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Engineering of composite metallic microfibers towards development of plasmonic devices for sensing applications

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Abstract. The paper discusses the analysis of tapered hybrid composite microfibers based on a metal-core and dielectric-cladding composite material system. Its advantages over the pure metal tips conventionally used, are the inherent enhanced environmental robustness due to inert borosilicate cladding and the capability of multiple excitation of the tapered nanowire through the length of the fiber due to the enabled total internal reflection at the borosilicate/air interface. Simulations through finite element method (FEM) have demonstrated an improved field enhancement at the tapered region of such microfibers. Furthermore, experimental results on tapering in copper based microfibers together with light coupling and propagation studies will be demonstrated revealing the potential for the development of plasmonic devices for sensing applications.

1. Introduction

Surface plasmon polaritons (SPPs) are surface electromagnetic waves travelling along a metal/dielectric interface, whose field decays exponentially in both media. SPPs have attracted great interest and have found many applications in biosensing, surface-enhanced Raman spectroscopy (SERS) and also microscopy, since they offer high field enhancement and confinement beyond the diffraction limit [1].

The field enhancement at the apex of metallic tips have been extensively studied theoretically [2-4], however it has been clearly identified lately the need for further research towards the engineering of physically realizable and robust plasmonic structures with enhanced performance. In this study the performance of tapered hybrid copper-core/borosilicate-cladding microfiber is analyzed. Their advantages over the metal tips are the absence of impurities and the multiple excitation of the nanowire through the length of the fiber due to the repeated total internal reflection at the silicate/air interface [5]. High field enhancement is expected at the apex of such tapers.

2. Modelling

For metallic core nano-wires of radius R_1 surrounded by a dielectric layer of radius R_2, the amplitudes of the electric and magnetic fields for TM_{01} mode [6] are:

$$\boldsymbol{E}(\rho) = \begin{cases} A_1\left[-i\left(\frac{\beta}{\alpha_1}\right)I_1(\alpha_1\rho)\hat{e}_\rho + I_0(\alpha_1\rho)\hat{e}_z\right], & \rho \le R_1 \\ \left(\frac{\beta}{\alpha_2}\right)[-iA_2I_1(\alpha_2\rho) + B_2K_1(\alpha_2\rho)]\hat{e}_\rho + [A_2I_0(\alpha_2\rho) - iB_2K_0(\alpha_2\rho)]\hat{e}_z, & R_1 \le \rho \le R_2 \\ A_3\left[\left(\frac{\beta}{\alpha_3}\right)K_1(\alpha_3\rho)\hat{e}_\rho - iK_0(\alpha_3\rho)\hat{e}_z\right], & \rho \ge R_2 \end{cases} \quad (1)$$

$$H_\varphi(\rho) = k \times \begin{cases} A_1\left[-i(\frac{\varepsilon_1}{\alpha_1})I_1(\alpha_1\rho)\right], & \rho \le R_1 \\ \left(\frac{\varepsilon_2}{\alpha_2}\right)[-iA_2I_1(\alpha_2\rho) + B_2K_1(\alpha_2\rho)], & R_1 \le \rho \le R_2 \\ A_3\left[(\frac{\varepsilon_3}{\alpha_3})K_1(\alpha_3\rho)\right], & \rho \ge R_2 \end{cases} \quad (2)$$

where β is the propagation constant, ε_1, ε_2 and ε_3 are the relative permittivities of metal core, dielectric cladding and air respectively, $\alpha_j = (\beta^2 - \varepsilon_j k^2)^{1/2}$ for j=1,2,3, I and K are the modified Bessel functions of the first and second kinds and A_1, A_2 and A_3 are the complex constants.

The dispersion equation can be derived by the continuity of the tangential components of the fields at the interfaces $\rho = R_1$ and $\rho = R_2$:

$$\varepsilon_1\alpha_2 I_1(\alpha_1R_1)[\alpha_2\varepsilon_3K_1(\alpha_3R_2)M_{00} + \alpha_3\varepsilon_2K_0(\alpha_3R_2)M_{10}] = -\varepsilon_2\alpha_1 I_0(\alpha_1R_1)[\alpha_2\varepsilon_3K_1(\alpha_3R_2)M_{01} + \alpha_3\varepsilon_2K_0(\alpha_3R_2)M_{11}] \quad (3)$$

where $M_{ab} = I_a(\alpha_2R_2)K_b(\alpha_2R_1) - (-1)^{a+b}I_b(\alpha_2R_1)K_a(\alpha_2R_2)$.

