Surface plasmon resonance enhanced coupling to whispering-gallery modes in optical micropillar resonators

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Abstract: We report surface plasmons enhanced coupling to whispering-gallery modes in micropillar resonators. We observe a 4-fold coupling enhancement using a glass prism coated with a 20-nm gold film and coupled to a silica micropillar resonator.

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Recently, surface plasmon resonance (SPR) [1] enhanced optical phenomena have been attracting considerable interest in a wide range of applications including biochemical sensing [2, 3] and microscopy. Here we report initial experimental demonstrations of SPR enhanced coupling to whispering-gallery modes (WGMs) in silica micropillar resonators. Compared with microsphere resonators, micropillar resonators offer a long mm-cm length for coating with biochemical molecules for SPR-enhanced sensing [2].

Fig. 1 (a) Schematic of the experimental setup using the conventional Kretschmann-Raether ATR coupling system. Inset illustrates a right-angle prism with the lower half of the prism surface sputtered with a 20-nm gold thin film. (b) - (i) show typical images of the circular micropillar resonator taken on the transmission side at $\theta \sim 49.18^\circ$.

Fig. 1(a) shows the schematic of our experimental setup using the conventional Kretschmann-Raether ATR coupling system. We use a glass (BK7) right-angle prism with a 20-nm thin gold film sputtered on the prism surface. We employ a standard singlemode silica optical fiber as a 125- μm -diameter micropillar resonator. The micropillar resonator is attached onto the gold-coated prism surface. Only the lower half of the prism is sputtered with gold (inset) in order to enable control experiments without gold-film coating on the same prism-fiber setup. A laser beam from an external-cavity wavelength tunable diode laser (675 nm - 693 nm) is weakly focused onto the prism-fiber coupling surface at an incident angle θ above the critical angle for total internal reflection. We use TE-polarization to excite SPR effects. We measure the internal reflection spectra at the far field after a 50- μm -size pinhole using a photodiode. We also image the fiber sidewall transmission onto a CCD camera.

Figs. 1(b) - 1(e) show typical fiber images taken at the transmission side in TE polarization. We compare the transmission intensity levels between typical on- and off-resonance wavelengths in the same z region (both with and without gold coating). We see that the on-resonance image with gold coating (Fig. 1(d)) exhibits a pronounced enhancement compared with the off-resonance image (Fig. 1(e)). Whereas, the on-resonance image without gold coating (Fig. 1(b)) only exhibits a marginal enhancement compared with the off-resonance image (Fig. 1(c)). We also image the fiber transmission in TM polarization (by rotating the laser beam polarization from TE to TM), as shown in Figs. 1(f) - 1(i). While the on-resonance intensity (Fig. 1(f)) is enhanced compared with the

off-resonance intensity (Fig. 1(g)) in the z-region without gold coating, the on-resonance intensity (Fig. 1(h)) is essentially the same as the off-resonance intensity (Fig. 1(i)) in the z-region with gold coating.

Fig. 2(a) shows two measured TE-polarized reflection spectra (in log scale) at $\theta \approx 48.5^\circ$. The multimode spectrum (red) from a z-position with gold coating exhibits more pronounced resonance dips than the control multimode spectrum (blue). Mode A with gold coating displays a coupling efficiency of $\sim 70\%$, whereas mode B (control) at essentially the same wavelength only reveals a coupling efficiency of $\sim 22\%$. Both modes A and B have similarly high $Q \sim 10^4$.

Fig. 2(b) shows the measured coupling enhancement factor (normalized coupling efficiency between modes A and B) as a function of θ . We observe a maximum enhancement factor of 4 near $\theta = 48^\circ$ with an angular width of $\sim 4.3^\circ$. We confirm that the coupling enhancement is due to SPR by comparing with the normalized reflected light intensity (reflectance) at an off-resonance wavelength (~ 687 nm) as a function of θ , as shown in the inset of Fig. 2(b). We observe a pronounced reflectance dip at $\theta \approx 47.8^\circ$ with an angular full-width half-maximum of $\sim 5.4^\circ$, which is consistent with our observed angular span of the enhanced WGM coupling. We remark that TM-polarized internal reflection spectra from gold-coated prism-fiber coupling only display attenuated resonances.

Fig. 2 (a) Measured TE-polarized reflection spectra at $\theta \sim 48.5^\circ$. The red curve is taken from a region with 20-nm gold coating. The blue curve is taken from a region without gold-film coating. (b) The normalized coupling efficiency of mode A to mode B at various incident angles. Inset shows the measured surface plasmon resonance reflectance dip.

In summary, we demonstrated surface plasmon resonance enhanced coupling to whispering-gallery modes in a large-sized silica optical micropillar resonator. We observed a maximum of 4-fold coupling enhancement in TE polarization by using a 20-nm-thin gold film coated glass prism that is coupled to a 125- μm -diameter micropillar resonator. We observe that the angular span of the coupling enhancement is consistent with the measured surface plasmon resonance reflectance dip. Our on-going experiments focus on optimizing the gold-film thickness and also exploring plasmon enhanced coupling to polygonal micropillar resonators. Future experiments will investigate sensitizing the silica glass fiber for surface plasmon resonance enhanced WGM-based bio-molecules sensing.

References

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