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Enhanced coupling between light and surface plasmons by nano-structured Fabry–Pérot resonator

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We demonstrate enhancement of photon to surface plasmon (SP) coupling using subwavelength metallic gratings and a variable gap Fabry–Pérot (FP) resonator. Strengthened SPs and light modes are launched by laser excitation in-coupling. Enhancements of out-coupled light intensity up to 15× are measured when compared to systems with no resonator. Out-coupled intensities show a FP type resonance when the resonator gap is scanned. Finite-element time and frequency domain simulations support measured results. © *2011 American Institute of Physics*. [doi:10.1063/1.3638127]

The applicability of surface plasmons (SPs) has been widely demonstrated in the emerging field of nanoplasmonics. This is a result of their unique properties, e.g., confinement to metallic surfaces and the ability to be focused to lateral dimensions well under the excitation light's wavelength.[1–5]

Light can be scattered into a propagating SP by a periodic structure if the excitation parameters, interfacial dielectric properties and periodicity of the structure satisfy a coupling condition. For a metal-dielectric interface the frequency of SP oscillations is tied to the wavevector $\mathbf{k}^{SP}$ by $k^{SP} = (\omega/c)\sqrt{\varepsilon_m(\omega)\cdot\varepsilon_d/(\varepsilon_m(\omega)+\varepsilon_d)}$ where $\varepsilon_m(\omega)$ and ε_d are the dielectric functions of the metal and dielectric. For light normally incident on a grating, conservation of energy and quasi-momentum can be satisfied if $k^{SP} = \pm\ 2\pi n/a$, where n is a positive integer and a is the grating period.[6]

The successful integration of nano-plasmonics with silicon technology radically depends on the conversion efficiency of light into SP modes.[7,8] In this letter we demonstrate a significant enhancement of free space light conversion efficiency into SP modes using a nano-structured Fabry–Pérot (FP) resonator coupler whose implementation could progress the development of plasmonic devices.

We fabricated metallic subwavelength gratings by sputtering a Au film (185 nm with a 10 nm TiO_2 adhesion layer) onto a glass microscope coverslip. Slits were then ion milled completely through the Au film with a focused ion beam to form pairs of transmissive periodic gratings or single slits. The grating period (725 nm), slit width (350 nm), slit length (4.3 μm) and separation (15 μm) were measured by scanning electron microscope imaging (Fig. 1(c)). Grating periodicity and slit width were calculated to maximize SP coupling at the Au/air interface.

A FP resonator was created by placing a Au mirror (Au side down) on top of the grating patterned Au film (Au side up). The mirror was made by depositing a Au film onto a second glass microscope coverslip. The minimum resonator gap occurs when the two Au surfaces touch. A vertical support was then secured to the top glass disk and the entire top mirror assembly was rigidly fixed to a vertical z piezo positioner (Fig. 1(a)) creating a scannable FP resonator mirror.

Using an inverted optical microscope, a 780 nm laser (2 mW) was focused to a Gaussian spot (6 μm diameter) on the Au/glass interface and positioned onto an in-coupling transmission grating (Fig. 1). The gap between reflectors (Δz) was then scanned with a piezoelectric scanner. At each Δz in- and out-coupled light (collected by the same focusing objective) was imaged with a thermo-electrically cooled charge coupled device camera (Fig. 1(b)).

The enhancement in out-coupled light intensity can be seen in Fig. 2. Enhancement is defined as I_{max}/I_{NR} where I_{max} is the maximum out-coupled intensity with top reflector and I_{NR} is the intensity with no top reflector. The overall amplification is due to the enhancement at the in- *and* out-couplers. Both are Fano resonances in that there is a direct path *light to SP* conversion (background process) as well as an indirect path *light to FP to SP* conversion (phase dependent resonant process).

Black dots (Fig. 2) show integrated out-coupled intensity versus Δz for a pair of nano-gratings. The periodicity of the peaks is 390 nm ± 20 nm = $\lambda_{laser}/2$, indicative of a FP resonance. The intensity measured after removing the top reflector (lower left black bar) gives an enhancement of 15 ± 2.

Subwavelength grating periodicity restricts the diffraction of transmitted light to zeroth order and the small number of slits results in a grating with low resolving power. These two factors combined with the small NA of the incident light (NA = 0.08) means that light emerging from the grating will be centered on the normal and have an angular spread somewhat larger than the incident NA.