Figures 1 and 2 show the real and imaginary part of the effective refractive index (n_{eff}) as a function of the wavelength for different radii of the copper core. As the radius of the copper tip decreases, both the real and imaginary parts of n_{eff} increase. This means that, toward the apex of the metal tip, the effective wavelength of the plasmon wave decreases and the losses increase. For radii of the metal tip larger than 50nm the losses are relatively low. As the radius decreases the losses become significant and they are minimum for wavelength around 800nm.

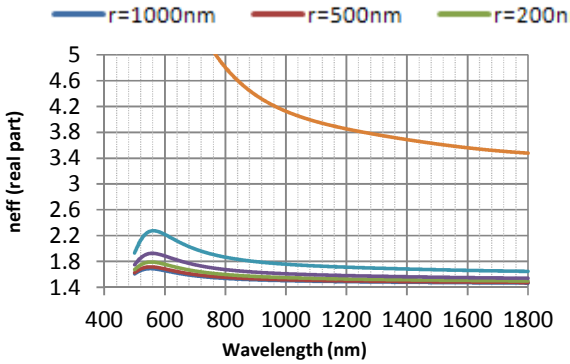

Figure 1. Real part of the effective refractive index (n_{eff}) as a function of the wavelength for different radii of the copper core.

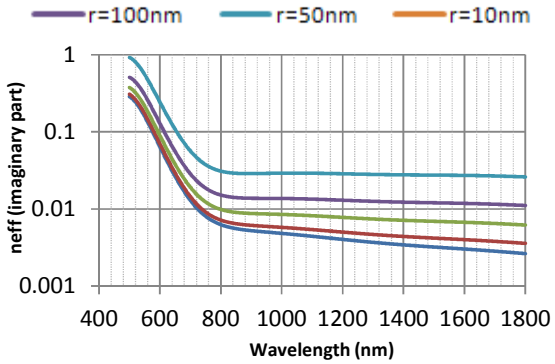

Figure 2. Imaginary part of the effective refractive index (n_{eff}) as a function of the wavelength for different radii of the copper core.

2.1. FEM simulations of tapered composite microwire

The simulated structure is a copper cone with semi-angle, a=3.43°, input radius of r_{input}=150nm and output radius r_{output}=3nm to avoid singularities. The cone is surrounded by a borosilicate layer with a thickness that decreases so that the ratio of outer radius/core radius remains constant (~ 12.5). The launched mode is TM_{01} (P_{input}=1W) and the transmission is along the z direction. Figure 3 shows the maximum normalized electric field at the apex of the tip as a function of the wavelength. We observe that periodic peaks appear in the field enhancement spectrum. These peaks appear when the tip length is more than 1 μm due to SPPs that propagate along the tip. When the SPPs meet the end of the tip, they are reflected and form cavity modes [7].

The highest enhancement factor, defined as the maximum intensity I at the apex of the tip divided by the intensity I_o at the copper/borosilicate surface at the input of the fiber tip, is ~1.1x10^4 for λ=837nm (Fig. 4).

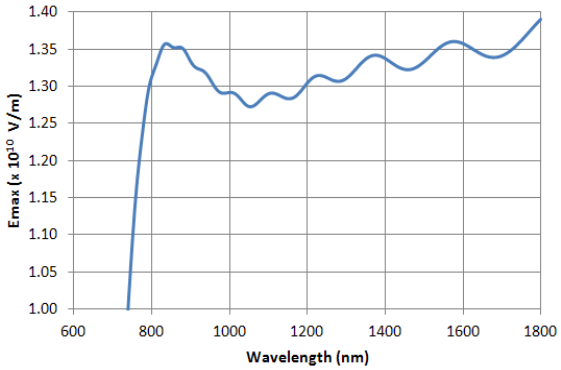

Figure 3. The maximum normalized electric field at the apex of the tip as a function of the wavelength.

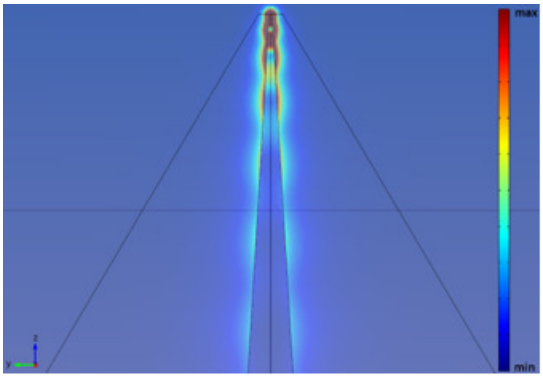

Figure 4. Normalized electric field for λ=837nm.

