Coupling efficiency enhancement between SU-8 waveguides and plasmonic nanostructures through indium tin oxide thin films

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***Abstract* — We present an optical analysis of the light coupling between a SU-8 polymer waveguide and a nano-cylinder surface array, for biosensing applications with scattering-induced fluorescence. The coupling efficiency was studied in the 490-590 nm range using Finite Difference Time Domain (FDTD) method and scattering theory. We modeled thin films of indium tin oxide (ITO) buffer layers with different thicknesses to evaluate the behavior of the device in a sandwich configuration. We found that ITO enhances the waveguide-array coupling efficiency up to 5 times.**

Keywords — FDTD, plasmonic nano-array, SU-8 waveguide, indium tin oxide, BK7 glass, gold nano-cylinders.

I. Introduction

Plasmonic nanostructures have been extensively researched for their role as enhancers of phenomena such as fluorescence, Raman scattering, and dichroism, due to the several potential applications in sensing for Biology and Chemistry [1-3]. Among the various measurement setups, integrated optics may enable multiple advantages, such as low energy, use of little reagents consumption, and lower costs in large-scale production [4]. Some of the authors published a solution where a plasmonic nano-array was positioned upon a low-index contrast, ion-exchanged glass waveguide, showing a control over far-field radiation. This structure has promising applications in integrated optical setups for fluorescence and Raman spectroscopy that can be engineered by changing the nanostructures features [5]. Such approach may require a fine tuning of the amount of interaction between waveguide signal and metallic elements. In this work, we numerically investigated the use of indium tin oxide (ITO) as a buffer layer between plasmonic nano-array and a low-index SU-8 polymer waveguide, to achieve control over the amount of waveguide-array interaction. More specifically, we studied the effect in the coupling efficiency of gold nano-cylinders arrays placed upon an ITO thin film, powered by the evanescent fields of light propagating through an underlying low-index waveguide. The analysis was mainly operated through Finite Difference Time Domain (FDTD) method, combined with mathematical calculations.

II. Structure under Analysis

The proposed structure is based on a 5µm-thick and 5µm-wide SU-8 polymer waveguide (with refractive index n=1.59 at the wavelength λ=540 nm) on a BK7 glass substrate (n=1.52 at λ=540 nm) immersed in water (n=1.33 at λ=540 nm). An array of gold nano-cylinders is placed onto the waveguide. The nano-array covers a 100µm-long path, for a total surface coating of (5·100) µm^2. The nano-cylinders present a thickness of 250 nm and a radius of 50 nm. The array pitch is 250 nm. An ITO thin film (n=1.87 at λ=540 nm) is placed between the waveguide and the nano-array as coupling enhancer. Figure 1 depicts such configuration.

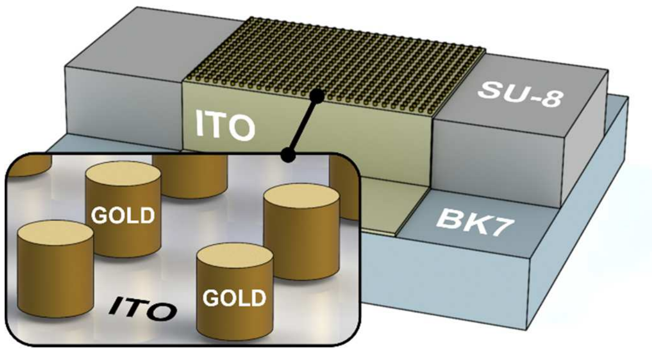

Figure 1: Schematic view of the structure under analysis. The inset shows the detail of the gold nano-array.

III. Simulated Model

The structure was numerically analyzed with and without the gold nano-array, supposing different thicknesses for the intermediate ITO film. Solutions for the electromagnetic field were searched for Maxwell's equations, with an excitation source in the visible spectrum (from 490 nm to 590 nm), using a 3D-FDTD simulation model. Figure 2a schematically depicts the longitudinal section of the 3D simulated model. Figure 2b and Figure 2c show the optical power flowing in the waveguide along the longitudinal section and through a cross section of the model, respectively. These results show part of the light coupled to the ITO/nano-array structure.

The coupling efficiency between the SU-8 waveguide and the plasmonic nano-array was then calculated, taking into account the geometries under analysis and the different losses which can take place in a waveguide. The difference between the input guided power P_{in} and the output guided power P_{out} can be considered as:

$$P_{in} - P_{out} = P_{guide} + P_{ITO} + P_{array} + P_{scat} \qquad (1)$$

The input guided power is partially lost in the waveguide material (P_{guide}) and into the ITO layer (P_{ITO}), scatters from the ITO film (P_{scat}), and is absorbed/scattered by the nano-array (P_{array}). In our analysis, P_{guide} and P_{ITO} resulted to be negligible, due to the optical transparency of both ITO and SU-8 in the visible spectrum [7]. Moreover, P_{scat} was found very small (corresponding to propagation losses of about 10^{-4} dB/cm), due to the small ITO thickness compared to the waveguide.

