Controlling Light Emission with Photonic Funnels

J. LaMountain[1], E. Simmons[1], A. J. Muhowski[2], K. Li[2], J. Xu[2], D. Wasserman[2], and V.A. Podolskiy[1]
[1]*Department of Physics and Applied Physics, University of Massachusetts Lowell, One University Avenue, Lowell, MA 01854, USA*
[2]*Department of Electrical and Computer Engineering, University of Texas Austin, Austin, Texas 78758, USA*

Abstract: We analyze the interaction between a nanoscale emitter and a photonic funnel with a metamaterial core and demonstrate that funnel structures can significantly improve out-coupling efficiency of light as compared with their planar plasmonic counterparts.

Modulation of light emission as result of interaction between a point emitter and its environment represents a promising avenue for engineering a new generation of light sources and detectors [1]. The Purcell effect, providing a modulation of the radiative lifetime due to enhancement of the photonic density of states, has been observed throughout the electromagnetic spectrum. Recently, significant enhancement of both photo- and electro-luminescence has been demonstrated in the mid-infrared frequency range, resulting from the interaction between the emitters and a highly doped "designer metal" plasmonic layer [2]. However, since the "added" density of photonic states results from guided surface plasmon polariton modes, the observed phenomenon necessarily represents a compromise between enhancing Purcell effect and enhancement of outcoupling efficiency[2,3]. Here we explore the emitter-environment interaction within a novel material platform of photonic funnels, conically-shaped structures with anisotropic (hyperbolic) metamaterial cores that has been recently shown to provide non-resonant confinement of light to the nanoscale[4] with a goal to break the above compromise.

The photonic funnels, realized in our work, utilize the semiconductor-based designer metal platform to achieve a hyperbolic response at mid-infrared frequencies [5]. The initially planar hyperbolic metamaterials, with the help of chemical etching are transformed into conical structures (Fig.1a, inset). Our analysis of the SEM images of different funnel structures suggests that the procedure results in cones with virtually flat sidewalls with inclination angle $\theta \simeq 30^o$ (see Fig.1a). Note that the structures used in this work are of different geometry and composition (see below) than the ones previously reported in Ref.[5]. These geometrical constraints are embedded into the theoretical simulations that are described below.

The effect of the photonic funnels on the emission of nanoscale light sources is modeled with finite-elementmethod (FEM) solutions of Maxwell equations where the point source is modeled as a free-current region (with diameter and height of 400 nm and 200 nm, respectively). The models used in the study analyze the total power emitted by the source, as well as the energy flux in the far field of the source, in the "reflected" direction (away from the tip of the funnel). A combination of the above parameters, as well as comparison of these parameters to their counterparts for an emitter in vacuum provide enough information to estimate the contributions of the Purcell effect as well as contributions due to emission directionality reshaping. To enhance the emission of light into reflected domain, and to provide quantitative comparison between the performance of the funnels with existing state of the art, we assumed that the funnels are fabricated on top of homogeneous 1um-thick plasmonic "designer metal" layer.

Explicitly, we estimate Purcell factor P as the ratio of the total power radiated by current in the vicinity of the funnel to the total power emitted by the same current source in vacuum. We also introduce the efficiency ratio S that represents the ratio of far field energy flux in reflected direction to the total power emitted by the source. For an emitter with internal quantum efficiency q_i the total detectable optical signal in the far field is proportional to $S \cdot \tilde{q}$ with effective quantum efficiency $\tilde{q} = \frac{P q_i}{1+(P-1)q_i}$ [2].

Fig 1(c…f) summarizes the results of this study, presenting the dependence of the emission enhancement by the photonic funnels with height, with 1-um-thick plasmonic substrate layer, to the base-case scenario of an emitter on top of homogeneous plasmonic film that was previously realized in experiments in Ref.[2]. It is seen that the 3D structure of the funnels provides orders of magnitude enhancement in outcoupling efficiency in the "reflected" geometry, as compared with the homogeneous plasmonic layer, without sacrificing the enhancement in effective quantum efficiency (we use $q_i = 5\%$, a typical value for mid-IR emitters). As result, we expect drastic enhancement of photoluminescence in funnel composites.

Fig. 1(d,e) also reveal the physics behind the emission enhancement. In hyperbolic composites high-index (high-optical density of states) modes originate from coupling between surface plasmon polaritons propagating at the interfaces between doped and undoped layers. When the number of layers is small, increasing the thickness of the composite (and thus the number of the plasmonic layers) initially increases the number of the SPPs that contribute to the density of states and increases the Purcell factor of the metamaterial. However, when the number of SPPs is

increased beyond a certain threshold (~5 bilayers in this work, assuming layer thickness of all components of metamaterial to be 80 nm), the dispersion of the multi-layered converges to that of a homogenized bulk material, and the Purcell factor cannot be further increased. The finite radius of individual plasmonic layers enhances the outcoupling efficiency of the high-index modes. The geometry of the funnel can therefore significantly affect the outcoupling efficiency of light in both non-resonant and Mie-type resonant regimes.

