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Unidirectional and bidirectional coupling of surface plasmons based on a nonperiodic nano slit array

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Abstract—A 2D structure is proposed, made up of nano slits to couple free space mode of any given wave front to a propagating Surface Plasmon Polariton (SPP) mode of Metal Insulator Metal (MIM) waveguide. The structure can be designed to act as either a unidirectional or bidirectional coupler. Designed structures are simulated using an FEM technique and results for circular and plane wave fronts are demonstrated. From the results obtained, it is observed that there is an optimum aperture size for coupling maximum power into the MIM waveguide for the case of a circular wave front.

SPPs are propagating electromagnetic waves confined to a metal dielectric interface, generated by coupling of photons and plasmons [1]. One of the most attractive features of these waves is that they can be confined well below the diffraction limit and hence be manipulated in subwavelength scales. Due to this there has been a growing interest in developing plasmonic structures for nanophotonics and it is believed that SPPs are a promising candidate enabling technology for the next generation of ultra-compact all optical integrated circuits.

An important functional requirement in interfacing nanophotonic systems devised using SPP technology to diffraction-limited conventional optics would be an efficient mode-conversion capability. In a more specific sense, it is essential to address efficient coupling of free space mode to SPP mode. For exciting SPPs on a single metal-insulator interface, a number of subwavelength metallic structures have been proposed [2, 3]. However, considering the confinement of optical fields propagating as SPP waves, MIM waveguides are preferred over a mere metal-insulator interface. Hence in this paper, we concentrate only on MIM waveguides. While there has been a few published papers which address the coupling of free space plane waves to SPP modes in an MIM waveguide, either their operating principle [4, 5] or intended application [6, 7] is different. There were a few slit based structures explored in recent years with either single or double slits but their conversion efficiency could be low due to their tiny aperture size [8-10].

In this paper, we propose a technique based on an array of subwavelength slits carved on an MIM waveguide, and the principle of equal Optical Path Length (OPL) [11] to couple free space waves of any wave front to a propagating mode supported by an MIM waveguide. We consider a circular and plane wave front for demonstration of our structure. Using this technique, we demonstrate possible applications such as unidirectional as well as bidirectional couplers. The functioning of all proposed structures is simulated using COMSOL Multiphysics.

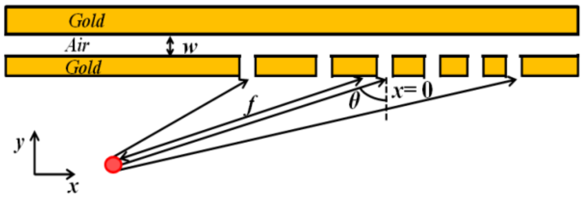

Fig. 1. MIM bus waveguide structure carved with an array of slits on one side. The point source is placed at a distance *f* with an angle θ as shown with respect to the slit at *x*=0.

Consider a structure as shown in Fig. 1. One of the slits carved on the MIM waveguide is positioned at the origin of *x*-axis (*x*=0). The position of the other slits in the structure with reference to this slit will depend on the function to be performed by this structure.

We first consider the point source for unidirectional coupling on to an MIM waveguide. The point source is located at a distance *f* from the slit at *x*=0 in such a way that it defines an angle θ with respect to the normal drawn to that slit. When light is incident on the slits, SPP will be excited in each slit and they couple into the MIM waveguide. Without any intervention, the power of these coupled SPP waves will have a tendency to split and propagate on either side. To ensure unidirectional propagation, it is necessary that the phase of that component of a coupled SPP from each of the slits in the direction of desired propagation add up constructively.

For propagation towards the left (negative *x* direction), with reference to the slit at *x*=0, the position of subsequent slits is arrived at as follows. Using the principle of equal OPL, and as shown in Fig. 2, the position *x* of the other slits which constitute the structure, the solution for *x* in the equation will be given below:

$$k_0 f_{extra} + \beta x = 0 \ (\mathrm{mod} \ \ 2\pi) \ , \qquad (1)$$

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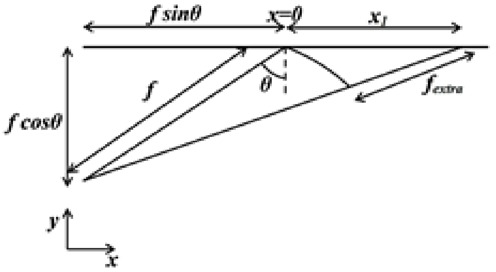

Fig. 2. Schematic of free space wave propagating from a point source towards slits at x=0 and at x=x_1. The source is located at a distance of f and defines an angle θ as shown.

