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Toward plasmonic control of light propagation in an optical fiber

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ABSTRACT

The objective of this study was to control the transmission, dispersion and, eventually, the nonlinearity of an optical fiber by intercepting and manipulating the evanescent field extending from the core to the cladding with a variety of plasmonic and metamaterial nanostructures. The access to evanescent waves is enabled by placing the core close to the flat surface of the cladding in the so-called D-shaped fiber design. In the first phase of the project, reported here, the numerical simulations of D-shaped fibers with deposited metal (Au) have been performed. We, furthermore, demonstrated that the fiber transmission can be controlled by highly concentrated rhodamine 6G molecules deposited onto the fiber's flat surface.

Keywords: Transmission, Dispersion, Nonlinear, Plasmons, Metamaterials, D-shaped Fiber, R6G etc.

1. INTRODUCTION

In the last two decades, it has been repeatedly demonstrated that the strong light-matter interactions in composite metal-dielectric devices, mediated by localized and propagating surface plasmons, open new scientific and technological avenues [1],[2]. Surface plasmon polaritons (SPPs) are electromagnetic surface waves propagating at the interface between metal and dielectric, coupled with oscillations of free electrons in metal. These plasmonic waves are strongly confined to the metal-dielectric interface, enabling high-precision control and enhancements of electric fields, which are essential for many linear and nonlinear photonic devises.

Merging plasmonic and optical fiber technologies has been studied previously mainly for sensing applications, leaving novel device opportunities yet to be explored [1]. The present study is aimed at merging the two fields to form a new paradigm of tailoring optical complex transmission functions to plasmonic fiber segments for controlling short pulses in laser systems front-end. The basic proposed design is a thin metal or dielectric layer deposited on the flat surface of a D-shaped fiber segment. Modification of the structural properties of the metal or dielectric layer and its distance from the core controls the coupling between the plasmonic mode and the fiber core modes. In this structure, the core-guided mode coupled to the metal or dielectric supported plasmonic mode can be affected by reducing the distance between the core and the flat surface of the D-shaped fiber. At the frequency of enhanced coupling to the plasmonic mode, the attenuation of the propagating mode would be enhanced, resulting in a notch filter. This basic configuration sets the infrastructure for controlling the optical properties of the plasmonic fiber and the in/out coupling to this fiber segment.

In the study presented below, two sets of tasks have been performed in parallel: (i) numerical simulation of light propagation in D-shaped optical fibers with deposited plasmonic metal (Au), (ii) experimental demonstration of the notch filter functionality. Merging these two components as long as the fabrication of a D-shaped fiber is the subject of the future work to be published elsewhere.

2. NUMERICAL SIMULATIONS

The computer simulations of D-shaped fiber have been performed using the COMSOL software. The two-dimensional configuration of the structure is shown in Fig. 1 (left). Figure 1 (right) shows the mesh generated by the COMSOL simulator.

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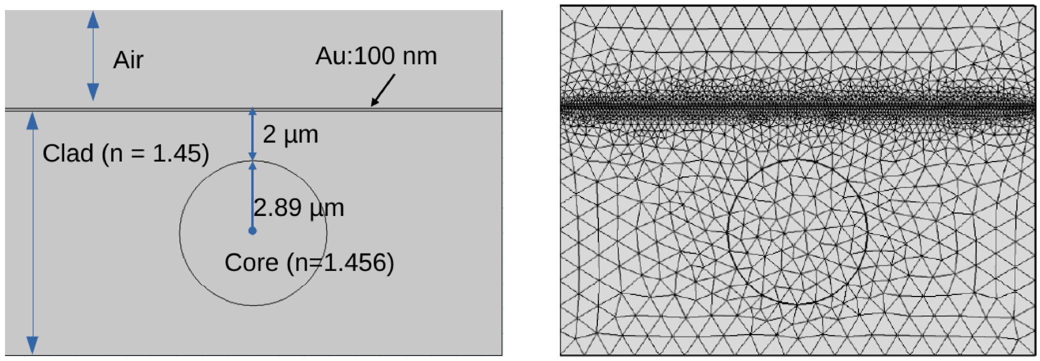


Fig. 1. Schematic of simulated structure (left) and the mesh generated for simulation (right).

