Novel Sensor Concept Based on Microstructured Optical Fiber with Metal Inclusions

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Abstract

We propose surface-plasmon-resonance sensor design based on suspended-core optical fiber with gold inclusions. Auxiliary dielectric layer is considered to provide tunable loss level and single-mode operation.

Introduction

Recently, Sazio *et al*. [1] demonstrated that high-pressure deposition techniques can be used to coat the hole surfaces of a microstructured optical fiber (MOF) with a variety of materials. In particular, with metal inclusions [2,3], the MOF can act as a compact surface-plasmon-resonance (SPR) sensor device for an analyte infiltrated into the fiber pores. The refractive index of the analyte can be retrieved either by measuring the transmission spectrum of the sensor fiber or by monitoring the transmitted power at certain wavelength.

In this paper, we propose a SPR sensor design based on coating the inner surfaces of a suspended-core MOF with gold. Besides making the gold directly contact the fiber surface, we also consider the use of an auxiliary low-index dielectric layer sandwiched between the MOF and the gold layer to provide tunable transmission losses and single-mode operation.

Sensor design and modeling

We start by considering a suspended-core silica MOF, such as the one shown in Fig. 1(a). We assume that the hole surfaces are covered with a low-refractive-index dielectric layer of thickness *s* on top of which a gold layer of thickness *d* is deposited. The parametrization of the design is illustrated in Fig. 1(b).

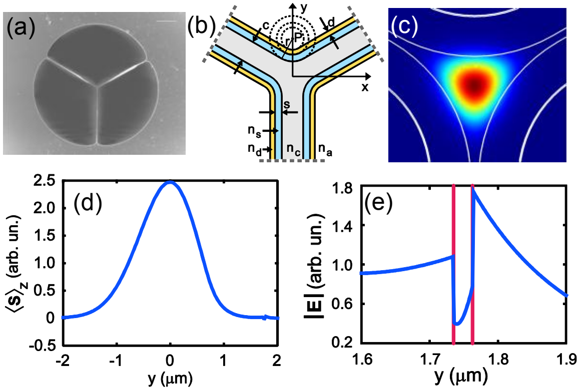

Figure 1: (a) Suspended-core fiber [4]. (b) Parameters of the proposed sensor fiber. (c) Example mode profile (power flow along the fiber). (d) Mode profile along the vertical axis. (e) Close-up of the field amplitude in the vicinity of the gold layer.

The center of curvature dictating the core shape (point *P*) is taken to shape the coated layers as well [1]. The parameters *s*, *c*, and *d* denote the thickness of the low-index layer, the core strut, and the gold layer, respectively. The corresponding refractive indices are denoted with n_s, n_c, and n_d, respectively. Lastly, we assume that the fiber holes are filled with an aqueous analyte of refractive index n_a.

We solve the electromagnetic mode of the sensor fiber with the finite element method (FEM) by using COMSOL Multiphysics [5]. To establish the plasmonic character of the fundamental mode, we consider its spatial profile exemplified in Fig. 1(c). Here, the values λ = 530 nm, n_c = 1.46, n_s = 1.44, n_a = 1.33, and *s* = 1 µm are used along with the geometry parameters *r* = 4 µm, *d* = 30 nm, and *c* = 200 nm. For the dielectric function of gold, we use the tabulated values with linear interpolation. The vertical cut of the plot in Fig. 1(c) is shown in Fig. 1(d), and the close-up of Fig. 1(e) reveals the characteristics of plasmon excitation at the metal-analyte interface. We characterize the modal loss due to plasmon excitation by considering the attenuation constant $\alpha = 2k_0\mathrm{Im}(n_{\mathrm{eff}})$ of the mode. Here, k_0 and n_{eff} denote the free-space wavevector and the effective index, respectively.

Results

We first vary the thickness parameter *s* and show that the plasmon amplitude and thus the overall loss of the sensor can be tuned to a tolerable level at will. This is exemplified in Fig. 2 where the values n_a = 1.33 and n_a = 1.34 are used for the analyte refractive index to assess the refractive-index resolution of the device. The peak wavelength and the analyte-dependent shift in the resonance peak, $\Delta\lambda_{\mathrm{peak}}$, are identical for all values of *s*. Thus, the thickness-parameter *s* lends itself well to exclusively controlling the overall loss.

