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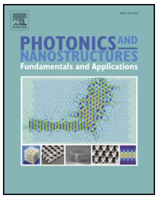

Invited Paper

Plasmonic nanostructures with waveguiding effect

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ABSTRACT

A mutual coupling of a surface plasmon polariton (SPP) with an optical mode excited in a planar waveguide (WG) is discussed. A planar layered structure is studied consisting of a coupling prism, an Au film and a high-index interlayer for SPPs generation, and a dielectric waveguide composed of a ferromagnetic garnet on a (CaMgZr)-doped gallium–gadolinium garnet substrate (GGG) separated by an air gap. The dependence of coupling resonances on the gap thickness and the interlayer refractive index is analyzed to obtain an optimal field intensity enhancement for future designs of plasmonic and magneto-plasmonic sensing elements.

1. Introduction

The coupling of resonance states in various optical nanostructures referred as the optical Fano effect offers many promising ways for the development of new photonic devices. Optical structures exhibiting this phenomenon produce strong resonances that induce enhanced electromagnetic fields and thus have a considerable application potential. This expectation follows the recent results obtained for coupled modes occurring in peculiar plasmonic metal-dielectric nanostructures [1–3]. Also, the effect of coupling between surface plasmon polariton and a waveguide mode has been widely investigated [3–6].

In this paper, we present several theoretical results obtained for the Fano line shapes in a planar multilayer system based on concatenation of the Kretschmann type plasmon-generating system (coupling prism/Au-film/dielectrics) with a dielectric planar waveguide (PWG) containing a ferromagnetic waveguide layer. Since the air gap separating given sub-structures is not sufficient to obtain mutual coupling, embedding of an appropriate interlayer is needed, the material and thickness of which are specified below in our simulations. Furthermore, the roles of waveguide geometrical parameters as well as the effect of coupling intensity controlled by the air gap thickness are analyzed. The sensing ability of the proposed system is tested by a change in the refractive index of water through monitoring of the Attenuated Total Reflection (ATR) response via reflectometric outputs. The basic idea here is that when employing a medium with induced anisotropy, which is in our case magnetically induced anisotropy in bismuth-doped gallium–gadolinium iron garnet (Bi:GIG), one can introduce a pilot (trigger) frequency into the signal (i.e. the reflectivity spectrum) by modulating the external magnetic field. This enables one to use the lock-in detection technique that, as a result, increases the sensors sensitivity significantly.

2. Optical Fano effect

2.1. SPP-PWG structure

Although planar waveguide/SPR sensor structures have been reported, coupling between the surface plasmon polariton and a guided mode has not been obtained. The reason is that when a planar waveguide is placed directly onto the surface of a metallic plasmonic layer, effective refractive index matching of SPP and waveguide modes is not possible, and so is not the wave coupling [5]. The optical Fano resonance as mutual interaction between waveguide and plasmonic modes can be initiated, besides other means, in an ATR structure with a coupling prism, where a noble metal layer allowing an SPP excitation is added onto a PWG structure (Fig. 1) using a suitable dielectric interlayer, thus obtaining a common acting of the both effects.

In our recent works [7,8] we discussed physical properties of Bi:GIG prepared on a gallium–gadolinium garnet (GGG) substrate. Refractive indices of these materials at the wavelength 633 nm ($n = 2.4619 - 0.0042i$ for Bi:GIG, $n = 1.9648$ for the GGG substrate) enable to analyze waveguiding properties of such a structure with an air-gap superstrate separating these two materials from the coupling prism. As the coupling prism must have a material with a relatively high refractive index, a rutile prism ($n = 2.584$ at the wavelength 633 nm) was used. The coupling interlayer (aluminium-doped zinc

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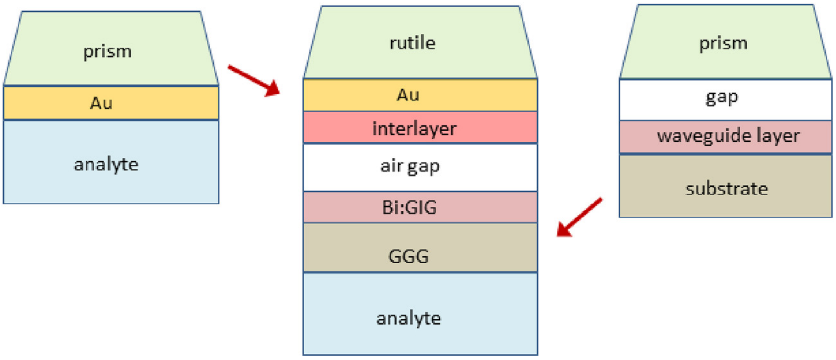

Fig. 1. SPP-PWG system scheme.