When no FP resonator is present light at the input grating both couples to propagating SPs and is transmitted as

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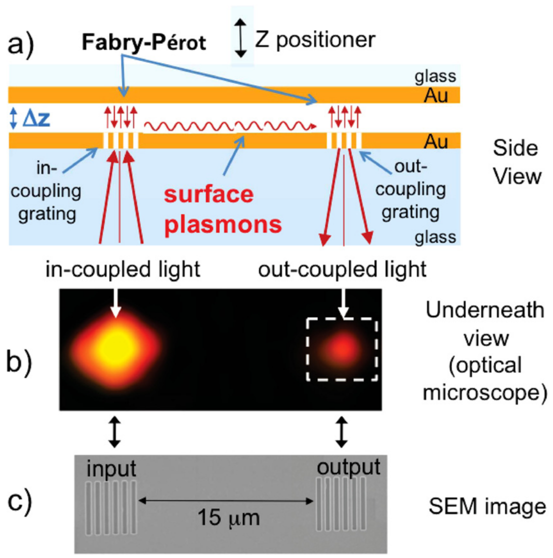

FIG. 1. (Color online) (a) The top Au reflector moves up and down with respect to the bottom patterned Au film via a piezo positioner. The gratings couple light and SPs. Fabry–Pérot resonance conditions occur above the gratings and are responsible for out-coupled light enhancement. (b) Optical image taken in cross polarization from below (see (a)) showing input laser (left) and the weaker out-coupled light (dashed box defines integration area). (c) Scanning electron microscope image of Au film gratings.

just described. At the output grating SPs decouple back to light (Fig. 2 black bar). When a reflector is placed above the gratings enhanced coupling occurs. We believe several processes explain this enhancement. *In-coupling*: (1) scattering of the incident light into SPs, (2) transmitted light (zeroth order diffraction) couples to SPs via the FP resonator, and (3) light with angles too large to reflect back onto the in-coupler undergoes multiple reflections toward the out-coupler. *Out-coupling:* When the FP gap equals $n\lambda_{laser}/2$ (n is an integer), the result of (1) and (2) is an enhanced propagating SP that de-couples into light at the out-coupler. Light collected from the out-coupler is the result of interference between the de-coupled SPs and light from (3). The phase of the light modes depends on the reflector gap much more strongly than the SP mode, which is confined to the vicinity of the bottom metal film, thus interference is a likely explanation for the multiple peaks per period observed. Similar enhancements and interference peaks are seen when pairs of single slits are used for in- and out-coupling.

We have modeled a grating coupler of light into SPs using a finite element frequency domain simulation. Grating slits were assumed to be infinitely long and Maxwell's equations were solved for harmonic propagation, TM polarization (magnetic field along the slits, electric field in the plane of Fig. 1(a)) for various values of the FP resonator gap. Lateral power flow confined between the two reflective surfaces was computed 20 μm to the side of the grating, showing that 60–70% is in the SP mode (Fig. 3(a)). The rest is in laterally traveling optical modes confined between the gold film and the reflector. Simulations using finite-difference time-domain[5] method with HASP (high accuracy scattering and propagation) code[9] obtained very similar predictions. Both SP and all the modes combined have a form characteristic of Fano scattering mediated by the FP resonance in the cavity.

For qualitative illustration, we calculate a coupling enhancement that might result in the multiple peaks per period seen in Fig. 2. First we estimate the SP mediated coupling between the input and output gratings by taking the single grating coupling amplitude to the power of 2. Then we add another channel by assuming that there is a second optical mode traveling between the two gratings that accounts for the total power difference between the red and the black curves in

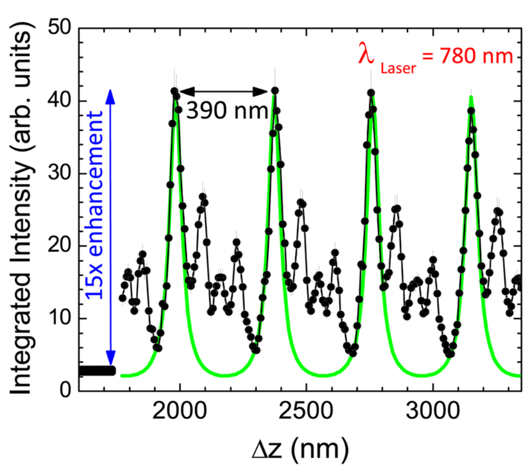

FIG. 2. (Color online) Integrated intensity of out-coupled light from grating vs FP resonator separation Δz (Fig. 1). Horizontal line (lower left) is the integrated intensity with *no resonator* (= 2.8 ± 0.2). The enhancement is the peak intensity (= 42 ± 3) w/resonator divided by the intensity w/o resonator and equals 15 ± 2. Green smooth solid curve is a fit to main FP resonance (interference induced side resonances are discussed in text and Fig. 3(b)) using the function[10] $T(\Delta z) = [1 + [4R\sin^2(2\pi\Delta z/\lambda)/(1-R)^2]]^{-1}$ for the FP transmittance. The fit gives $R = 0.63$ which is the effective reflectance of the two resonator surfaces. Uncertainty at 95% confidence level is indicated by error bars and was determined by statistical analysis of both the reproducibility of the z piezo position and stability of the imaging system.

