Subwavelength Plasmonic Resonator

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Abstract We simulate a novel plasmonic resonator at a center wavelength of λ=737nm based on a gold cavity with Q≈53 and ~40% of the energy in the dielectric. We achieve a normalized mode volume of $V_{cav}/(\lambda/2n)^3 \approx 0.36$.

Introduction

Interest in nanophotonics in recent years has fostered the use of plasmonics to confine and propagate light at nano-length scales. However, extreme sub-wavelength resonators have yet to be achieved, since a conventional dielectric cavity is limited to one-half of a light wavelength in the dielectric material. However, recent work by Sarychev *et al.*[1] suggests that traditional "c-shaped" or "horseshoe-shaped" microwave resonators (figure 2) also work at optical frequencies, allowing for the formation of a subwavelength plasmonic cavity. Such cavities can be modelled as an RLC resonator circuit[1], with the capacitance being formed across the inside of the cavity, and the resistance and inductance being formed from the complex ohmic resistance of the gold. A good resonator is mostly characterized by a high quality factor Q. In the case of gold plasmonic cavities, however, the resistance of the metal limits the quality factor Q. Therefore, by confining the light preferentially to the dielectric material, a high quality factor resonance can be created at very small normalized mode volumes.

The plasmonic horseshoe resonator proposed by Sarychev[1] can be implemented easily by at least two methods. One implementation involves etching a "nanoridge" and subsequently covering it with gold. However, an easier method involves etching nanotrenches and subsequently coating the inside walls with gold. Therefore, the trench, being the easiest structure to fabricate, will be studied for the rest of the paper.

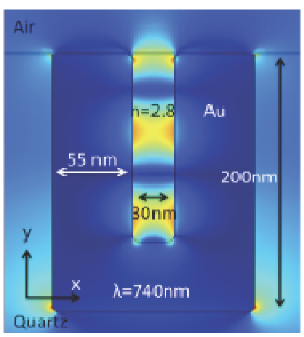

Fig. 1: FEM plot of $|E_x|$ for the trench configuration

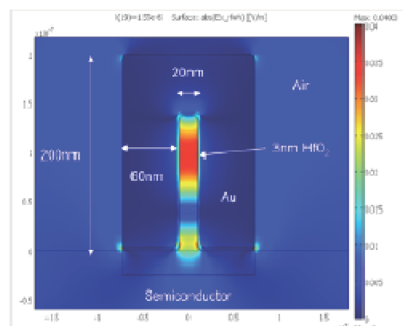

Fig. 2 FEM plot of $|E_x|$ for the ridge configuration

Results

In COMSOL Finite Element Method (FEM) simulations, the nanotrench resonator was simulated using both 2-D and 3-D simulation modes. A monochromatic plane wave was used to excite the resonator by specifying matched and scattering boundary conditions. 3-D simulations all assumed that the length of the cavity was 200nm in the z-direction. In the 2-D simulations, the magnetic field was assumed to be transverse (out of the plane of the simulation), and the E-field was polarized along the x-direction, as seen in figure 1. In this configuration, the magnetic field will drive the current to oscillate between the two prongs of the resonator. Perfectly Matched Layer (PML) boundary conditions were used to absorb all outgoing radiation[2]. In all cases, the PML was at least one-half wavelength thick to effectively absorb all reflected radiation. The PML was made using manually tuned tensor dielectric constants that absorbed radiation preferentially in a certain direction. Meshing conditions were set so that each mesh element was smaller than 1 nm, allowing for about 30 elements within the skin depth of gold. Finally, the energy in both the dielectric and metal were calculated using the energy density formula from Landau and Lifshitz[3]:

$$u = \frac{\varepsilon_0}{4}\frac{d[\omega\varepsilon(\omega)]}{d\omega}E\cdot E^* + \frac{\mu_0}{4}\frac{d[\omega\mu(\omega)]}{d\omega}B\cdot B^*$$

The complex, dispersive refractive index of gold was used[4], and a real dispersive refractive index was used for the dielectric material. We assume the substrate that the trench is etched in is quartz, since quartz is transparent in the region near the surface plasmon frequency of gold.

FEM simulations show that there are multiple order plasmonic resonances in the nanotrench. This confirms the theory presented by Sarychev et al[1]. From figure 3, we simulate the presence of two higher order modes (3rd and 4th order). The third order resonance at 949 nm has a quality factor of Q≈30. The confinement of the mode to the dielectric was simulated to be around 62%. The fourth order resonance at 737nm has Q≈53. The confinement factor for this mode dropped to around 40%. From figure 4, it is apparent that higher order modes are less confined to the dielectric, and therefore the maximum field enhancement is lowered as well. This follows the fundamental relationship observed in classical metal-insulator-metal structures, where higher wavevector modes require more electromagnetic field in the metal and therefore propagate for shorter distances[5]. The resonance, however, gets sharper with increasing mode order. The sharp resonance can be explained intuitively by noticing that the boundary conditions imposed by the trench become more important for these modes. The current in the metal therefore will not find a minimum energy configuration unless its distribution is very close to the optimal limit (i.e. a resonance).

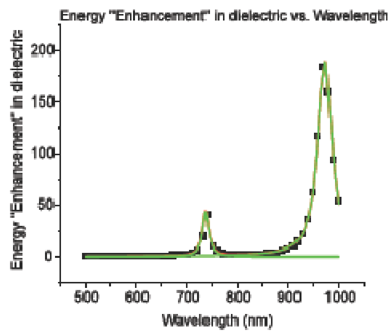

Fig. 3: Energy "Enhancement" in dielectric of Nanotrench

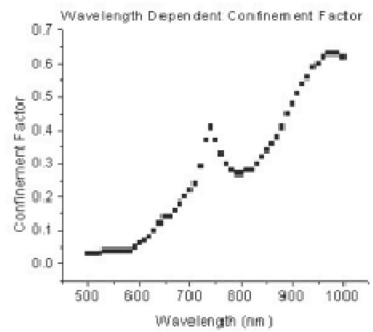

Fig. 4 Confinement Factor for Nanotrench

Conclusions

COMSOL FEM simulations were done to show that a trench plasmonic resonator has great potential to serve as a high quality factor resonator. The quality factor of the 4th order resonance in the structure was found to be ~54, and the ~40% of the field energy was confined to the dielectric gain media. In the future, applications of such a resonator will encompass cavities for enhanced Raman spectroscopy, and narrow band light sources.

References

1 Sarychev, A. et al, Physical Review B, Volume 75 (Feb 2007)
2 Berenger, J., Journal of Computational Physics, Volume 127 (1996), pp. 363-379
3 Landau, L., *Electrodynamics of Continuous Media*, 1960, pp. 276
4 Palik, E., *Handbook of Optical Constants of Solids*, 1998, Elsevier, pp. 286-295.
5 Maier, S., *Plasmonics: Fundamentals and Applications*, 2007, Springer.

Amit Lakhani received his BS degree from North Carolina State University in 2007 in Electrical Engineering. Amit's research interests currently are in the area of novel applications of plasmonic nanostructures. He has authored 5 papers in leading technical journals and conferences. He has received the McCormick Award for Undergraduate Research from N.C. State University and the Frank and Margaret Lucas Scholarship from U.C. Berkeley.

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