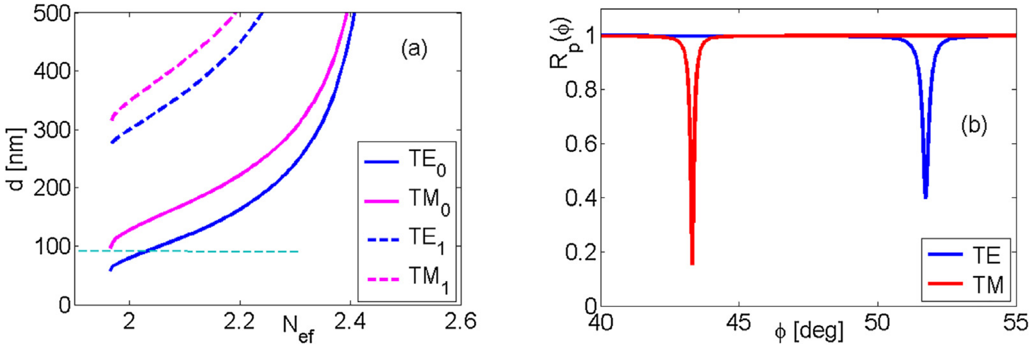

Fig. 2. Bi:GIG waveguide: (a) dispersion curves, (b) resonance dips of the TE_0 and TM_0 mode with thicknesses 0/80/120/100/100 (Au/interlayer/air gap/Bi:GIG/GGG).

oxide, AZO, $n_i = 1.8$) enables one obtain resonance angles related to the prism–multilayer interface, in this case around 45°.

Basic waveguiding properties are illustrated by dispersion curves of the zero- and the first-order modes shown in Fig. 2a. The working thickness of the waveguide, $d = 100$ nm, was chosen to be near the critical one for zero modes ($d_c = 96.9$ nm) in order to obtain only one resonance angle for TM_0 wave – see the resonance dips in Fig. 2b.

Here as well as in what follows the sequence of numbers denotes the inner layers thicknesses in the order Au/AZO/air gap/Bi:GIG/GGG between rutile prism and the water analyte. Introducing a null point indicates expresses a fact that the gold film is not present in this case. Adding a 44 nm Au film along with suppressing the waveguiding ability leads to an SPP response illustrated in Fig. 3a; thereby the penetration depth of a transverse magnetic evanescent wave into the air gap is around 150 nm at the SPR angle – see Fig. 3b.

2.2. Fano effect

The presence of both resonance minima demonstrated for the TM wave in Figs. 2b, 3a gives a rise of the Fano-like line shapes of the resulting reflection curves. The mutual coupling leads to a giant field enhancement shown in Fig. 4a.

The reflection response of the proposed SPP-PWG structure is affected by more factors. Since the material properties are given, we are concerned with the geometrical parameters. An increase in the substrate thickness leads to a shift of both resonance minima towards a larger incidence angles. The shift of the WG dip is greater that of the SPP's one; therefore, one observe its positioning from the left to the right side of the SPR minimum – see Fig. 4b, where the red Fano shape line is seen in Fig. 4a. The violet line corresponding to the thickness of 150 nm represents roughly a balanced state that we use as a reference for other cases. The proposed methodology demands of sufficiently sharp PWG minima. As the balanced resonance state leads to flattening of them (see the reflection dips demonstrated in the Fig. 5a) the

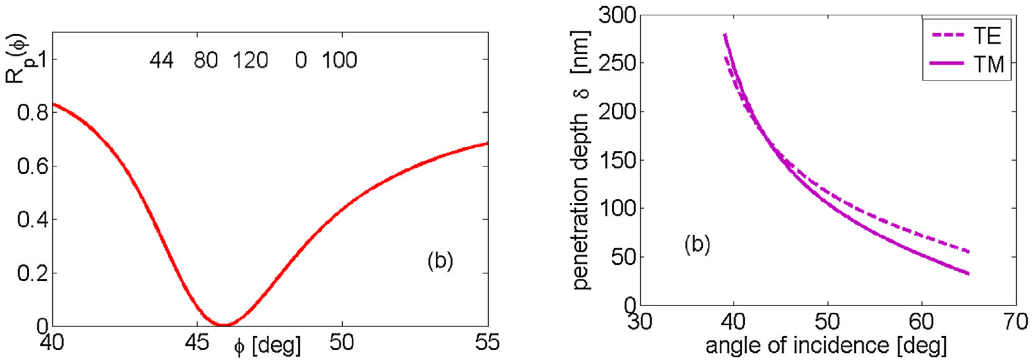

Fig. 3. SPR response: (a) SPR minimum, (b) penetration of evanescent wave into air gap.