We have performed modal analysis of the structure at wavelength λ= 1 µm. The samples of the modes in normalized electric fields are shown below. We do see the excitation of fundamental LP02 (left panel in Fig. 2) and higher order modes LP11 with x and y-polarization (center and right panels in Fig. 2).

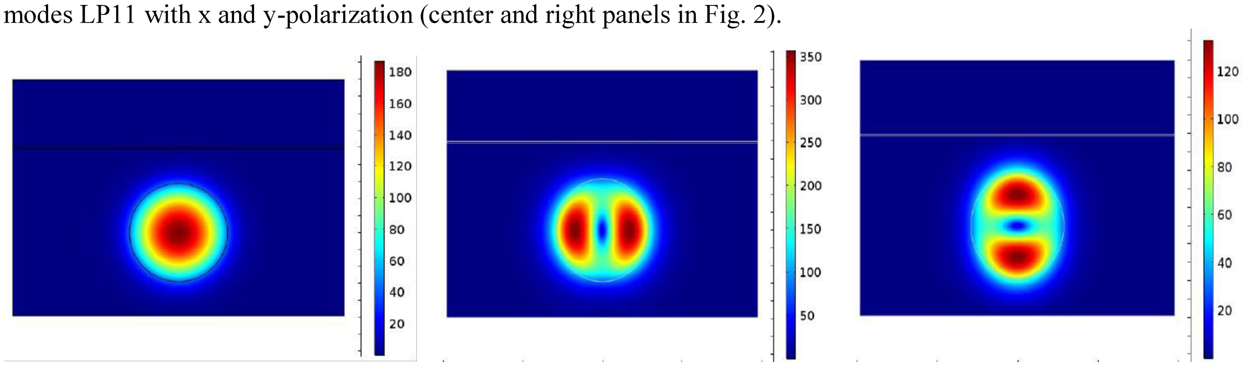


Fig. 2. Fiber modes: LP02 (left), LP11 x-polarized (center), LP11 y-polarized (right).

We have extended this study to 3D configuration where the propagation of modes and its coupling to the gold layer can be analyzed.

Three-dimensional analysis

The parameters of this study are shown below:

Wavelength	2 µm
Refractive Index of Core	1.456
Refractive Index of Cladding	1.45
Radius of Core	2.89 µm
Gap between core and cladding	5 - 8 µm
Thickness of Au layer	1 µm
Length of the structure	500 µm
Au index of refraction @ λ = 2µm (data from nanohub.org)	n_r = 0.8488 n_i = 12.596

The geometry of the structure in Finite-Element mesh is shown in Fig. 3.

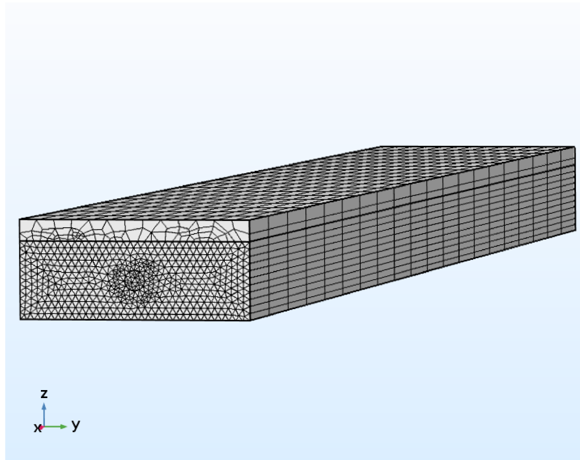


Fig. 3. 3D COMSOL mesh of the D-shaped structure.

Field components

Figure 4 shows the distribution of the electric field components E_X (Fig. 5 left), E_Y (Fig.5 center) and E_Z (Fig. 5 right) for the gap size of 8 µm. We see that only E_Z (right panel in Fig. 5) component is significantly noticeable.

