

SUPPLEMENTAL MATERIAL

Plasmonic off-axis unidirectional beaming of luminescence

Jeff DiMaria, Emmanouil Dimakis^{}, Theodore D. Moustakas, and Roberto Paiella[†]*

Department of Electrical and Computer Engineering and Photonics Center,
Boston University, Boston, MA 02215

Sample fabrication. The InGaN/GaN QW active material was grown by rf-plasma-assisted molecular beam epitaxy on a 9- μm -thick GaN template on c-plane sapphire. Its emission spectrum is centered near 495 nm, with a full width at half maximum of about 50 nm. To fabricate each sample tested in this work, a 2.5-nm-thick Ni adhesion layer and the Ag film are first deposited on a small die of the epitaxial material using electron beam evaporation. The nanoparticle arrays are then fabricated on top of this film using electron beam lithography to pattern a poly(methyl-methacrylate) (PMMA) resist, followed by Ag deposition and liftoff. The array periodicity and nanoparticle dimensions are characterized using SEM. The typical array size is $50\times 50\ \mu\text{m}^2$.

Angle-resolved photoluminescence. In the photoluminescence measurements, the QWs are pumped at normal incidence using light from a 375-nm-wavelength diode laser, which is focused onto the sample from the substrate side using a long-working-distance

^{*} Present address: Institute of Ion-Beam Physics and Materials Research, Helmholtz-Zentrum Dresden-Rossendorf, Germany

[†] E-mail: rpaiella@bu.edu

20 $\times$ objective lens. The luminescence signal is measured from the sample top surface, with the collection optics rotated about the excitation spot using a piezo-controlled rotational stage. The collection optics include a collimating lens, a long-pass filter to suppress the pump light, an adjustable aperture to control the measurement angular resolution, a polarizer to discriminate between s and p polarizations, and a focusing lens to couple the output light into an optical fiber. The aperture diameter is typically set to 2 mm, corresponding to an estimated angular resolution of 4°. The collected light is then analyzed using a fiber-coupled Ocean Optics grating spectrometer. The far-field radiation patterns are finally obtained by plotting the light intensity (averaged over a bandwidth of about 10 nm near the peak of the luminescence spectrum) as a function of collection angle.

Simulations. The theoretical far-field radiation patterns are calculated using FDTD simulations based on the principle of reciprocity. In these simulations, the plasmonic nanostructure under study is excited with an external plane wave incident from air along a given direction $\hat{\mathbf{k}}$ on the plane perpendicular to the sample surface and to the grating lines (i.e., the x - z plane in Fig. 1 of the main text). The resulting field-intensity distribution is then integrated over the plane of the QWs. By reciprocity, the result of this integration is proportional to the optical power radiated by the QWs along the $-\hat{\mathbf{k}}$ direction and with the same polarization as the incident wave.¹ The one-dimensional rectangular gratings of Figs. 1(a) and 1(b) and the triangular nanoantenna arrays of Fig. 1(c) are modeled via two-dimensional and three-dimensional simulations, respectively. In each case, the computational domain includes a single unit cell, with Bloch boundary condi-

tions along the x direction and perfectly matched layers in the z direction. In the three-dimensional simulations, symmetric boundary conditions are further used along the y direction. The dielectric functions of the semiconductor light emitting material (treated as bulk GaN for simplicity) and the Ag nanostructures are interpolated from tabulated experimental data.^{2,3}

