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High efficient unidirectional surface plasmon excitation utilizing coupling between metal-insulator-metal waveguide and metal-insulator interface☆

Zhixiang Huang*, Ke Xu, Deng Pan

Key Laboratory of Intelligent Computing & Signal Processing, Ministry of Education, Anhui University, Hefei 230039, China

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ABSTRACT

A new structure is proposed, which can realize parallel coupling between metal-insulator-metal (MIM) waveguide and plasmon on metal-insulator (MI) interface. An example for wavelength of 680 nm shows the coupling efficiency can be high as 82%, with short coupling length of 1.2 μm. By using MIM waveguide with proper length, a unidirectional plasmon generator is realized. The generator shows excitation efficiency as high as 78%, with high extinction ratio as 1:170. It also shows a good tolerance for the wavelength. The results are of vital importance for optical integration and unidirectional plasmon excitation.

1. Introduction

Surface plasmon polaritons (SPPs) have received great attention in recent years for its potential application on integrated optical circuit, sensing and so on. Metal-insulator-metal (MIM) waveguide [1,2] and Metal-insulator (MI) interface [3] are two important nano-optical elements based on SPPs. To explore the full potential of SPP, it is necessary to control both its propagation direction and strength. The efficient unidirectional SPP source is also a common requirement for plasmonic integrations. The common way to realize unidirectional SPP excitation is applying an oblique incidence. Unidirectional SPP excitation can be achieved under normal incidence by breaking the symmetry of a single slit or grating [4,5]. Based on MIM waveguide, many optical elements have been proposed with normal incidence, including splitters [6], Mach–Zehnder interferometers [7], optical filters [8] and so on. The MI interface, is useful for detection and sensing [9].

MIM waveguide takes advantages in confining and guiding light. SPPs be excited in high efficiency as stated in [10,11]. MI interface is more preferable for sensing, for the field is exposed to the outer environment. But the usual method for excitation of plasmon on MI interface need large devices or gratings [12].

In this work, we study the coupling of MIM waveguide and MI interface. The result shows the coupling can be realized with high efficiency, if the structure parameter is properly designed to fulfill mode index match. An example structure for the coupling is shown. At wavelength of 680 nm, the coupling.

efficiency is high as 82% and coupling length is short as 1.2 μm. Applying this kind of coupling, and using the MIM waveguide with suitable length, a structure for unidirectional surface plasmon excitation is designed. The excitation efficiency can be much high as 78%, with extinction ratio of 1:170. These results are meaningful for the excitation of surface plasmon on single MI interface, or squeezing light into MIM waveguide, and arising new notion for optical integration.

2. Coupling characteristic of MIM/MI structure

2.1. Design of MIM/MI Structure

Fig. 1(a) shows a composite structure, named MIM/MI structure, which includes an MIM region and an MI interface. Dielectric in the MIM region is set to be air. Generally, the permittivities of the metal and the dielectric above the MI interface are ε_M and ε_D. The width of air layer in MIM region is d, and the thickness of metal film between MIM region and MI interface is t. This structure can be roughly taken as a coupling structure for MIM waveguide and MI interface. In next section, based on this structure, coupling from independent MIM waveguide to MI interface will be shown.

Now we illustrate how to choose the material and structural parameters to fulfill mode index match condition, by analyzing dispersion of individual MIM waveguide and MI interface. As we know, only if the two propagation modes have close propagation constant at a given frequency, can they show a strong coupling. The dispersion relations of plasmon on MI interface and even mode in MIM waveguide are shown in Fig. 1(b), following [12]:

$$\beta = k_0\sqrt{\varepsilon_D\varepsilon_M/(\varepsilon_D+\varepsilon_M)}\ (for\ MI\ interface) \quad (1)$$

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* Corresponding author.
E-mail address: zxhuang@ahu.edu.cn (Z. Huang).

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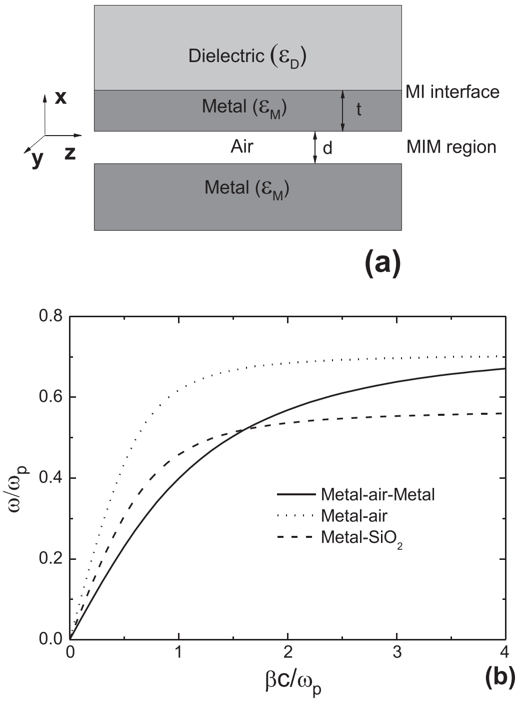

Fig. 1. (a) MIM/MI structure for coupling between MIM waveguides MI interface. (b) Dispersion relations for modes on independent MI interface, and for even modes in independent MIM structure, with $d = 0.1\lambda$. ($\lambda_p = 2\pi c/\omega_p$, c is the velocity of light in vacuum).