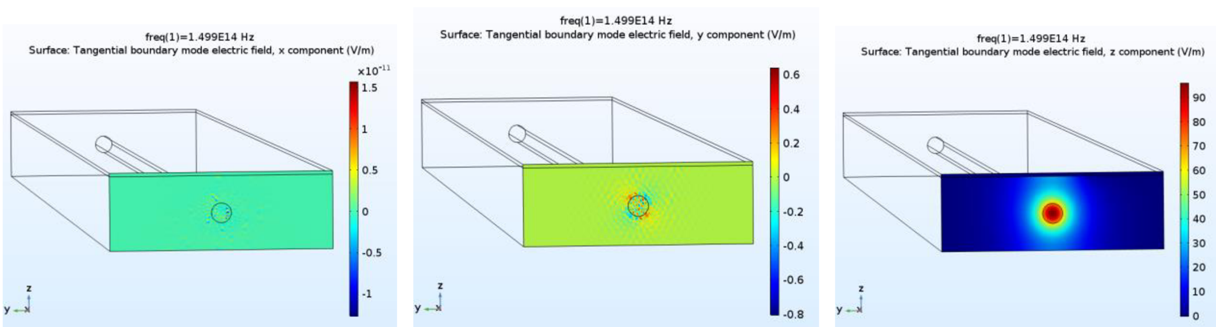


Fig. 4: Electric field components E_X (left), E_Y (center) and E_Z (right).

Coupling for different gap sizes

The electric field coupling to the metal for two different 'gap' sizes of 5 µm (left panel) and 8 µm (right panel) are shown in Fig. 5. Figure 5 (left and right) illustrate the surface distribution of the E_Z field component. It is important to note that the strength of the field in the core of the fiber reduces as the gap size is getting smaller. The electric field strengthens near the metal interface.

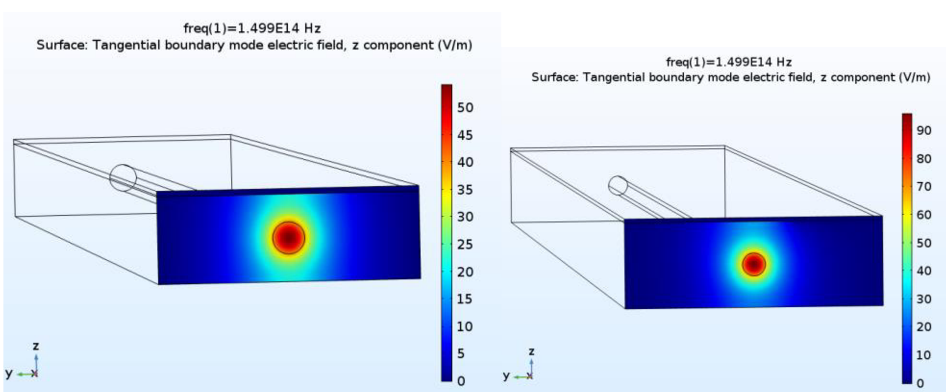


Fig. 5: Electric field coupling to the gold layer of thicknesses 5 µm (left) and 8 µm (right).

A comparison of the normalized electric field for gap sizes 5 µm and 8 µm is illustrated in Fig. 6.

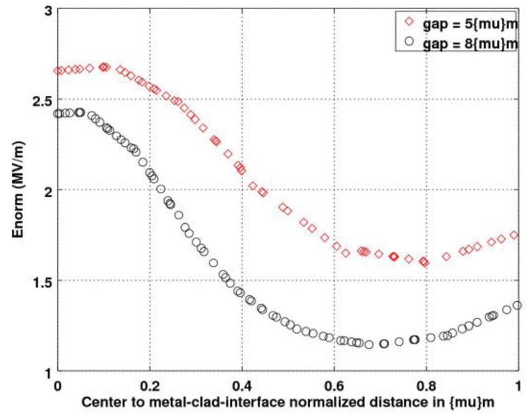


Fig. 6. 1D plot of normalized electric field for gap sizes 5 µm and 8 µm.

The electromagnetic power loss is mainly concentrated near the metal as shown in Fig. 7.

