THREE-DIMENSIONAL SUBWAVELENGTH CONFINEMENT OF A PHOTONIC NANOJET USING A PLASMONIC NANO-ANTENNA GAP

Authors: Mehdi Hasan* and Jamesina J. Simpson

Address: Department of Electrical and Computer Engineering, 50 S. Central Campus Dr., Rm 3280,

University of Utah,

Salt Lake City, UT 84112, USA

Corresponding author: email: *m.hasan@utah.edu ; Fax: (801) 581-5281

Key terms: Photonic nanojet; Plasmonic Nano-antenna gap; Subwavelength confinement; Whispering gallery mode, FDTD

ABSTRACT:

Using 3-D finite-difference time-domain (FDTD) modeling, a microsphere-generating nanojet and gold nano-antenna gap are optimized to achieve 3-D nanojet confinement to a subwavelength volume of about 0.009 μm^3 (wherein the edges of the volume are defined at $1/e^2$ of the maximum electric-field intensity) for an incident wavelength of 633 nm.

UU IR Author Manuscript

UU IR Author Manuscript

1. INTRODUCTION

A 2004 paper [1] reported the existence of a "photonic nanojet," which was discovered using finite-difference time-domain (FDTD) [2] simulations. FDTD-predicted photonic nanojets have since been experimentally observed [3, 4, 5]. A photonic nanojet is a subwavelength waist, high-intensity electromagnetic beam capable of propagating multiple wavelengths from the shadow-side surface of an illuminated lossless dielectric microcylinder or microsphere [1, 6, 7]. Photonic nanojets are formed for a wide range of microcylinder / microsphere diameters (from ~ two wavelengths, λ, to greater than 40λ) if the refractive index contrast relative to the background is less than about 2:1 [7, 8, 9]. Photonic nanojets have been proposed for applications ranging from optical data storage [5, 10] to ultra-microscopy [1], high-speed photodetectors [11], enhanced fluorescence correlation spectroscopy [12], localized detection of embedded ultra-subwavelength inhomogeneities [13], and optical lithography [14] etc. The photonic nanojets that have been generated and utilized to date are scientifically interesting and useful for a variety of applications because the transverse beam waist of the nanojet can be made somewhat smaller than the diffraction limit (to ~ λ/3). However photonic nanojets generated by plane-wave illumination do not yield three-dimensional (3-D) subwavelength light confinement. For plane-wave illumination, the nanojet longitudinal length may extend ~ 2λ from the edge of the sphere and even up to 20λ [13]. It is possible to generate 3-D confinement of a photonic nanojet in both longitudinal and transverse directions using a highly specialized source (e.g. a tightly focused Gaussian beam [15]), however this confinement is only useful under specific circumstances in which there is flexibility to choose and control the source.

We report a new means to confine photonic nanojets in 3-D to a subwavelength volume by placing in its path a plasmonic dipole nano-antenna gap (a.k.a a truncated plasmonic waveguide) [16]. This 3-D subwavelength confinement is achieved for plane-wave illumination, thereby providing a new feature for nanojets and opening up new application possibilities, such as high-speed photodetectors [11], nanoscale light sources [17], optical lithography [18], etc. Additionally, we find that by placing a subwavelength nano-antenna gap into the path of the nanojet increases the intensity of the nanojet [19]. Plasmonic dipole nano-antenna gaps are known to concentrate electromagnetic energy into a subwavelength volume at the exiting side of the nano-antenna gap for plane-wave illumination [16, 20]. We find here that a nano-antenna gap can be used to provide

3-D subwavelength confinement of a nanojet. This phenomenon is also observed when a whispering gallery mode (WGM) is excited in the microsphere.