$$\tanh(\sqrt{\beta^2 - k_0^2}) = -\sqrt{\beta^2 - k_0^2 \varepsilon_M}/\varepsilon_M \sqrt{\beta^2 - k_0^2} \ (for\ MIM\ waveguide) \tag{2}$$

where βis the propagation constant, k_0 is the wave vector in vacuum. Here, the permittivity of the metal is described by lossless Drude model: $\varepsilon_M = 1 - {\omega_p}^2/\omega^2$, where ω_p is the bulk plasma frequency of the metal. The dispersion curve of even mode of the metal-air-metal waveguide lies below the dispersion of single metal-air interface without an intersection. For single MI interface, the wave vector increase monotonically with the frequency, and goes to infinite when the frequency approach the surface plasmon frequency:$\omega_{sp,D} = \omega_p/\sqrt{1 + \varepsilon_D}$. So, the phase match condition between the metal-air-metal waveguide and upper MI interface, can be fulfilled by increasing the permittivity of dielectric medium above.

According to the discussion above, material and structural parameters are set as follow. The dielectric above MI interface is set to be silica, with the permittivity:$\varepsilon_D = 2.1$. Hereinafter, the metal is chosen as silver, with the permittivity interpolated from experimental data [13]. We pay attention to the wavelength of 680 nm, where $\varepsilon_M = -21.52 + 0.418i$. With these parameters, to fulfill the phase match condition, thickness of the air layer in the MIM waveguide d is set to be 37 nm. Another structural parameter t is not predominant to achieve efficient coupling, and mainly influence the coupling length. At first, t is set to be 25 nm, which is reasonable for field penetration. The effect of t on the coupling will be discussed later.

2.2. Eigenmode of the MIM/MI Structure

Fig. 2 shows the x direction electric field component of two eigenmodes supported by the MIM/MI structure, obtained by finite element method method. For one mode, the field in the MIM region is in phase with the field above the MI interface, while for the other one, the fields in the two regions are out of phase. Define the former as quasi-even mode, and the latter as quasi-odd mode. Since the size of the mode is mainly decided by the field above the MI interface, here the mode width of the two modes is defined as the distance over which the field decreases down to $1/e$ of its value on the MI interface. The quasi-even mode have a relative wide mode distribution and the mode width is about 1 μm, while for the single MI structure, the mode width is 260 nm. As for quasi-odd mode, the field is greatly localized that the mode width is 120 nm.

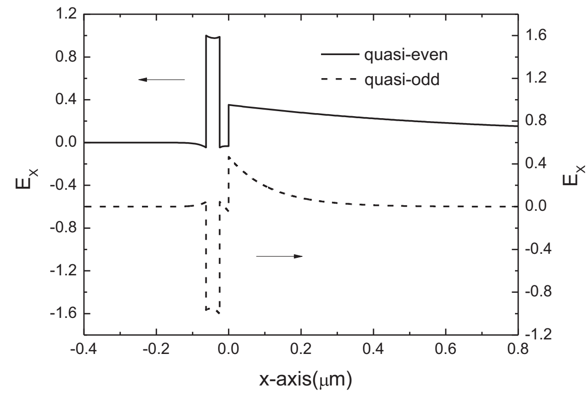

Fig. 2. Distribution of E_x of quasi-even and quasi-odd mode.

Denote the field of the two eigenmodes as $E_o(x)$ and $E_e(x)$. The total field of the composite waveguide can be expressed by a linear combination of the two eigenmodes [14]:

$$E(x, z) = c_o E_o(x)\cdot e^{i\beta_o z} + c_e E_e(y)\cdot e^{i\beta_e z} \tag{3}$$

where β_o and β_e are the complex propagation constant of the two eigenmodes. The great discrepancies in the field distribution of the two modes lead to differences in their effective refractive index. The real parts of effective refractive index of the quasi-even and quasi-odd modes are n_e=1.455 and n_o=1.733. The imaginary parts of effective refractive index correspond to the loss of the modes. The quasi-even mode with wide distribution, has a much low loss of −0.06 dB/μm. For quasi-odd mode, it has great localized field, which mean more power penetrating into metal, so that it suffer a much high loss of −0.75 dB/μm. The coefficient is decided by the initial input field distribution. After the coupler is excited at z=0 from one port, most part of the field energy is transferred into the two eigenmodes and propagated. The coupling length L_C is where the two eigenmodes have phase difference of π:

$$L_c = \lambda/[2\cdot(n_e - n_o)]. \tag{4}$$

where λ is the wavelength in the vacuum. That gives L_C of 1.22 μm for 680 nm.

2.3. Coupling Properties in MIM/MI Structure

First, Fig. 3(a) shows an intuitive picture for the coupling. The field is excited in MIM part at z=0, with a mode distribution of the uncoupled MIM waveguide. After exciting at z=0, with z increasing, the energy is gradually coupled to the upper MI interface. At z=L_C the energy in the MIM region reach the minimum and most are transferred to the upper MI interface. As z increases more, the energy above the MI interface again squeeze back into the MIM region. Fig. 3(b) shows the energy flow along z direction at different z position in the MIM region and above MI interface. The energy flow of the MIM port is measured, just taking into account the power in the air layer region. Considering the mode width of the two eigenmodes discuss in last section, we here define the energy flow within a wavelength above the MI interface as the energy flow of the MI port. At coupling length L_C=1.22 μm from the input, 82% energy is coupled to the upper MI interface, and the ratio of the energy flow in two port here is 27:1. The attenuation of the total field is −0.61 dB/μm, lies between the attenuation of the two eigenmodes. It should be clarified that the radiation part by the exciting is small. We can see that in the propagation, the fields above the MI