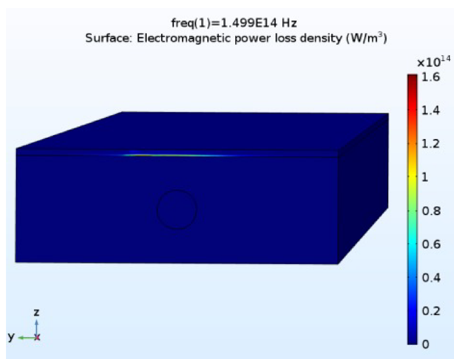


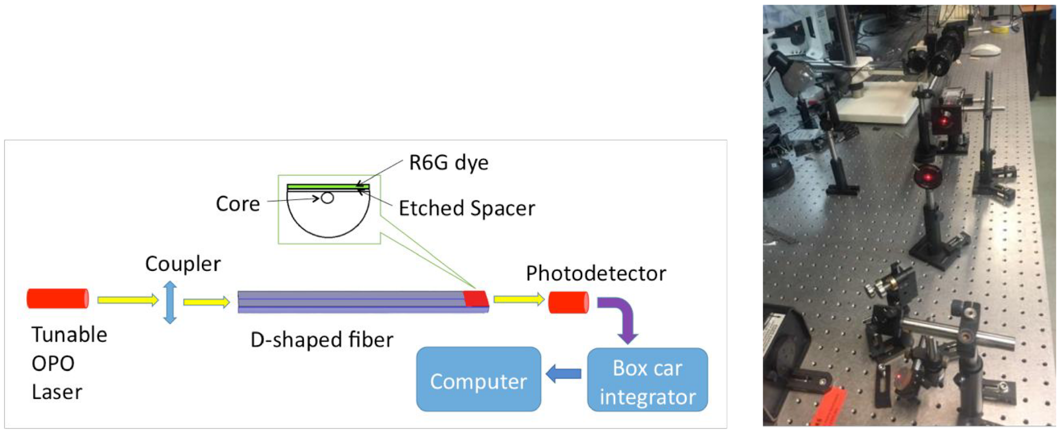
Fig. 7: Electromagnetic power loss density.

3. OPTICAL MEASUREMENTS

The D-shaped fiber in our studies was Side Polished Optical Fiber (Model: SPF-C-Sm-0-30mm, Serial: SPF-49161) from Phoenix Photonics. According to the specs, the spacer thickness (the distance between the core and the flat polished surface) was between 1 µm and 2 µm. The core had the diameter 8.2 µm and the refractive index 1.4682. The cladding had the diameter (before polishing) 125±0.7 µm and the refractive index 1.4468. The fiber was coated with the Corning's enhanced, dual acrylate CPC protective coating (removed from the polished side) with diameter 245±5 µm.

Using the air-to-fiber coupler (Model: F-1015, Newport), we were able to propagate through the core of the fiber 48% of radiation of the CW 632.8 nm HeNe laser. The quality of the beam of the nanosecond OPO laser (Panther III from Continuum) was rather poor and the fraction of the incident light coupled to the core of the fiber was smaller. In order to investigate the functionality of the D-shaped fiber filter, we first recorded the transmission spectrum of the neat fiber by tuning the OPO laser between 470 nm and 630 nm, in the setup depicted in Figs. 8a and 8b. After that, we deposited (in situ) the R6G dye onto 15 mm segment of the D-shaped side of the fiber and repeated the measurement. (The dye was dissolved in Methylene dichloride in concentration 90 g/L and deposited onto the fiber using the pipet.) When the transmission spectrum measured in the fiber with the dye was normalized by that in the fiber without the dye, we did not see any spectral feature that could be attributed to the absorption of the R6G dye (compare Fig. 9 and brown trace in Fig. 10). We then etched the fiber's cladding and, in particular, it's polished side (also in-situ), in the solution containing 0.25 gram of NH_4F per cubic centimeter of a 49% aqueous HF acid solution. The reduction of the transmitted light intensity as the function of the etching time is shown in Fig. 11. The etching was stopped at ~80 seconds, when the intensity of the transmitted light decreased by approximately

30%. After that, we (i) measured the transmission spectrum (without dye), (ii) deposited R6G dye on the flat surface and (iii) retaken the transmission measurements (with dye). In this experiment, the normalized transmission spectrum showed the band (at ~540 nm) that is characteristic of the absorption spectrum of a highly concentrated R6G dye (see blue trace in Fig. 10). Therefore, we have demonstrated that dye (and potentially a plasmonic structure) deposited onto the flat surface of the D-shaped fiber can control fiber's transmission.



(a) (b)

Fig. 8. Schematics (left) and photograph (right) of the experimental setup.

