WT2 (Invited)
16.00 - 16.30

Plasmonic Metamaterials

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Abstract – **We experimentally and theoretically determine the plasmon dispersion in coaxial waveguides. We demonstrate strong optical confinement at energies below the surface plasmon resonance. Furthermore, we find that the reflection coefficients of the coax end facets can be strongly tuned by changing the coax dispersion and surrounding dielectric, which provides a new route to optical cavities with ultrasmall mode volumes.**

I. INTRODUCTION

Coaxial waveguides composed of a circular dielectric channel separating a metal core and cladding enable strong optical confinement. This opens up exciting opportunities for miniaturization of optical circuits and the realization of nanoscale optical cavities.

Here, we study the propagation characteristics of light in coaxial plasmonic waveguides experimentally and theoretically. At energies below the surface plasmon resonance we find that a reduction of the dielectric gap-width to only a few times the plasmon skin depth gives rise to significantly shortening of the wavelength of light [1].

We also find that plasmons acquire a non-trivial phase shift upon reflection off the end facets of coaxial cavities. We show that the reflection can be very well controlled using the surrounding dielectric index. This creates opportunities to realize ultrasmall optical cavities with lengths well below λ /2 [2].

II. METHODS AND RESULTS

We experimentally determine the plasmon dispersion in coaxial waveguides from transmission experiments of isolated coaxial apertures. Coaxial channels are prepared by focused ion-beam milling of 20-100-nm wide circular channels through Ag films of incrementally varied thickness in the range 250-500 nm.

Using confocal microscopy we obtain the optical transmission spectra of individual coaxial waveguides which are normalized to the transmission spectrum of an open area without Ag. The normalized transmittance spectra show clear resonances at wavelengths that red-shift with increased length of the coaxial waveguides. The resonances are also very sensitive to the lateral coax geometry. In-filling the waveguides with spin-on-glass (SOG) results in a red-shift of the resonance spectrum.

We attribute the observed behavior to Fabry-Pérot resonances of the coaxial waveguide. The spectral position of the resonances depends on the length of the cavity, the plasmon dispersion in the cavity and the phase shifts that the plasmons undergo upon reflection. Fig. 1(a) shows the plasmon dispersion relation determined from measurements on coaxial waveguides with 50-nm-wide air channel and lengths varied between 250-500 nm.

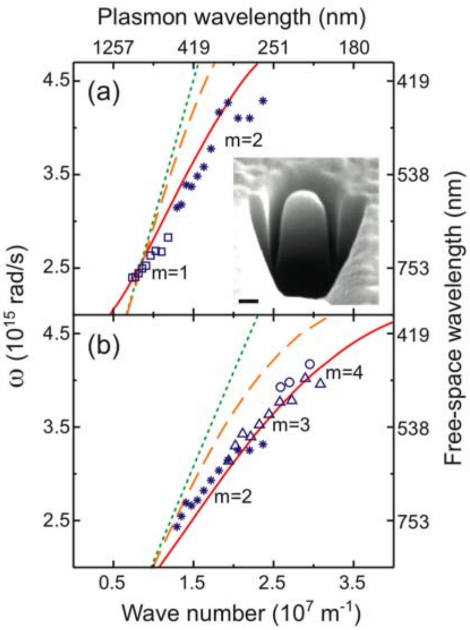

Fig. 1. Comparison between measured (points) and calculated (red lines) dispersion relations for 50-nm wide coaxial channels filled with air (a) and SOG (b). Also shown are the dispersion in the dielectric medium (dotted lines) and the plasmon dispersion for a flat interface (dashed lines). The inset shows an electron micrograph of a cross-sectioned 50-nm wide, 485-nm long coaxial cavity. Scale bar is 100 nm.

At a free-space wavelength of 500 nm we measure a plasmon wavelength of only 200 nm in waveguides with ~50-nm-wide SOG-filled channels. This demonstrates that the wavelength of light is shortened significantly when it is coupled into the coaxial plasmon waveguide.

To compare our measurements with theory we calculate dispersion curves by solving Maxwell's equations analytically for the cylindrical coaxial geometry. Our experimentally determined dispersion relations agree very well with the analytical calculations.

In the final part we discuss the reflection coefficients of the end facets of the coaxial waveguides. Our experiments point

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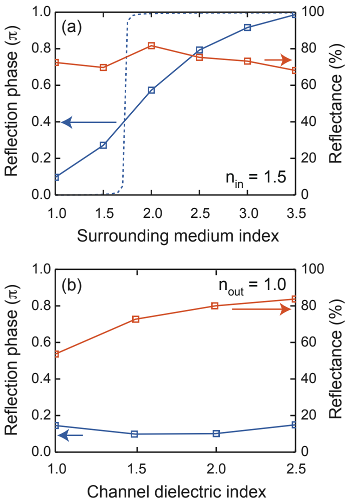

Fig. 2. Reflection phase and reflectance at the ends of a coaxial waveguide with 75-nm wide dielectric channel and outer radius of 175 nm at a wavelength λ_0 = 800 nm derived from finite difference time domain simulations. (a) Dependence on surrounding dielectric index for waveguides with fixed dielectric channel index of 1.5. (b) Dependence on the refractive index of the dielectric coax channel surrounding index fixed to 1.0.

out that the coaxial geometry and composition strongly affect the phase shifts acquired upon reflection off the cavity ends. Using finite difference time-domain simulations we obtain the field intensity profile in a coaxial waveguide, from which the reflection phase and reflectance at the end facets are calculated.

Fig. 2(a) shows the effect of changing the refractive index of the dielectric medium outside a coaxial cavity composed of 100-nm-wide Ag core, surrounded by 75-nm-wide dielectric channel with index 1.5, clad in Ag. By varying the outer index from 1.0 to 3.5 it is possible to tune the reflection phase from 0 to π, while the reflectance remains at a value of ~70%. In Fig. 2(b) the dielectric index of the 75-nm wide circular channel is varied. As the index is raised the reflectance value increases, while the reflection phase remains near constant.

Fig. 2 shows that is possible to tune the phase shift and reflectance at the cavity ends independently. This opens up ways to improve the quality factor while reducing the mode volume of a coaxial cavity.

III. CONCLUSIONS

We have shown that coaxial waveguides can strongly confine light in the dielectric gap between a Ag core and cladding. At a free-space wavelength of 500 nm we observe a more than twofold reduction of the wavelength in coaxial waveguides with 50-nm-wide silica channel. We also find that the reflection coefficients of the coax end facets strongly affect the waveguide resonances. From simulations we conclude that the reflection coefficients can be controlled using the dielectric index inside and outside the coaxial channels.

REFERENCES

[1] R. de Waele, S. P. Burgos, A. Polman, and H. A. Atwater, "Plasmon dispersion in coaxial waveguides from single-cavity optical transmission measurements," in press.

[2] E. Feigenbaum, M. Orenstein, "Ultrasmall Volume Plasmons, yet with Complete Retardation Effects", *Phys. Rev. Lett.*, vol. 101, 163902 (2008).