3-D FDTD modeling is used to demonstrate the 3-D subwavelength confinement and enhanced optical energy concentration capability of a photonic nanojet-nano-antenna gap light-collection system, both when WGM resonances are and are not excited in the microsphere. We find that for plane-wave illumination of a 3.1 μm (~ 5λ) - diameter polystyrene microsphere with a gold nano-antenna gap of transverse dimensions 100 x 200 nm^2 in its path can yield:

- A 3-D confinement of the nanojet in to a subwavelength volume of about 0.009 μm^3 (wherein the edges of the volume are defined at $1/e^2$ of the maximum electric (E)-field intensity) for an incident λ = 633 nm.
- A doubling of the electric field magnitude in the gap region and just beyond the nano-antenna gap, compared to the nanojet-only case (no nano-antenna gap included).
- An absorption enhancement factor of nearly 200 in a subwavelength volume of about 0.002 μm^3 just behind the exiting end of the gold nano-antenna gap.
- Enhanced, 3-D subwavelength concentration of light for both resonant and non-resonant plasmonic nano-antennas.
- A 3-D confinement of the nanojet into a subwavelength volume of about 0.01 μm^3 when the WGM at an incident wavelength λ = 786.95 nm is excited (which is not far from the incident wavelength of 633 nm).

We note that the works of ref. 21 and ref. 22 involved placing a nano-aperture into the path of a nanojet. However, the studies performed in those papers are 2-D and they do not cover the 3-D nanojet confinement capabilities of the nanojet+nano-antenna gap system.

2. GENERAL GEOMETRY

Figure 1 illustrates the device geometry (not to scale). The overlying microsphere is comprised of polystyrene (refractive index, n = 1.59) and is of diameter (D = 5λ) 3.1 μm. The dipole nano-antenna gap has an area of W x S nm^2 in the x-y plane respectively, with S = 2W; the antenna length D = 3.1 μm. W = 100 nm ≈ λ/6 is chosen to obtain a tight confinement of modes through the nano-antenna gap. It is illuminated from the top (+z-direction) by an x-polarized plane wave.

Figure 1 Two cross-sectional views (not to scale) of the 3-D sphere-generating nanojet and nano-antenna geometry. The microsphere diameter (D) is 3.1 μm, W = width of the nano-antenna gap, and L = thickness of the nano-antenna.

The geometry of Fig. 1 yields a light-collection system that first employs a polystyrene dielectric microsphere to form a nanojet somewhat smaller than the diffraction limit in the transverse directions (x- and y-directions), and then utilizes a subwavelength nano-antenna gap to: (1) further confine the nanojet to ultra-subwavelength dimensions in the transverse directions; and (2) confine the nanojet to a subwavelength dimension in the longitudinal direction. For all simulation cases, the incident wavelength is λ = 633 nm when the nanojet induced mode (NIM) is excited and λ = 786.95 nm when the WGM is excited in the microsphere. The gold is modeled using a Lorentz-Drude model [2, 23], for which the parameters are taken from ref. 23. A uniform cubic grid cell size of 10 nm is used and the entire modeling space spans 6 μm x 6 μm x 6 μm. A time step set to the Courant limit is utilized as well as a convolutional perfectly matched layer (CPML) for the absorbing boundary condition [24] and all the results are generated after sufficient time steps to ensure steady state condition.

3. OPTIMIZED 3-D SUBWAVELENGTH CONFINEMENT OF A PHOTONIC NANOJET

In this Section, the homogeneous polystyrene microsphere is modeled in air by itself in the FDTD grid for an incident λ = 633 nm. The resulting nanojet generated by the microsphere is shown in Fig. 2(a). Note that the microsphere (size and composition) has been designed to provide a nanojet focal point immediately adjacent to the sphere surface [9]. Focusing the nanojet at the sphere surface will yield the smallest possible subwavelength 3-D confinement when the nano-antenna gap is placed in its path. Note that the nanojet of Fig. 2(a) is visually not very pronounced. This is because a colorbar scale of 0-20 (V/m) is used in Fig. 2(a) so that it may be directly compared with the results of Fig. 2(b).

