Nanofabrication and Optical Characterization of Optical Transformer with 2-D Tapered Tip

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Using electron-beam induced deposition and focused ion-beam milling[1], we have fabricated plasmonic optical transformers with a tapered tip (*Fig 1*). The fabricated transformers are composed of Au/SiO_2/Au layers and have tips that linearly taper in two dimensions. The thickness of the SiO_2 layer, fabricated using e-beam induced deposition, decreases from 200 nm down to < 15 nm, which is the important feature of the transformer.

The concept of the optical transformer and its optimized dimensions (from COMSOL simulation) are shown in *Fig 2*. The optical transformer is an impedance transformer at optical frequency. The gradually decreasing vertical gap and horizontal width of the structure along the optical axis increase its impedance and strongly enhance the electric field at the tapered end. The two major advantages of the optical transformer over conventional plasmonic antennas are (a) much improved enhancement of electric field ($>10^3$ with an efficient optical coupler); and (b) excellent impedance match to analyte molecules.

Our fabrication process is illustrated in *Fig 3*. We first deposit a 50-nm-thick gold layer (*Fig 3 (a)*). The dielectric material, which is SiO_2, is deposited using electron-beam induced deposition (*Fig 3 (b)*). The tapering geometry is achieved by controlling the scan (deposition) area and the dose of the electron beam and by performing multi-layer depositions. The process has enabled us to obtain tapering angles between 5 - 45 degrees and deposit layers as thin as 5 nm. Following the SiO_2 deposition, another 50-nm-thick gold layer is deposited (*Fig 3 (c)*). The final shape of the transformer is defined by performing focused ion-beam milling (*Fig 3 (d)*).

Using 120-fs Ti-sapphire-laser pulses at 830 nm (focused down to a diffraction limited spot, FWHM ~ 500 nm), we excited at the base of the transformer and collected the two-photon luminescence only from the tapered tip (*Fig 4 (a)* and *(b)*). From our optical measurements, we have calculated and found that, when compared to gold surface (peak-to-peak roughness of 8 nm), the optical transformer shows a much stronger enhancement of electric field (*Fig 4 (c)*) - at least a factor-of-14 improvement over the gold surface.

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1. I. Utke, P. Hoffman, J. Melngailis, “Gas-assisted focused electron beam and ion beam processing and fabrication,” Journal of Vacuum Science and Technology B, vol 26, no. 4, p. 1197-1276, 2008.
2. J Lu, C Petre, E Yablonovitch, J Conway, “Numerical optimization of a grating coupler for the efficient excitation of surface plasmons at an Ag–SiO 2 interface,” *Journal of the Optical Society of America B*, vol. 24, no. 9, p. 2268-72, Sept. 2007.

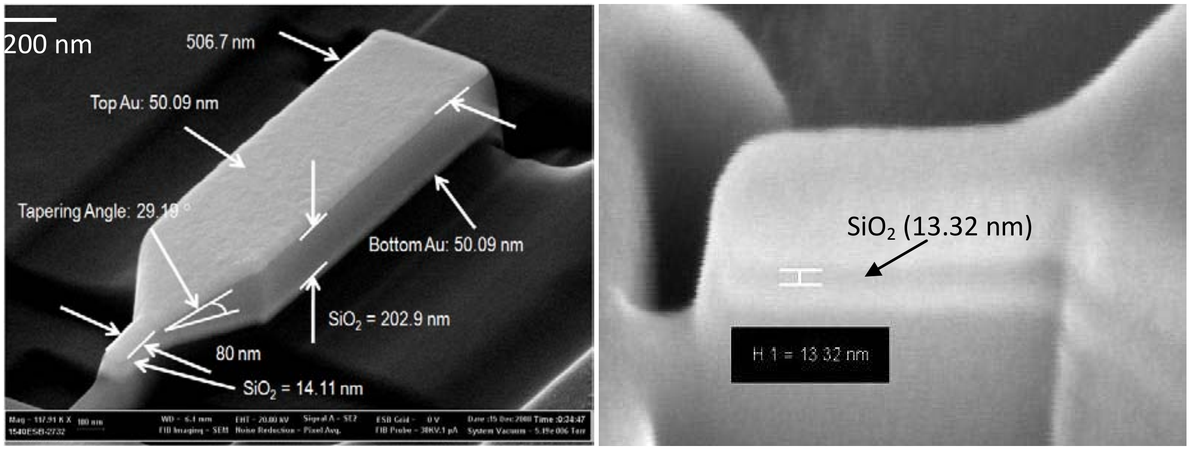

Fig 1: SEM images: fabricated optical transformer and side view of the tapered tip

