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Optimization of ITO-Based Plasmonic Slot Waveguide for CO_2 Mid-IR Absorption Sensors

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Summary:

In this work, an ITO-based plasmonic slot waveguide is numerically analyzed for CO_2 sensing applications. Our waveguide is designed based on Indium Tin Oxide on a silica substrate layer. As for sensing application both evanescent field ratio and propagation length play an important role, our structure is optimized based on the figure of merit defined by the product of the two aforementioned quantities. From our simulations, the optimum parameters for slot width and height of 500 nm and 1100 nm were obtained, respectively, based on this figure of merit.

Keywords: Plasmonic waveguide, ITO, sensing application, mid-infrared region, figures of merit

1- Introduction

Plasmonics has reached great attention due to enabling sub-wavelength photonics applications. The existence of surface plasmon polaritons (SPPs), which are the guided electromagnetic waves propagating along metal/dielectric interfaces with strong near-field confinements, allows for high light-matter interactions [1]. Traditionally, noble metals are widely used as plasmonic materials due to their chemical stability. However, they suffer from high intrinsic loss hampering practical applications. Transparent conductive oxides (TCOs) such as Indium Tin Oxide (ITO) can be good alternatives to replace noble metals. They not only show low loss in the infrared range but also indicate CMOS compatibility making them specifically appealing for easy integration of plasmonic devices. In this work, to the best of our knowledge, we propose a plasmonic slot-waveguide sensor platform using ITO for the first time, as illustrated in Fig. 1.

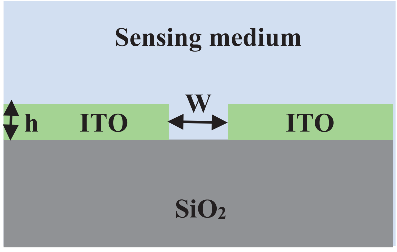

Fig. 1. The cross-sectional view of ITO-based plasmonic slot waveguide.

Our waveguide structure is designed for a wavelength of 4.26 µm, which corresponds to the absorption peak of CO_2. Two µm silica with a refractive index of 1.38 is considered as the substrate layer. ITO with a refractive index of -28.2+21.7i is placed on the top of the silica, and a small slot etched downward to form the waveguide. The sensing medium is assumed to be air. The modal properties of the proposed structure have been investigated using finite element method (FEM) implemented by COMSOL Multiphysics.

2- Results and discussions

2-1 Propagation length

The propagation wave vector of an SPP bounded mode at the metal/dielectric interface is given by [2]:

$$K_{SPP} = K_{re} + iK_{im} \qquad (1)$$

where K_{SPP} is the SPP wave vector. The propagation length of the SPP mode is given by:

$$L_{SPP} = \frac{1}{2K_{im}} \qquad (2)$$

The SPP mode on a metal/dielectric interface propagates but, owing to the presence of metal or metal-like material, gradually starts to attenuate. The propagation length of the fundamental mode of the structure as a function of ITO thickness (h) is indicated in Fig. 2 for different slot widths (w). Increasing both w and h results in an increase of the propagation length. This is due to the fact that the absorption loss in ITO reduces with the increasing w and h.

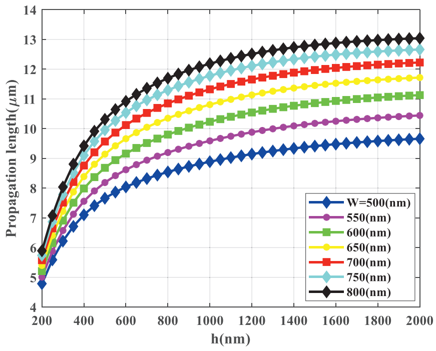

Fig. 2. The propagation length of fundamental mode as a function of h for different w.

2-2 Evanescent field ratio (EFR)

For sensing applications, the EFR plays a key role because it indicates the amount of fraction of electromagnetic field interacting with the surrounding gas. When the waveguide is surrounded by a gaseous analyte, which thus essentially forms the cladding of the waveguide, the evanescent field interacts with the gas by virtue of being absorbed by the gas. As a result, the transmitted light is attenuated at the absorption line of CO_2. The EFR is defined as the fraction of transmitted intensity in the gas to the total modal intensity:

$$EFR = \frac{\iint_{Gas} \varepsilon\left(E_x^2+E_y^2+E_z^2\right)dxdy}{\iint_{All} \varepsilon\left(E_x^2+E_y^2+E_z^2\right)dxdy} \qquad (3)$$

where E shows the electric field and ε indicates permittivity of each material and the integration is performed in the cross-sectional (xy) plane. Fig.3 presents the EFR of the fundamental mode of the proposed structure. It indicates that increasing w will lead to lower EFR. The reason is that, as the gap size increases, a part of the mode leaks into the silica results in decreasing the EFR.

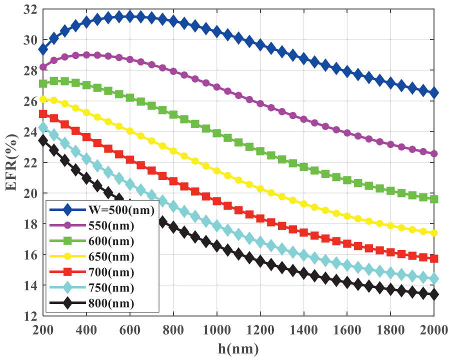

Fig. 3. EFR of fundamental mode as a function of h for different w.

As both EFR and propagation length are crucial for sensing applications, we introduce a figure of merit (FOM), which is defined as:

FOM = EFR × propagation length (4)

The optimization of our waveguide geometries based on this FOM is plotted in Fig. 4. It is observed that the maximum FOM occurs at 500 and 1100 nm for w and h, respectively corresponding to roughly 9 um propagation length and 30% EFR.

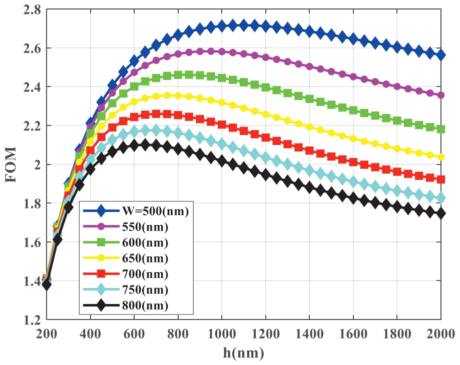

Fig. 4. FOM of fundamental mode as a function of h for different w.

The absolute value of electric field distribution (E_x) of SPP mode for the optimum values of the structure is depicted in Fig. 5 where it can be clearly observed that most of the mode is confined in the slot region, although a part of it leaks into the silica substrate.

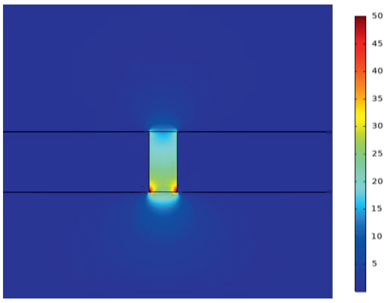

Fig. 5. The absolute value of electric field distribution (E_x) of SPP mode for optimum values of the structure.

3- Conclusion

An ITO-based plasmonic slot waveguide for the CO_2 sensing application was numerically investigated and optimized based on the figures of merit. The optimum parameters of 500 and 1100 nm for slot width and metal thickness were obtained, respectively.

Acknowledgment

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