Figure 2 Visualization of the FDTD-computed scattered E-field (|E|) for (a) a nanojet generated by a 3.1 μm diameter polystyrene microsphere in air, (b) a compressed nanojet generated by a 3.1-μm diameter polystyrene microsphere with a resonant gold nano-antenna gap (centered within the path of the nanojet and having W = 100 nm, S = 200 nm, and L = 150 nm), for an incident λ = 633 nm.

Figure 3 FDTD-computed intensity (normalized to the respective maximum) vs. distance along the z-axis from the microsphere's shadow-side surface (along the center axis of the nanojet and the nano-antenna gap) for the case of a NIM-excited microsphere with a plasmonic nano-antenna gap (W = 100 nm, S = 200 nm, and L =150 nm), a WGM-excited microsphere with a plasmonic nano-antenna gap of the same dimensions, and a ,NIM-excited microsphere only..

In Fig. 2(b), the plasmonic nano-antenna gap is introduced into the path of the nanojet of Fig. 2(a). Comparing Fig. 2(a) and Fig. 2(b), we see that the nano-antenna gap more than doubles the enhancement for the scattered E-field (|E|) in the gap region and just beyond (below) the aperture. Further, the nanojet is confined in all three Cartesian directions by the nano-antenna gap to a highly sub-wavelength dimension. The subwavelength confinement in the z-direction (longitudinal direction) will be quantified below using the results of Fig. 3. The transverse (x- and y-direction) subwavelength confinement of the nanojet+nano-antenna gap system will be further quantified in Section 4 using the results of Fig. 6.

Figure 3 plots the normalized intensity vs. distance from the microsphere along the center axis of the nanojet in the z-direction. It is apparent from Fig. 3 that the presence of the nano-antenna gap shifts the focus point of the nanojet from the surface of the microsphere to the exiting edge of the nano-antenna gap (the maximum intensity is shifted from z = 30 nm to 150 nm, when the nano-antenna gap is introduced). Further, we can now begin to quantify the subwavelength confinement of the nanojet due to the nano-antenna gap. We will define the longitudinal (z-direction) waist of the confined nanojet to be between $1/e^2$ of the maximum value and will be denoted by W_z. W_z is determined to be ~ 280 nm for the microsphere+nano-antenna gap NIM case (incident λ = 633 nm) and similarly it is ~ 270 nm for the microsphere+nano-antenna gap WGM case (incident λ = 786.95 nm). We believe these are the smallest longitudinal dimensions achieved to date in the scientific literature for photonic nanojets by a factor of at least four. For the microsphere-only NIM case W_z is much larger, at approximately 800 nm.

4. ENHANCED OPTICAL ENERGY CONCENTRATION IN A SUBWAVELENGTH VOLUME

Next, we analyze a photonic nanojet illuminating either resonant or non-resonant nano-antenna gaps [16, 17, 20]. We will use 3-D FDTD to quantify the absorption enhancement factor in a nanoscale volume of 1.5W x 1.5S x 50 nm^3 just beneath the nano-antenna gap, where W is the width of the nano-antenna gap (100 nm for the resonant case and 60 nm for the non-resonant case) and S = 2W.

Figure 4 (a) Plot of the absorption enhancement factor in a nanoscale volume directly beneath the nano-antenna gap as a function of the antenna thickness for two different nano-antenna gap widths (resonant W = 100 nm and non-resonant W = 60 nm) for an incident λ= 633 nm. These FDTD simulated results show agreement with the Fabry-Perot model [20]. (b) Schematic showing the relevant scattering coefficients used for the model.