If the refractive index of the core is varied, as in Fig. 3, both the peak wavelength and the analyte-dependent shift $\Delta\lambda_{\mathrm{peak}}$ will change. Here, we have fixed the parameter *s* = 1.5 µm. The peak shift is at its strongest when the parameter n_c is in value close to n_s. Besides improving the resolution, such a small index contrast will also limit the number of

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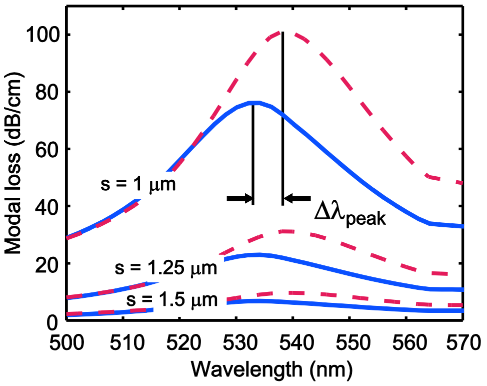

Figure 2: Modal loss α as a function of wavelength for two analytes with refractive indices n_a = 1.33 (solid) and n_a = 1.34 (dashed) when the dielectric layer thickness is varied.

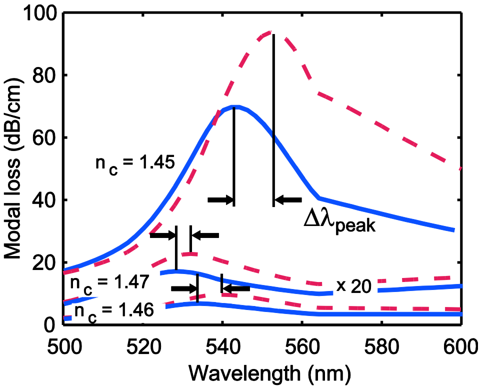

Figure 3: Modal loss α as a function of wavelength for the two analytes when the refractive index of the core is varied; data for the largest index is magnified by a factor of 20 for clarity.

core-confined modes. To estimate the required core dimension for single-mode guidance, we crudely approximate our sensor waveguide with a conventional step-index fiber that has an index contrast equal to $\Delta n = n_c - n_s = 0.01$. In such a case, the effective core radius, calculated through the V parameter, would have to be smaller than 1.1 μm. The dimensions of the sensor fiber considered above are on this order.

We have also investigated the possibility of having the gold layer directly on a silica MOF. Correspondingly, we set $s = 0$ and choose the core dimensions to be much larger than above to reduce the overall loss level. Figure 4 shows the plasmon resonance curves for the fundamental mode obtained with the parameters r = 11 μm and c = 2 μm. Here, we have used the Sellmeier equation to take into account the material dispersion of silica. According to our investigations, with large enough core dimensions the overall loss level can be made reasonably low, although higher-order modes might be introduced.

We estimate the resolution of the proposed sensor devices as follows. If one assumes that a 0.1-nm shift in the resonance peak of the spectrum can reliably be detected, the refractive-index resolution of the device will be 1×10^{-4}. A similar figure is obtained by assuming that a 1% change in the transmitted power at a selected wavelength can reliably be detected.

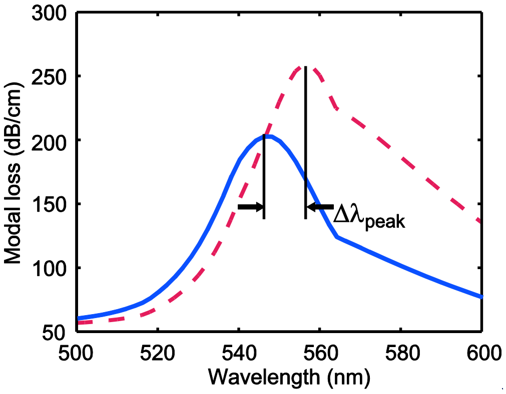

Figure 4: Modal loss α as a function of wavelength for the two analytes without the auxiliary dielectric layer.

Conclusions

We have proposed a novel surface-plasmon-resonance sensor design based on a suspended-core MOF with a dielectric layer and a gold layer. The presented approach has the following advantages. First, we have shown that the gold layer can be made to directly contact the silica fiber for sensor applications. Second, if the auxiliary dielectric layer is used, the loss level can be tuned and the sensor can be made to operate in a single Gaussian mode. Third, the holes of the suspended-core MOF can be tens of micrometers in diameter, which should facilitate the fabrication of the sensor structure and the infiltration of the analyte. Finally, the refractive-index resolution of the proposed sensors is on the order of 10^{-4}.

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References

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