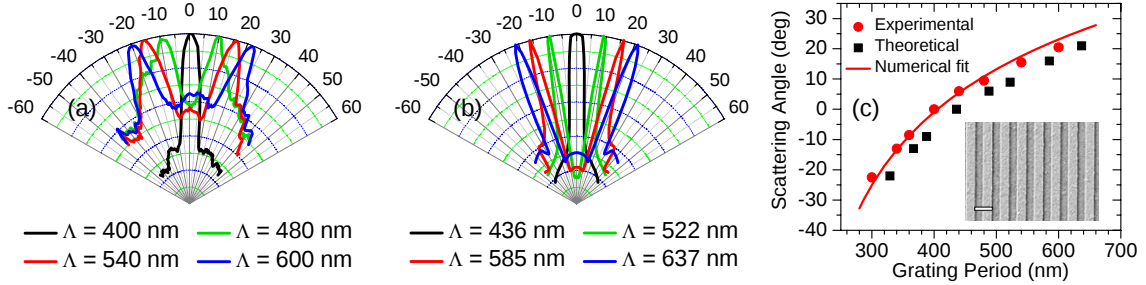


Figure S1. Plasmonic collimation and bidirectional beaming with a one-dimensional periodic array of rectangular Ag ridges on an ultrathin Ag film. (a) Experimental p -polarized far-field radiation patterns measured with four arrays of different period. (b) Numerical simulation results for similar array geometries. All traces in (a) and (b) are normalized to their peak values. (c) Experimental (red circles) and theoretical (black squares) beaming angles versus grating period. The solid line is a numerical fit of the experimental data to the expression for θ_1 given in the main text. Inset: top-view SEM image of a representative array (the scale bar is 600 nm).

Symmetric beaming with one-dimensional rectangular gratings. In this section we present experimental and simulation results related to the far-field radiation patterns of the one-dimensional rectangular gratings shown schematically in Figs. 1(a) and 1(b) of the main text. Specifically, the measured samples consist of a periodic repetition of parallel Ag ridges, having width equal to half the period (so as to maximize the first-order diffraction strength) and 30-nm height, fabricated on a 40-nm-thick Ag film on the light-emitting surface. A top-view SEM image of one of these samples is shown in the inset of Fig. S1(c). In Fig. S1(a) we show the p -polarized far-field intensity patterns measured

with four samples of different grating period Λ in the range 400 – 600 nm. The expected behavior is clearly observed in these plots. For $\Lambda = 400$ nm, strong collimation along the sample surface normal is obtained, indicating that the corresponding grating wavenumber $2\pi/\Lambda$ closely matches k_{SPP} . A divergence angle as small as 12° (full width at half maximum) is obtained in this case; by comparison, a value of about 120° is measured with the same QW samples without any metallic nanostructure, as shown in Fig. 3 of the main text. At larger grating periods, the far-field pattern consists of two output beams propagating along equal and opposite angles $\theta_{\pm 1}$, whose absolute value increases with increasing Λ . Once again, in all these grating samples the *s*-polarized emission is substantially weaker than the *p* component (by a factor of up to about 5), for the reasons discussed in the main text.

These data are well substantiated by our numerical simulation results. To illustrate, in Fig. S1(b) we plot the calculated far-field intensity profiles of four samples nominally identical to those of Fig. S1(a), except that their periods have been slightly adjusted so as to produce the same angles of peak emission as in the experimental data. Incidentally, it can be noted here that in the larger-period samples under study second-order diffraction of the excited SPPs is also possible (albeit quite weak), leading to the small peaks observed in the theoretical far-field patterns at larger angles. The circles and squares in Fig. S1(c) represent, respectively, the experimental and theoretical first-order diffraction angles plotted as a function of grating period for a broader set of samples. The same behavior is observed in these two traces, with a small offset of about 40 nm in grating period, which is mostly attributed to uncertainties in the material and structural parameters used in the simulations. The data plotted in Fig. S1(c) are also in good

agreement with a numerical fit based on the expression for θ_l given in the main text, as shown by the solid line in the figure. From this fit, we estimate a value of about 1.2 for the SPP effective index k_{SPP}/k_0 , relatively close to the refractive index of air, which again confirms that plasmonic beaming in these structures involves SPP modes that are mostly guided at the Ag-air interface. Finally, we note that the experimental beam profiles generally tend to be broader than their theoretical counterparts, likely due to fabrication imperfections and to the native roughness of the semiconductor sample surface. For the same reasons, the calculated p -to- s intensity ratios are typically found to be somewhat larger than the measured values.

References

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