Figure 4(a) shows the absorption enhancement factor plotted as the energy in a subwavelength volume just below the exiting end of the nano-antenna gap as a function of nano-antenna thickness for two different gap widths. Both curves are normalized to the energy in the same volume without the microsphere and the nano-antenna, which yields an absorption enhancement factor of nearly 200 for L ≈ 150 nm, W = 100 nm, and S = 200 nm in a subwavelength volume of about 0.002 μm^3. The length dependence of the absorption enhancement factor is quite similar to optical transmission, which is described with a Fabry-Perot resonator model [20]. The fundamental scattering coefficients of the metal-dielectric-metal (MDM) system are shown in Fig. 4(b). The analytic equation for the absorption in the subwavelength region is given by,

$Absorption = \frac{k_{23}|t_{12}|^2 e^{-2|k''_{MDM}|L}}{|1-r_{21}r_{23}e^{2ik_{MDM}L}|^2}$, where $k_{MDM} = k'_{MDM} + ik''_{MDM}$ is the complex wave vector of the gap plasmon mode, *t* is transmission coefficient and *r* is reflection coefficient [20]. The curves of Fig. 4(a) show agreement with the above Fabry-Perot model absorption equation. From Fig. 4(a), we see there is almost a width independent location of first-order resonance at L ≈ 150 nm for W = 100 nm and at L ≈ 160 nm for W = 60 nm. There is strong resonant enhancement for L = 150 nm and W = 100 nm, and there is also strong non-resonant enhancement for L = 100 nm and W = 100 nm. Also, from these absorption enhancement factor results, we observe that both resonant and non-resonant nano-antenna gaps yield substantial energy enhancement when illuminated by a photonic nanojet.

Figure 5 FDTD-calculated optical near-field intensity ($|E|^2$): (a) in the x-z plane for a resonant plasmonic nano-antenna gap with the nanojet producing microsphere; and (b) same as (a) but in the x-y plane 10 nm beneath the nano-antenna gap. For both cases, W = 100 nm, S = 200 nm, L = 150 nm, and an incident λ = 633 nm.

Figure 6 Intensity (normalized to respective maximum) variation (a) at the center of the grid in the y-direction and plotted along the x-axis at a depth of 10 nm (in the z-direction) below the nano-antenna gap, compared to the intensity variation for the case of only a microsphere (no nano-antenna gap) at the focus point (maximum intensity, 30 nm from the sphere surface), (b) same as (a) but at the center of the grid in the x-direction and plotted along the y-axis; an incident λ= 633 nm.

Next we examine cross-sectional results of the optical intensity for a resonant plasmonic nano-antenna gap with the nanojet producing microsphere. Figures 5(a) and (b), show significantly higher enhancement when a nanojet is used to illuminate the same nano-antenna gap. In Fig. 5(b) the lightning-rod effect [16] is clear for the resonant nano-antenna gap case. In Fig. 5(b) the maximum intensity is seen to be concentrated approximately over a subwavelength focus spot of area 100 x 200 nm^2 in the x-y plane 10 nm below the nano-antenna gap. Figure 6(a) shows the intensity variation at the center of the grid in the y direction along the transverse (x-) axis at a depth of 10 nm below the nano-antenna gap (in the z-direction) for a microsphere+nano-antenna gap case (i.e. W = 100 nm, S = 200 nm, and L = 150 nm). For comparison, the intensity variation provided by only a microsphere at its focus point (maximum intensity, 30 nm from the sphere surface) is shown for when the NIM is excited (λ = 633 nm). The transverse waist along the x-axis is defined as being between the $1/e^2$ of the maximum value and is denoted by W_x. W_x for the microsphere-only case is about 480 nm, whereas W_x is much smaller at 120 nm, for the microsphere+nano-antenna gap NIM case. Figure 6(b) then shows the intensity variation at the center of the grid in the x-directions along the transverse (y-) axis at a depth of 10 nm below the nano-antenna gap (in the z-direction) for a microsphere+nano-antenna gap case (i.e. W = 100 nm, S = 200 nm, and L = 150 nm). For comparison, the intensity variation provided by only a microsphere at its focus point (maximum intensity, 30 nm from the sphere surface) is shown for when the NIM is excited (λ = 633 nm). The transverse waist along the y-axis defined at $1/e^2$ of the maximum value and is denoted by W_y. W_y for the microsphere-only case is about 420 nm, and for the microsphere+nano-antenna gap case W_y is about 280 nm. Thus, using the results of Fig. 6 along with the results of Fig. 3, the photonic nanojet is confined to a subwavelength volume defined by W_x W_y W_z = 0.12 x 0.28 x 0.28 μm^3, which is equal to about 0.009 μm^3.