Since our study focuses on the waveguide/array interaction, we ascribed the input-output power decrease to the optical power coupled from the SU-8 waveguide to the gold

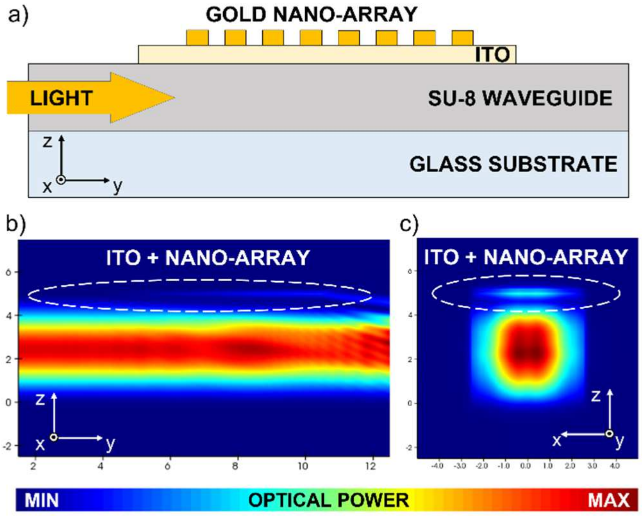

Figure 2: (a) Simulated model structure, longitudinal section (not in scale). (b) Optical power flux along the longitudinal section. (c) Optical power flux through the cross section.

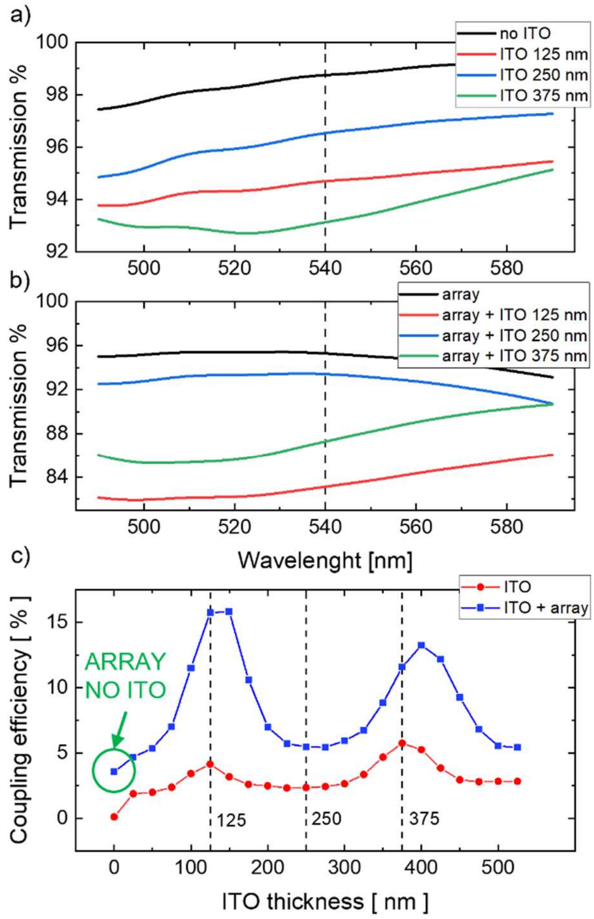

Figure 3: Light transmission out of the SU-8 waveguide vs wavelength for different ITO thicknesses (a) without or (b) with the array of nano-structures. (c) Coupling efficiency vs ITO thickness at 540 nm with (blue) or without (red) the gold nano-array.

nano-array. The coupling efficiency was then derived from the normalized difference between the optical power fluxes calculated before and after the light flow underneath the 100µm-long ITO/nano-array coating:

$$Coupling\ efficiency\ [\%] = \frac{P_{in} - P_{out}}{P_{in}} \cdot 100 \qquad (2)$$

IV. Results

The percentage of the transmitted input power to the output of the structure in the 490-590 nm range, with different ITO film thicknesses, without or with the gold nano-array are reported in Figure 3a and 3b, respectively: the presence of the nano-array reduces significantly the transmitted power. The ITO film plays a major role in enhancing this power decrease. Figure 3c plots the coupling efficiency at 540 nm wavelength for different ITO thickness, with (blue curve) or without (red curve) the gold nano-array. Here, the sole presence of the nano-array (corresponding to the blue curve at 0 nm ITO thickness) leads to a coupling efficiency of about 3%, whereas a 125 nm-thick intermediate ITO layer rises the efficiency up to 16%, enhancing coupling efficiency more than 5 times. Moreover, the sole ITO 125 nm-thick film corresponds to a coupling efficiency of about 4%: by adding the gold nano-array, it reaches 16%, with a 4-time increase. Furthermore, a similar logic is displayed for the 375 nm-thick ITO film. This cyclic behaviour, with a period corresponding to about half of the wavelength of the excitation light, is in agreement with previous results [6].

V. Conclusions

A sandwich structure composed by a SU-8 polymer waveguide coated by ITO and a gold plasmonic nano-cylinder array was modelled and the waveguide-array optical coupling was studied by means of FDTD in the visible wavelength spectrum. The results showed how the ITO/nano-array combination can achieve up to a 5-time enhancement of coupling efficiency with respect to a standard waveguide-array configuration. The reported results encourage further developments, being such configuration less expensive and easier to fabricate when compared to conventional, silicon-based structures [4]. Results showed how the ITO thickness represents a crucial parameter, together with the nano-array geometry, for the fine tuning of the optical power transfer from optical channels to plasmonic structures, for applications in the field of integrated scattering-induced fluorescence [8].

Acknowledgments

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