for Nonlinear Spectroscopy (LENS),
via Nello Carrara 1, 50019 Sesto Fiorentino (FI), Italy
e-mail: xuewen.chen@mpl.mpg.de

Abstract. We report on a new class of optical antennas that shorten the excited-state lifetime of optical emitters down to 100 fs in a broad spectral range, while maintaining quantum efficiencies as high as 80%. We combine metal nanoparticles with dielectric structures and exploit concepts from plasmonics and cavity quantum electrodynamics to maximize the local density of states and suppress dissipation losses in the metal. Our findings bring about the prospect of single-photon sources at the μW power level and promise significant impact on other research fields, including photophysics, ultrafast plasmonics, and Raman spectroscopy.

Keywords: Optical antenna, Single-photon source, Spontaneous emission.

PACS: 32.70.Cs, 42.50.Pq, 78.67.-n, 84.40.Ba

INTRODUCTION

Single-photon sources have been proposed as the building blocks of many emerging quantum technologies such as quantum key distribution, all optical quantum computation and radiometry.^{1,2} Individual emitters, such as atoms, organic molecules, defect centers and semiconductor nanocrystals, are important candidates for robust single-photon sources, because intrinsically a single quantum-mechanical two-level system cannot emit two photons simultaneously. Unfortunately, these sources are inefficient, because the spontaneous emission rate is very slow due to the small size of the dipole moment in free space. Many solid-state emitters, for example nitrogen-vacancy (NV) centers in diamond, have typical excited-state lifetimes of 10 ns.³ Moreover, a broad angular distribution of the radiated photons prevents from efficient collection. In this presentation, we propose a new class of optical antennas that reduce the excited-state lifetime of emitters to the order of 100 fs, while maintaining quantum efficiencies of about 80% and broadband operation. In addition, combining such antenna architecture with high collection-efficiency schemes^{4,5} hold promise for single-photon sources at the μW power level.

The modification of spontaneous emission has been a topic of intense theoretical and experimental research and it has given birth to the field of Cavity Quantum Electrodynamics (CQED).^{6,7} The central idea in this research area is to manipulate the local photonic

FIGURE 1. a) Sketch of a metalldielectric hybrid antenna. A gold nanocone is in contact with a high refractive index substrate, where a single emitter is embedded. b) A single emitter close to a dielectric surface. The double-arrow represents the emitter. c) Spontaneous emission rate enhancement factor as a function of wavelength for different refractive indices of the substrate.

density of states (LDOS) at the position of an emitter by placing material boundaries in its surrounding. Here, we combine metallic nanoparticles with planar dielectric structures and exploit design strategies from plasmonic nanoantennas⁸⁻¹¹ and concepts from CQED to maximize the LDOS and minimize nonradiative losses incurred by the metallic constituents.

RESULTS AND DISCUSSIONS

One realization of the hybrid antenna structure is sketched in Fig. 1a, where a metallic nanoantenna (MNA) is placed in contact with a dielectric substrate. The single emitter is embedded in the substrate very close to the interface. In such configuration, the emitter strongly couples to the MNA and acquires a much larger dipole moment, which radiates more efficiently. The traces in Fig. 1c present the spontaneous emission enhancement factor as a function of wavelength for different refractive indices of the dielectric substrate. Here the enhancement factor is defined as the ratio of the spontaneous emission rate for the emitter coupled to the metallodielectric antenna in Fig. 1a to that for the emitter close to the interface without the MNA as in Fig. 1b. This example shows that the metallodielectric hybrid antenna may enhance the radiative decay rate by up to 80000 times. In particular, this can take place with high quantum efficiencies in the visible range, whereas conventional MNA design strategies are challenged by absorption losses in the metal, especially in the visible.¹⁰ This is because, in the metallodielectric antenna the electric field in the metal is more homogenous than in the case where the dielectric interface is absent, which provides a larger effective dipolar polarizability. Moreover, the MNA is located on the low index side with a higher LDOS and its induced dipole could radiate more efficient.

The radiation pattern of the metallodielectric hybrid antenna is similar to that of a vertical dipole antenna above a high-index substrate and most of the emission funnels to the substrate. Recently, we have reported on a broadband high collection-efficiency scheme, which uses a multilayered structure for tailoring the angular emission of a single emitter.⁶ The schematics and a typical angular distribution of the emission are shown in Fig. 2. In such configurations, we may collect beyond 99% of the emitted photons from sources with arbitrary orientation of the transition dipole moment.

In the second part of the presentation, we will discuss possibilities for combining the aforementioned metallodielectric hybrid antenna structures with near unity collection-efficiency schemes. We introduce a

FIGURE 2. a) Schematics of a planar antenna structure for near unity efficiency in collecting the emission from a single-photon source. The refractive indices should be arranged as $n_1 > n_2 > n_3$. SIL: solid immersion lens. b) Emission power density and collection efficiency as a function of the collection angle.

multilayer metallodielectric antenna structure¹³ that could in principle achieve beyond 99% collection efficiency. With the ultrastrong enhancement of spontaneous emission and such high collection efficiencies, we bring about the prospect of triggered single-photon sources at the μW power level. Moreover, sub-picosecond radiative processes in the solid state are also interesting because they become comparable with or faster than vibrational and phononic interactions, leading to new regimes of photophysical dynamics.

ACKNOWLEDGMENTS

We acknowledge financial support from the Max Planck Society, the ERC advanced grant SINGLEION, the Alexander von Humboldt Foundation and the EU project QIBEC.

REFERENCES

1. B. Lounis and M. Orrit, Rep. Prog. Phys. 68, 1129–1179 (2005).

2. S. Scheel, J. Mod. Opt. 56, 141–160 (2009).
3. A. Beveratos, R. Brouri, T. Gacoin, J-P. Poizat, P. Grangier, Phys. Rev. A 64, 061802(R) (2001).
4. X.W. Chen, M. Agio, V. Sandoghdar, Phys. Rev. Lett. 108, 233001 (2012).
5. K. G. Lee*, X.W. Chen*, H. Eghlidi, P. Kukura, R. Lettow, A. Renn, V. Sandoghdar, S. Göttinger, Nat. Photonics 5, 166-169 (2011).
6. X.W. Chen, S. Göttinger, V. Sandoghdar, Opt. Lett. 36, 3545-3547 (2011).
7. H. Yokoyama and K. Ujihara, eds., *Spontaneous Emission and Laser Oscillation in Microcavities* (CRC Press, New York, 1995).
8. P. R. Berman, ed., *Cavity Quantum Electrodynamics* (Academic Press, Boston, 1994).
9. J.-J. Greffet, Science 308, 1561 (2005).
10. L. Rogobete, F. Kaminski, M. Agio, V. Sandoghdar, Opt. Lett. 32, 1623-1625 (2007).
11. P. Bharadwaj, B. Deutsch, and L. Novotny, Adv. Opt. Photon. 1, 438 (2009).
12. M. Agio and A. Alù, eds., *Optical Antennas* (Cambridge University Press, 2012).
13. X.W. Chen, M. Agio, V. Sandoghdar, to be submitted (2012).