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Mode conversion in asymmetric dielectric/metal/dielectric plasmonic waveguide using grating coupler

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ABSTRACT

Conversion of surface plasmon polaritons (SPPs) between the upper and under interfaces of an asymmetric dielectric/metal/dielectric (DMD) waveguide using a grating coupler has been investigated. The coupling efficiency of the under mode and the upper mode has been discussed. Various optical and geometrical parameters of the grating structure have been studied in detail and the related physical origins have been illustrated. Based on the Fabry–Perot resonance condition, a maximum coupling efficiency of more than 18% has been obtained at the optical communication wavelength, which could be devoted to the converter between the two modes for utilizing their respective specialty in plasmonic circuitry.

1. Introduction

Surface plasmon polaritons (SPPs), which originate from charge density oscillations coupled to the optical field, are transverse magnetic (TM) polarized optical surface waves that propagate along a metal-dielectric interface, typically at visible or infrared wavelengths [1]. In recent years, plasmonic circuitry has been drawing increasing attention from researchers, because integrated plasmonics combines merits of electronics and photonics, i.e., the compact size of electronics and the high speed of photonics [2]. However, one of the significant issues of the integrated circuitry is signal coupling between optical structures or devices. Extensive explorations in this aspect have been reported, e.g. the compact butt-coupling between high-index contrast dielectric slab waveguides and metal–dielectric–metal (MDM) subwavelength plasmonic waveguides [3–7], the coupling between the hybrid plasmonic waveguide and the conventional photonics waveguide [8–10], the evanescent field overlapping coupling [11–13], the different guiding characterization of the SRSPP-like and LRSPP-like modes in metal nanowires [14], the highly efficient coupling between the conventional dielectric waveguide mode and the long-rang surface plasmon polaritons (LRSPP) mode [15] or the short-rang surface plasmon polaritons (SRSPP) mode [16], etc.

However, the study of the coupling between SRSPP and LRSPP has been rarely reported so far. There may exist the LRSPP mode with symmetric spatial field distribution and the SRSPP mode with anti-symmetric spatial field distribution in symmetric DMD waveguides with sufficiently thin metal film [17]. In strongly asymmetric DMD waveguides, the major portion of the LRSPP mode field distributes on the side of lower refractive index dielectric while the SRSPP mode field on the side of higher refractive index dielectric. Here we call them upper surface plasmon polaritons (UPSPP) and under surface plasmon polaritons (UNSPP) modes, respectively. When the metal film becomes thick enough, the modes will eventually be reduced to two uncoupled single-interface SPPs on the upper and under sides of the metal (which are still called UPSPP and UNSPP in the context for simplicity) [17]. Due to its low propagation loss, the UPSPP can be used for signal transmission [18] and is very sensitive to the change of the dielectric environment above, a property that finds applications in biosensors [19]. In contrast to the UPSPP, the UNSPP has more compact mode size and much higher transmission loss, which has found its promising applications for broadband absorption enhancement to improve the performance of organic solar cells [20] and enhancement of the internal quantum efficiency of nanoporous silicon light emitter [21]. In addition, with a well-designed asymmetric dielectric/metal/dielectric (DMD) structure, we have experimentally demonstrated elongation of propagation of the UNSPP by stimulated amplification (SA) in electrically-pumped quantum wells (QWs), leaving the UPSPP unaffected [22]. In a broad sense, it is easier to modulate the under mode which is principally located in the substrate while it is easier to detect the upper mode which is principally located in the air. Therefore, for utilizing their respective specialties, it is of great importance to convert

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propagation modes between the UNSPP and the UPSPP. Some works mainly based on symmetric and passive DMD waveguides have been demonstrated [23,24].

In this paper, we investigate mode conversion between UNSPP and UPSPP in an asymmetric DMD waveguide structure using metal gratings as the converter to transfer plasmonic energy. Since the investigated UNSPP mode locates at the under interface of the metal film layer, utilizing metal gratings to couple it to the upper interface of the metal film layer is appropriately. Approaches such as butt-coupling and the evanescent field overlapping coupling have also been tried and tested before this simulation, which did not result in acceptable coupling efficiency. In addition, for a practical device, compared to end-butt coupler or prism coupler, grating coupler engraved in the metal film is more practically and easily implemented for example by focused ion beam (FIB) lithography technology. Coupling efficiencies of grating couplers with different structures are detailedly compared and the physical origins are analyzed. A maximum coupling efficiency higher than 18% has been obtained. All numerical simulations rely on a finite-element method (FEM), concentrating on the TM mode.

2. Structure details

The general scheme of the waveguide coupler is shown in Fig. 1. In our studied asymmetric waveguide structure, the gold film of certain thickness is sandwiched between two semi-infinite different-index media, a substrate with index $n_s=3.2$, the typical value for In*P* at telecom wavelength, at the bottom and the air ($n_a=1$) at the top comprises both the SPP-carrying film and the grating coupler.

The dispersions of the SPP modes with regard to the gold film thickness are illustrated in Fig. 2(a). As the gold thickness reaches around 100 nm, the coupled modes split into individually uncoupled single-interface SPPs, where the effective indices of both modes are kept constant as the thickness further increases. Choosing the gold thickness as 100 nm, we theoretically calculated the magnetic field |Hy| and plotted it in Fig. 2(b). As mentioned above the UPSPP mode is mainly distributed on the air side and the UNSPP mode is on the opposite.