where k_0 is the free space wave number, f_{extra} is as shown in Fig.2 and given by

$$f_{extra} = \sqrt{f^2 + x^2 + 2fx\sin\theta} - f \qquad (2)$$

and β is the SPP mode propagation constant [1]. As implied in Fig. 1, x can take negative values as well. The above equation says that the additional phase acquired by the wave as it propagates the distance f_{extra} in free space and the distance x in the form of an SPP wave has to be a multiple of 2π. Note that since all slits are identical, the phase accumulated in the slits was not considered in the above expression. Using similar principles, it can be shown that for propagation towards the right (positive x direction), x has to satisfy the relation

$$\beta x = k_0 f_{extra} + 0 \,(\mathrm{mod}\ \ 2\pi)\ . \qquad (3)$$

It will be of interest to see what happens in the above case if f approaches infinity. As f approaches infinity, f_{extra} can be expressed as

$$f_{extra} = f\sqrt{1+(x/f)^2+2(x/f)\sin\theta} - f \approx x\sin\theta\ . \qquad (4)$$

Since f = infinity suggests a plane wave front, the value of x which solves Eq. (1) with f_{extra} as given above will be the position of slits for the incidence of a plane wave. Thus for propagation towards the left, the position of the slits x can be arrived at by substituting Eq. (4) in (1) and will be:

$$x = \frac{0\,(\mathrm{mod}\ \ 2\pi)}{\beta + k_0\sin\theta}\ . \qquad (5)$$

Similarly, from (3) and (4), for propagation towards the right, x will be:

$$x = \frac{0\,(\mathrm{mod}\ \ 2\pi)}{\beta - k_0\sin\theta}\ , \qquad (6)$$

It can be noted from the above discussion that while the distance between any two adjacent slits remains the same for the case of plane wave incidence, it is not so for the incidence of a circular wave front.

While the above structures function as unidirectional couplers, through a simple extension of this structure, it is possible to realize a bidirectional coupler. However, the bidirectional coupler works only if θ=0. Consider a point source. Let there be a left or right coupling structure which has slits only on the negative or positive x–axis respectively (left or right side of x=0). Needless to say, the slit positions are obtained using Eq. (1) for the left coupling and similar appropriate equation for the right coupling. Having designed such a unidirectional coupling structure, we can easily obtain bidirectional coupling by simply reflecting the designed structure about the y axis at x=0. This is akin to mirror imaging the left or right coupling structure. The principle readily applies for plane waves as well. As mentioned earlier with regards to unidirectional coupling, the distance between slits for bidirectional coupling for a circular wave front will not be the same whereas for a plane wave front, it will be the same. Due to this very same reason, it is impossible to have unidirectional coupling for plane waves incident normally (θ = 0). This fact can also be easily interpreted from Eqs. (5) and (6) by setting θ=0. Having said that, it needs to be reiterated that, for a point source, such restrictions on θ for realization of unidirectional couplers do not exist.

Coming to the results, the metal in the structure is assumed to be gold with its dielectric constant calculated using the Drude model [12]. The operating wavelength is considered to be 650nm. All slits are assumed to be of the dimension 100nm×100nm, and the width w is assumed to be 100nm. The aperture size of the structures is fixed as 4µm, extending from –2µm to 2µm.

Figures 3a and 3b report the results for a unidirectional coupler for incidence from a point source. The coupler is designed to couple power from the incident field on to the left side. A total of 10 slits are accommodated over a distance of 4µm. Figures 3c and 3d report similar results for plane wave incidence. A total of 11 slits are accommodated over a distance of 4µm in this case. For the point source, f=4µm, and for both the cases above, θ=30°. As it is clearly observable from both the magnetic field intensity ($|H_z|^2$) as well as the magnetic field (H_z) distribution plots, the designed structure works as desired with negligible coupling of power on to the right side. Our calculations show that the extinction ratio [5] is 16.02dB for the point source while it is 16.05dB for the plane wave. These values are way above the accepted 10 dB level.

Figure 4 reports the results for a bidirectional coupler. As in Fig. 3, both magnetic field intensity as well as field distributions are shown. Again, it is clearly seen that the designed structure works as desired. A total of 7 slits are accommodated over a distance of 4µm for both the point source as well as plane wave cases. Our calculations show that the ratio between the power propagating towards the left and the power propagating towards the right is 1.008 for the point source while it is 1 for the plane wave.