5. WGM EFFECT ON OPTICAL ENERGY CONCENTRATION AND SUBWAVELENGTH CONFINEMENT

UU IR Author Manuscript

The WGM affects the focus properties, e.g. field enhancement and full width at half maximum (FWHM), of a microsphere [25]. The time-averaged energy flow spectrum of the 3.1 μm polystyrene microsphere averaged near the microsphere surface (i.e. the annulus of Fig. 7(b)) is shown in Fig. 7(a) [21, 22]. A strong WGM appears at an incident λ = 786.95 nm. Details of the distribution of the electric field at λ = 786.95 nm in the x-z plane and y-z plane is presented in Fig. 7(b) and Fig. 7(c) respectively. Note that the nanojet focus is now slightly inside the microsphere relative to the case when the WGM is not excited (in which case it is focused more just outside the surface as seen in Fig. 2).

Figure 7 (a) FDTD-calculated time-averaged energy flow, averaged over the area $A = \pi\ (3150^2 - 3100^2)\ nm^2 = 981747.7\ nm^2$ of an annulus surrounding the microsphere (see the two concentric circles in Fig. 7(b)) versus wavelength. Visualization of the FDTD-computed scattered E-field (|E|) for a 3.1 μm diameter polystyrene microsphere when a WGM is excited at an incident wavelength λ = 786.95 nm for (b) x-z plane, (c) y-z plane.

Using the results of Fig. 7, cross-sectional results are examined for the optical intensity of a microsphere+nano-antenna gap system when a strong WGM is excited in the microsphere at the incident λ = 786.95 nm. Figs. 8(a) and (b) still show significant enhancement when a WGM is excited in the microsphere to illuminate a nano-antenna gap relative to Fig. 5 (note the change in the colorbar scale used in Figs. 5(a) and (b) versus Fig. 8(a) and (b)). In Fig. 8(a) a reduction in maximum intensity is seen compared to Fig. 5(a) because the nano-antenna gap does not yield maximum enhancement at λ = 786.95 nm. This is due to the fact that the nano-antenna gap dimensions are not optimized for an incident λ= 786.95 nm. In Fig. 8(b) the maximum intensity is concentrated approximately over a transverse focus spot of area 100 x 200 nm^2 in the x-y plane 10 nm below the nano-antenna gap, similar to Fig 5(c).

Figure 8 FDTD-calculated optical near-field intensity ($|E|^2$): (a) in the x-z plane for a plasmonic nano-antenna gap with a microsphere (when the WGM is excited); (b) same as (a) but in the x-y plane 10 nm beneath the nano-antenna gap. For both cases, W = 100 nm, S = 200 nm, L = 150 nm, and an incident λ = 786.95 nm.

Figure 9 Intensity (normalized to the respective maximum) variation (a) at the center of the grid in the y-direction and plotted along the x-axis at a depth of 10 nm (in the z-direction) below the nano-antenna gap, compared to the intensity variation for the case of only a microsphere (no nano-antenna) at the focus point (maximum intensity, 10 nm from the sphere surface); (b) same as (a) but at the center of the grid in the x-direction and plotted along the y-axis; an incident λ = 786.95 nm.