In our calculation, the material refractive indices are obtained from [25,26]. The permittivity of Au corresponding to the given wavelength 1.55 μm is $\varepsilon_{Au}=-131.95+12.56i$, and the permeability is assumed to be $\mu_r=1$ for all materials.

3. Numerical calculation

The grating coupler that locates in the metallic layer as illustrated in Fig. 1 is characterized by its period *D*, its air gap width *W* and the number of periods *N*. The grating coupler provides momentum compensation between the UNSPP and UPSPP modes, and thus

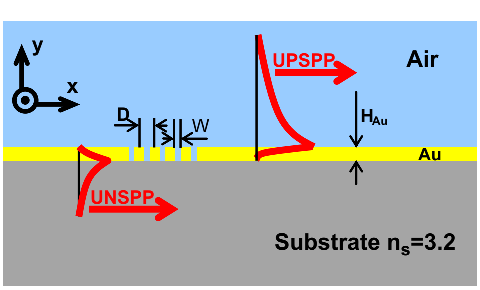

Fig. 1. Schematic of the studied waveguide structure: a thin gold film sandwiched between two semi-infinite different-index media, a substrate at the bottom and the air at the top. The red curves represent the typical mode profiles of the two modes to be coupled. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

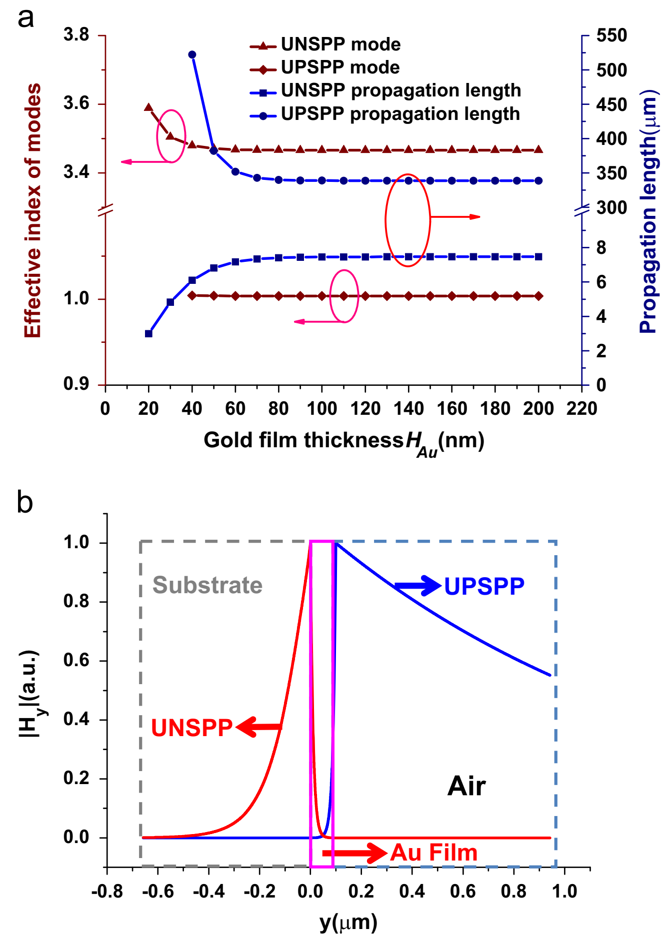

Fig. 2. (a) Calculated effective mode index (red line) and mode propagation length (blue line) for the UNSPP mode and UPSPP mode versus the thickness of the metal film. The propagation lengths saturate when the Au film thickness is larger than about 100 nm. (b) The amplitudes of the magnetic field Hy component associated with UPSPP and UNSPP which are normalized to that at the surface of the substrate. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

efficient coupling is expected when their wavevectors k_{UNSPP} and k_{UPSPP} approximately satisfy the condition of momentum conservation,

$$k_{UPSPP}=k_{UNSPP}+m\times\frac{2\pi}{D} \quad (1)$$

where *m* is an integer. In the present structure we choose $m=-1$.

The commercial software COMSOL Multiphysics based on FEM was employed to numerically simulate the coupling process. In the simulation, the short-range TM bound mode, was obtained in advance using the transfer matrix method (TMM) and Cauchy integration method (CIM) [27,28], and then saved in the COMSOL data format as the input file for launch source. Except that the left boundary of the rectangular computation region was defined as the field launched boundary, all other boundaries were surrounded by perfectly matched layer (PML) domains to avoid reflections. For a practical device, a groove can be fabricated by etching off the entire metal layer and a small portion of the substrate dielectric layer under the metal on certain area at one end of the DMD waveguide, then the UNSPP mode can be excited by a near-field probe placed in the groove or a grating engraved in the bottom of the groove. This is because the UNSPP mode and UPSPP mode respectively locate at the under and upper interface of the metal film and their field distribution hardly overlap especially when the metal film is thick enough, which can be found from Fig. 2(b). Other excitation method such as butt-coupling could