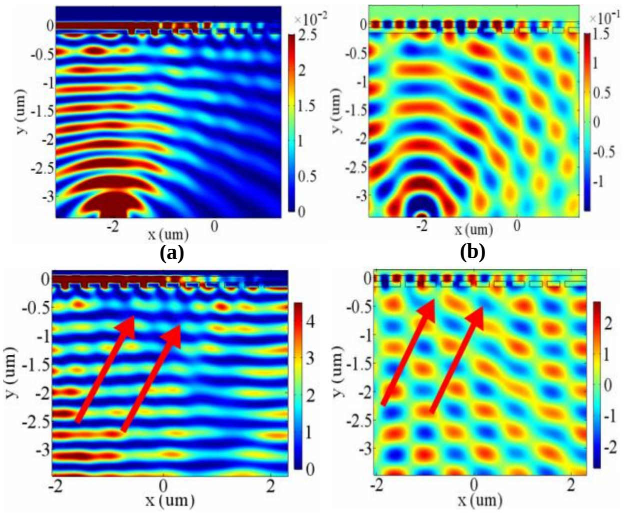

Fig. 3. Magnetic field intensity ($|H_z|^2$) and magnetic field (H_z) distribution for the designed unidirectional coupler: (a)÷(b) with a point source and (c)÷(d) with a plane wave. The angle of incidence is 30^0 in both cases.

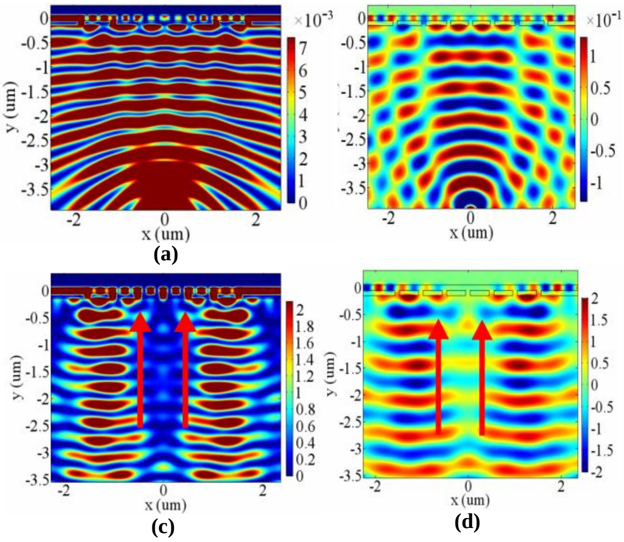

Fig. 4. Magnetic field intensity ($|H_z|^2$) and magnetic field (H_z) distribution for the designed bidirectional coupler: (a)÷(b) with a point source and (c)÷(d) with a plane wave.

We have also considered the effect of aperture size of the coupler on the amount of power coupled to the waveguide. The aperture size varied from 0.5μm to 15μm for the case of a point source with $\theta=30^o$ and unidirectional (left) coupling. This resulted in one slit for an aperture size of 0.5μm and 34 slits for an aperture size of 15μm. Figure 5 shows the power available at the exit of the structure towards the left, plotted as a function of aperture size. As can be seen, there is an optimum size of aperture which couples maximum power into the MIM waveguide. If the aperture size is less than this optimum value, power drops due to the fact that there is no sufficient number of slits to collect the power. On the other hand, increasing the aperture size above the optimum value will not result in a significant increase in power since the power density at slits located far away from the point source drops as per inverse square law. Further, due to metal loss, and possible leakage from the slits, the power coupled into the waveguide could be lost. Note that this is significant because the coupled power is measured at the extreme end of the structure. Due to these effects, the power coupled into the waveguide drops if the aperture size is increased beyond the optimum value. Though not included in the results here, we have seen a similar behaviour in the case of bidirectional couplers for the point source. It needs to be added that for the case of plane waves, both unidirectional and bidirectional coupling, no such optimum aperture size was observed. The power coupled into the waveguide increases as the aperture size increases.

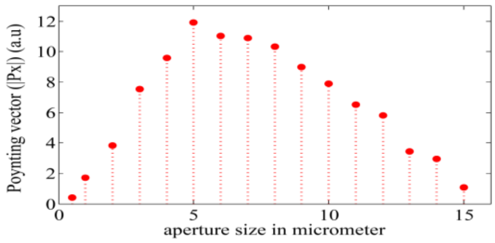

Fig. 5. Plot of Poynting vector ($|P_x|$) at the left extreme of aperture as a function of aperture size for a point source at f=4μm and $\theta=30^o$.

To conclude, a free space to an MIM plasmonic waveguide coupler composed of an MIM bus waveguide carved with nano slit structures is proposed and simulated. Using the principle of equal OPL, the proposed structure can be engineered to function as either a unidirectional coupler for any arbitrary angle of incidence, or a bidirectional coupler for normal incidence. The simulated results confirm the validity of the proposed structure and its design. The existence of an optimum aperture size for couplers acting with point sources was demonstrated.

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