Experimental validation of the theoretical predictions reported in Fig.1 is in progress.

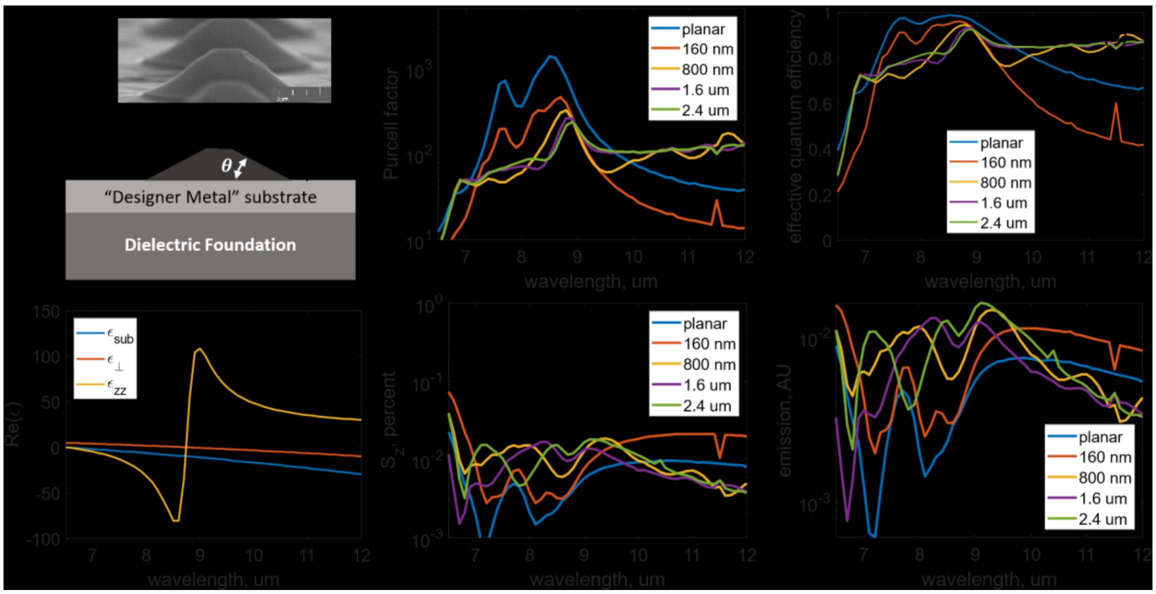

Figure 1: (a) Illustration of a photonic funnel-based emitter with relevant geometric parameters; inset illustrates the geometry of as-fabricated funnels. (b) permittivity of the doped substrate and of the effective medium response of the funnel core; (c) Purcell factor of the emitter placed at the center top of the funnel as a function of wavelength and funnel height (multiple of 160-nm-thick bilayers; see legends); (d) effective quantum efficiency $\tilde{q}$ of such an emitter; (e) outcoupling efficiency of the structure away from the funnel [toward top of the schematic in (a)]; (f) far-field emission intensity assuming wavelength-independent emissivity of the source with intrinsic quantum efficiency of 5%;

This work has been supported by the NSF (grant ## DMR- 2004298, 2004422)

References

[1] J. D. Jackson, Classical Electrodynamics, John Wiley & Sons, New York, NY 1999; L. Novotny and B. Hecht, Principles of Nano-Optics (Cambridge U, 2012); .J. Vuckovic, D. Fattal, C. Santori, G. S. Solomon, and Y. Yamamoto, Appl. Phys. Lett. **82**, 3596 (2003); M. S. Eggleston, K. Messer, L. Zhang, E. Yablonovitch, and M. C. Wu, Proc. Natl. Acad. Sci. USA **112**, 1704 (2015); R. Fleury and A. Alù, Phys. Rev. B **87**, 201101 (2013); T. Galfsky, J. Gu, E.E. Narimanov, and V.M. Menon, Proc. Natl, Acad. Sci. USA **114**, 5125 (2017)

[2] L. Nordin, K. Li, A. Briggs, E. Simmons, S. R. Bank, V. A. Podolskiy, and D.Wasserman, Appl. Phys. Lett. **116**, 021102 (2020); A.F. Briggs, L.J. Nordin, A.J. Muhowski, E. Simmons, P. Dhingra, M.L. Lee, V.A. Podolskiy, D. Wasserman, and S.R. Bank, Optica, **7**, 2334 (2020) [3] J. B. Khurgin and A. Boltasseva, MRS Bull. **37(8),** 768 (2012) and refs therein

[4] K. Li, E. Simmons, A. Briggs, L. Nordin, J. Xu, V. Podolskiy, D. Wasserman, Adv. Opt. Mat., **24**, 2001321 (2020)

[5] A. J. Hoffman, L. Alekseyev, S. S. Howard, K. J. Franz, D. Wasserman, V. A. Podolskiy, E. E. Narimanov, D. L. Sivco, C. Gmachl. Nature Materials, **6**, 946-950 (2007); S. Law, V. Podolskiy and D. Wasserman. Nanophotonics, **2** (2013): 103-130;