3. Experimental

The hybrid metal-core/dielectric-cladding microfibers that we used (Fig. 5), manufactured within the ORC [8], have copper core and borosilicate cladding with diameters of 2μm and 25μm, respectively. The nanowires are excited by coupling light of 671nm into the silicate enclosure. As expected we observe two peaks in the 2D beam profile at the copper/silica interface for the fundamental mode (Fig.6). The two observed peaks correspond in good agreement to the illustrated modelled mode profile. In order to obtain the beam profile we used a 60x objective lens to image the near-field intensity distribution at the fiber output and a scanning slit optical beam profiler.

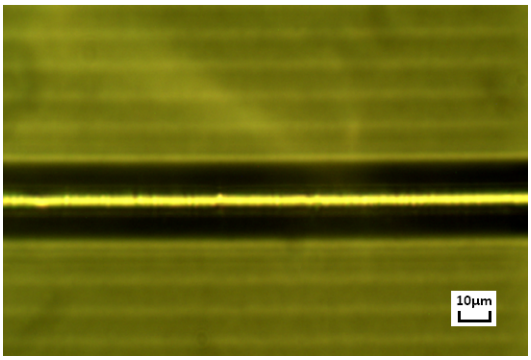

Figure 5. Microscope image of copper core micro-wire with borosilicate cladding.

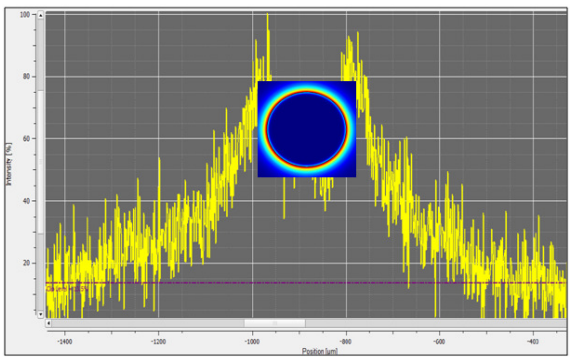

Figure 6. Beam profile of a hybrid microfiber and the corresponding modelled TM_{01} mode profile.

3.1. Tapering process

The microfiber was tapered with the method of heating and stretching [9]. Two linear stages stretch the microfiber while a third one moves the flame along the fiber axis (Fig. 7). Due to the low melting point of copper the fast and cold method was used in order to avoid the breakdown of the microfiber. The final waist radius of the copper core and the final waist length was 200nm and 13mm, respectively (Fig. 8).

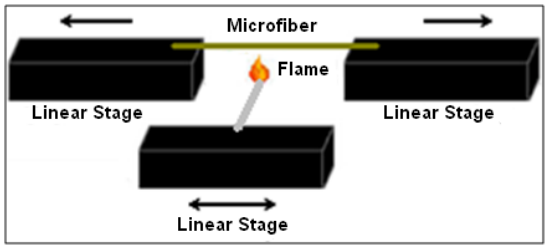

Figure 7. Schematic representation of the fiber tapering rig.

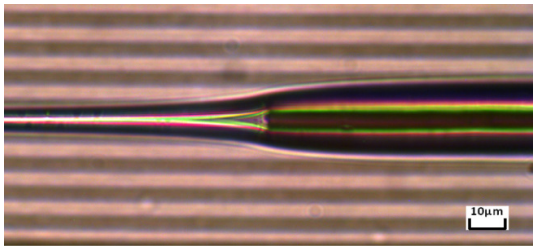

Figure 8. Microscope image of a tapered microfiber after the end of the tapering process.

4. Conclusions

The demonstrated results suggest that the hybrid copper-core/dielectric cladding microfibers are a very promising platform that can provide high field enhancement and confinement. The field enhancement expected at the apex of these tips is $E_f \sim 1.1 \times 10^4$ at λ=837nm making their use for sensing applications feasible. Their advantage over bare metal tips used is their low loss due to multiple reflections at the borosilicate/air interface that can provide higher intensities at their apex. We were able to taper them down to a core radius of 200nm using the heating and stretching method. Further research is ongoing for the optimization of the tapering conditions in a variety of metal-silicate composite systems, in order to achieve uniform and extremely thin tapered microfibers with optimised field enhancement.

Acknowledgements

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