Figure 9(a) shows the intensity variation at the center of the grid in the y direction along the transverse (x-) axis at a depth of 10 nm below the nano-antenna gap (in the z-direction) for a microsphere+nano-antenna gap case (i.e. W = 100 nm, S = 200 nm, and L = 150 nm). For comparison, the intensity variation provided by only a microsphere near its focus point (maximum intensity, 10 nm from the sphere surface) is shown for when the WGM is excited (λ = 786.95 nm). W_x for the microsphere-only case is about 500 nm, whereas W_x for the microsphere+nano-antenna gap is 120 nm. Figure 9(b) shows the intensity variation at the center of the grid in the x direction along the transverse (y-) axis at a depth of 10 nm below the nano-antenna gap (in the z-direction) for a microsphere+nano-antenna gap case (i.e. W = 100 nm, S = 200 nm, and L = 150 nm). For comparison, the intensity variation provided by only a microsphere near its focus point (maximum intensity, 10 nm from the sphere surface) is shown for when the WGM is excited (λ = 786.95 nm). W_y for the microsphere-only case is about 420 nm, and W_y for the microsphere+nano-antenna gap case is about 310 nm. Using also the results of Fig. 3, the nanojet is confined in a subwavelength volume defined by W_x W_y W_z = 0.12 x 0.31 x 0.27 μm^3, which is equal to about 0.01 μm^3, just slightly larger than the NIM results of Section 4.

6. CONCLUSION

In conclusion, a new means of achieving 3-D light confinement for a photonic nanojet has been demonstrated by placing a plasmonic dipole nano-antenna gap in its path. 3-D FDTD results illustrated that a gold nano-antenna gap of width 100 nm, length 200 nm, and thickness 150 nm confines a nanojet generated by a polystyrene microsphere of diameter 3.1 μm (5λ) to a subwavelngth volume of about 0.009 μm^3 for an incident λ = 633 nm. An absorption enhancement factor of nearly 200 can be achieved in a subwavelength volume of about 0.002 μm^3 behind a gold nano-antenna gap when illuminated by the nanojet+nano-antenna gap system. Enhanced concentration of light in a subwavelength volume is achieved for both resonant and non-resonant plasmonic nano-antenna gaps. 3-D FDTD results also demonstrated that a gold nano-antenna gap of width 100 nm, length 200 nm, and thickness 150 nm confines the nanojet to a subwavelngth volume of about 0.01 μm^3 when the

WGM is excited at an incident λ = 786.95 nm. These results may find utility in applications such as high-speed photodetectors, nanoscale light sources, optical lithography, etc.

ACKNOWLEDGEMENT

The authors acknowledge the University of Utah Center for High Performance Computing (CHPC) for providing supercomputing resources.

UU IR Author Manuscript

UU IR Author Manuscript

REFERENCES

1. Z. Chen, A. Taflove, and V. Backman, Photonic nanojet enhancement of backscattering of light by nanoparticles: a potential novel visible-light ultramicroscopy technique, Opt. Express 12 (2004), 1214–1220.

2. A. Taflove and S. C. Hagness, Computational electrodynamics: The finite-difference time-domain method, 3rd ed. Artech, Boston, MA, (2005).

3. P. Ferrand, J. Wenger, A. Devilez, M. Pianta, B. Stout, N. Bonod, E. Popov, and H. Rigneault, Direct imaging of photonic nanojets, Opt. Express 16 (2008), 6930–6940.

4. M. Kim, T. Scharf, S. Muhlig, C. Rockstuhl, and H. P. Herzig, Engineering photonic nanojets, Opt. Express 19 (2011), 10206–10220.

5. S. C. Kong, A. Sahakian, A. Heifetz, A. Taflove, and V. Backman, Robust detection of deeply subwavelength pits in simulated optical data-storage disks using photonic nanojets, Appl. Phys. Lett. 92 (2008), 21102-1-3.

6. X. Li, Z. Chen, A. Taflove, and V. Backman, Optical analysis of nanoparticles via enhanced backscattering facilitated by 3-D photonic nanojets, Opt. Express 13 (2005), 526–533.

7. S. Kong, A. Taflove, and V. Backman, Quasi one-dimensional light beam generated by a graded-index microsphere, Opt. Express 17 (2009), 3722–3731.