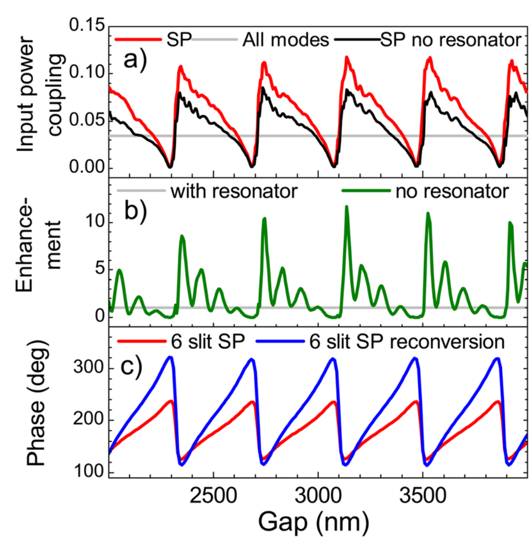

FIG. 3. (Color online) (a) Optical power coupling through a single grating from a Gaussian incident beam into the SP mode (black, bottom) and total lateral power flow from all modes (red, top) with reflector, as well as coupling into SP mode without a resonator (gray horizontal line). (b) Modeled enhancement resulting from two grating couplers with (green) and without (gray horizontal line) a resonator and interference between SP and other guided modes. (c) Gap-dependence of the phase variation of SPs produced at a six slit in-coupler (red, bottom) and the corresponding phase variation of the reconverted light exiting normal to the film at the out-coupler (blue, top).

Fig. 3(a)), and has the same in- and out-coupling amplitudes. If we assume the phase of this mode as a function of gap is $16\pi\ \Delta z/\lambda - \pi/2$, e.g., due to multiple reflections, the resulting interference pattern is qualitatively similar to the experiment (Fig. 3(b)). Note that the minimum in the interference pattern in Fig. 3(b) is near the level when there is no resonator, similar to that in the experiment in Fig. 2.

Using an analytic diffraction theory approach with effective medium theory, we can estimate the phase variation with gap of both the SPs produced at the in-coupler and the zeroth order light emitted from the out-coupler from the reconverted SPs (Fig. 3(c)). For the six slit gratings the SP phase can vary with gap over 100° and almost 200° after reconversion at the out-coupler. The large phase variation allows considerable possibility for large interference effects with other fields present, e.g., the light described in (3) above (which has its own phase variation with gap) after reconversion at the out-coupler. The calculations used above also indicate magnifications of the SP intensity and out-coupling light of about 2.4 and 5.3, respectively, over having no FP resonator for the six-slit gratings. The SP intensity enhancements are in agreement with those we obtain in finite-element time and frequency domain simulations.

In summary, we have experimentally demonstrated a significant coupling efficiency enhancement of $15\times$ from the out-coupled light of a three component photo-plasmonic device (two nano-structures in a resonator) when compared to the same device with no resonator. Computational models of the device support experimental results showing a FP enhancement in simulations and offer a possible explanation to the complex peak structure seen as due to interference between diffracted light modes and SPs. Fabrication of a monolithic device might incorporate a transparent dielectric film instead of an air gap with thickness calculated to maximize constructive FP interference and grating periodicity to match the dielectric constant.

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[1] I. I. Smolyaninov, Y. J. Hung, and C. C. Davis, Science **315**, 1699 (2007).
[2] D. K. Gramotnev and S. I. Bozhevolnyi, Nat. Photon. **4**, 83 (2010).
[3] W. L. Barnes, A. Dereux, and T. W. Ebbesen, Nature **424**, 824 (2003).
[4] A. V. Zayats, I. I. Smolyaninov, and A. A. Maradudin, Phys. Rep. **408**, 131 (2005).
[5] D. Egorov, B. S. Dennis, and G. Blumberg, Phys. Rev. B **70**, 033404 (2004).
[6] H. Raether, *Surface Plasmons on Smooth and Rough Surfaces and on Gratings* (Springer, New York, 1988).
[7] E. Ozbay, Science **311**, 189 (2006).
[8] M. J. Preiner, K. T. Shimzu, J. S. White, and N. A. Melosh, Appl. Phys. Lett. **92**, 113109 (2008).
[9] M. I. Haftel, C. Schlockermann, and G. Blumberg, Appl. Phys. Lett. **88**, 193104 (2006).
[10] M. Born and E. Wolf, *Principles of Optics* (Cambridge University Press, Cambridge, 1999).