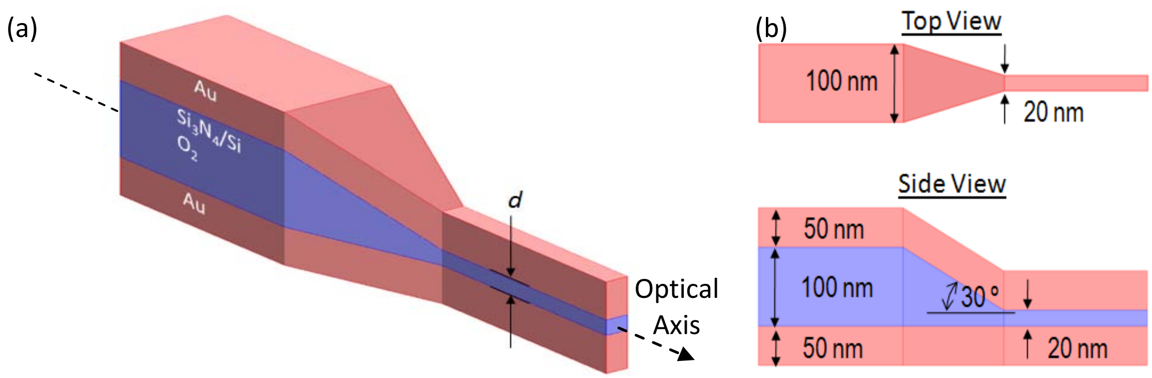

Fig 2: (a) The concept of an optical transformer; and (b) optimized dimensions (from COMSOL simulation) – A smaller plate separation at the tapered end will result in stronger e-field enhancement.

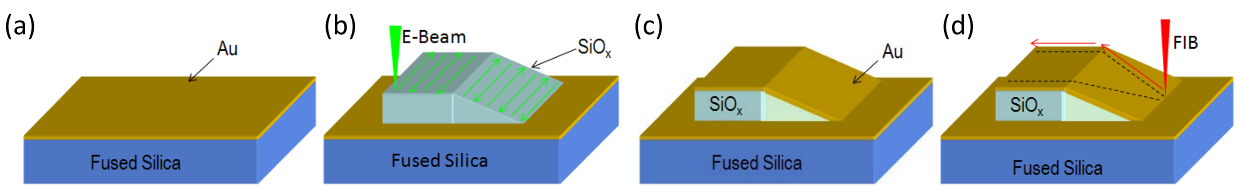

Fig 3: Fabrication process: (a) Au deposition; (b) electron-beam induced deposition of SiO_2; (c) Au deposition; and (d) final patterning using focused ion beam

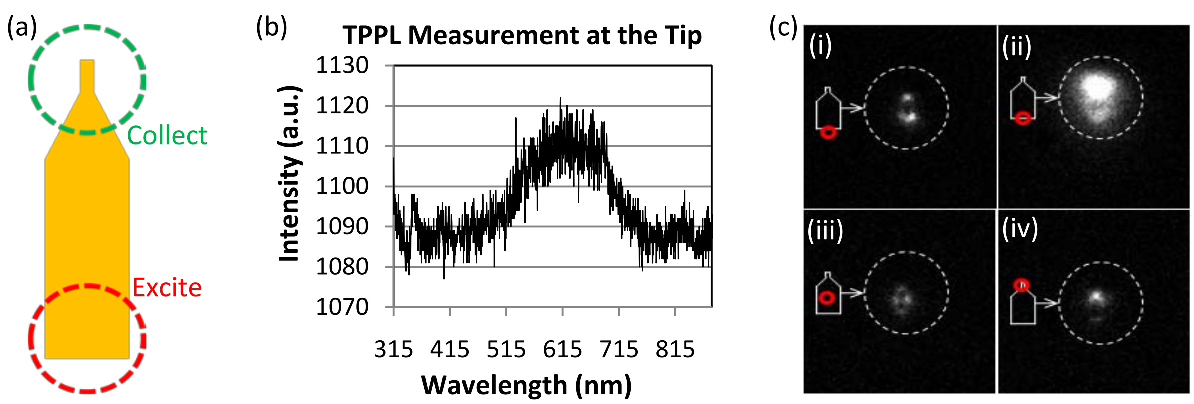

Fig 4: (a) Excitation at base and collection at tip; (b) TPPL from the tip corresponding to the method depicted in (a); and (c) TPPL images for excitation at (i) near base, (ii) at base (strongest emission), (iii) at middle, and (iv) at tip (the red circles indicate the excitation locations)