8. A. Heifetz, S. C. Kong, A. V. Sahakian, A. Taflove, and V. Backman, Photonic nanojets, J. Comput. Theor. Nanosci. 6 (2009), 1979–1992.

9. S. Lecler, Y. Takakura, and P. Meyrueis, Properties of a three-dimensional photonic jet, Opt. Lett. 30 (2005), 2641–2643.

10. S. C. Kong, A. Sahakian, A. Taflove, and V. Backman, Photonic nanojet-enabled optical data storage, Opt. Express 16 (2008), 13713–13719.

11. M. Hasan and J. J. Simpson, Photonic nanojet-enhanced nanometer-scale germanium photodiode, Appl. Opt. 52 (2013), 5420–5425.

12. J. Wenger, D. Gerad, H. Aouani, and H. Rigneault, Disposable Microscope objective lenses for fluorescence

correlation spectroscopy using latex microsphere, Anal. Chem. 80 (2008), 6800–6804.

13. C. Mendez-Ruiz and J. J. Simpson, Detection of embedded ultra-subwavelength-thin dielectric features using elongated photonic nanojets, Opt. Express 18 (2010), 16805–16812.

14. W. Wu, A. Katsnelson, O. G. Memis, and H. Mohseni, A deep sub-wavelength process for the formation of highly uniform arrays of nanoholes and nanopillars, Nanotech. 18 (2007), 485302-1-4.

15. A. Devilez, N. Bonod, J. Wenger, D. Gerard, B. Stout, H. Rigneault, and E. Popov, Three-dimensional subwavelength confinement of light with dielectric microspheres, Opt. Express 17 (2009), 2089–2094.

19. J. A. Schuller, E. S. Barnard, W. Cai, Y. C. Jun, J. S. White, and M. L. Brongersma, Plasmonics for extreme light concentration and manipulation, Nature Mat. 9(2010), 193–204.

16. Y. C. Jun, R. D. Kekatpure, J. S. White, and M. L. Brongersma, Nonresonant enhancement of spontaneous emission in metal-dielectric-metal plasmon waveguide structures, Phys. Rev. B 78 (2008), 153111-1-4.

17. L. Wang and X. Xu, Numerical study of optical nanolithography using nanoscale bow-tie shaped nano-apertures, J. Microsc. 229 (2007), 483–489.

18. A. Devilez, B. Strout, and N. Bonod, Compact metallo-dielectric optical antenna for ultra-directional and enhanced radiative emission, ACS Nano 4 (2010), 3390–3396.

20. J. S. White, G. Veronis, Z. Yu, E. S. Barnard, A. Chandran, S. Fan, and M. L. Brongersma, Extraordinary optical absorption through subwavelength slits, Opt. Lett. 34(2009), 686–688.

21. F. J. Valdivia-Valero and M. Nieto-Vesperinas, Enhanced transmission through subwavelength apertures by excitation of particle localized plasmons and nanojets, Opt. Express 19 (2011), 11545–111554.

22. F. J. Valdivia-Valero and M. Nieto-Vesperinas, Optical forces on cylinders near subwavelength slits illuminated by a photonic nanojet, Opt. Comm. 294 (2013), 351–360.

23. A. D. Rakic, A. B. Djurisic, J. M. Elazar, and M. L. Majewski, Optical properties of metallic films for vertical-cavity optoelectronic devices, Appl. Opt. 37 (1998), 5271–5283.

24. J. A. Roden and S. D. Gedney, Convolutional PML (CPML): An efficient FDTD implementation of the CFS- PML for arbitrary media, Microwave Opt. Tech. Lett. 27 (2000), 334–339.

25. Y. Duan, G. Barbastathis, and B. Zhang, Classical imaging theory of a microlens with super-resolution, Opt. Lett. 38 (2013), 2988–2990.

UU IR Author Manuscript