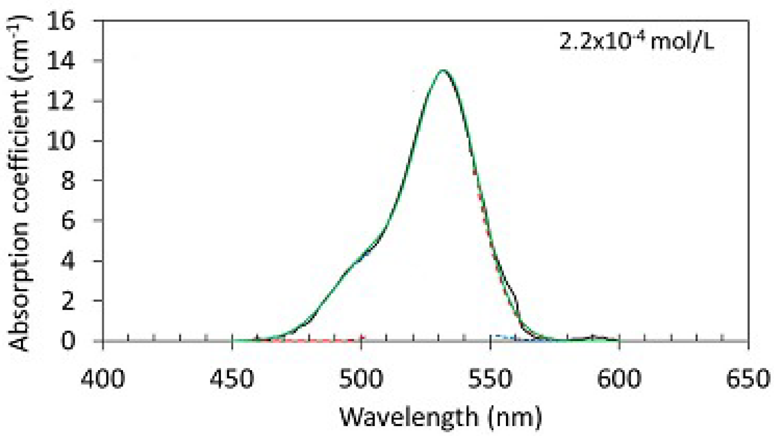


Fig. 9. Absorption spectrum of Rhodamine 6G (R6G) dye of concentration 2.2x10^{-4} mol/L in PMMA[5].

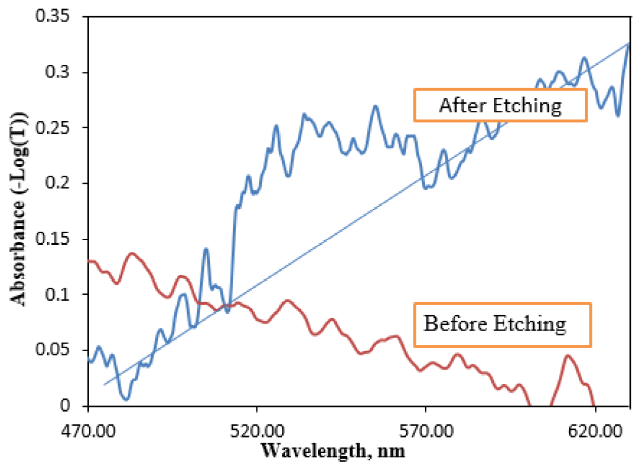


Fig. 10. Absorbance spectrum of the D-shaped fiber with deposited R6G dye before etching (brown trace) and after etching (blue trace). (Transmission of the fiber with dye was normalized by that without dye.)

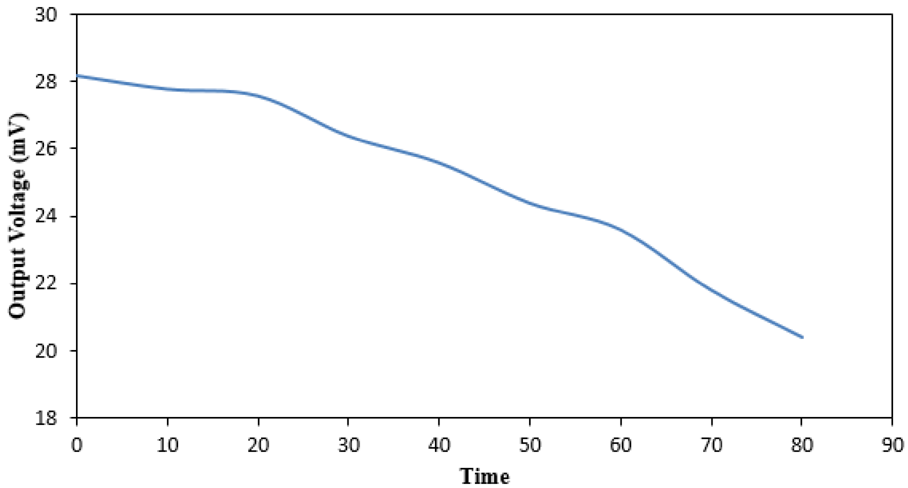


Fig. 11. Reduction of the light intensity transmitted by the fiber as the function of time, in the process of in situ etching.

4. SUMMARY

The aim of this study was control of light propagation in D-shaped fiber by plasmonic structures deposited on the fiber's flat surface. In the first phase of this research, we (i) numerically modeled light propagation and attenuation in the fiber, (ii) demonstrated functionality of a notch filter (using R6G dye as absorbing medium). These promising results warrant detailed comprehensive studies of the plasmonic D-shaped optical fibers.

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