RESEARCH ARTICLE

Plasmonic nanoslit-based dual-wavelength multiplexer

U. Aparna[1] · H. S. Mruthyunjaya[1] · M. Sathish Kumar[1]

Abstract A novel plasmonic dual-wavelength multiplexer to couple free-space waves to metal–insulator–metal (MIM) waveguides is proposed, designed and simulated. The proposed structure is based on two nanoslits carved on a metal film. Through an appropriate spacing between the nanoslits, it is possible to design this structure to couple two different wavelengths onto MIM modes such that they propagate in the same direction. The designed structure is simulated using FEM technique, and results for circular and plane wave fronts are demonstrated. High extinction ratio of greater than 10 dB is obtained in all the cases.

Keywords Surface plasmons · Metal–insulator–metal waveguide · Unidirectional couplers · Plasmonic multiplexer · Extinction ratio

Introduction

Surface plasmon polaritons (SPPs) are propagating electromagnetic waves along metal–dielectric interface and are generated by interaction of photons with collective oscillations of surface electron on the metal surface. SPPs are attracting tremendous attention due to their outstanding capability of breaking the diffraction limit and are therefore an ideal candidate for construction of the future miniaturized integrated all optical circuits [1]. In recent years, data traffic has increased dramatically and there is a need for design and implementation of high-speed as well as large-capacity information processing systems. Large-capacity optical information processing systems with very small footprint are achievable only through complete exploitation of bandwidth available in plasmonic systems. A possible method to achieve this is applying wavelength division multiplexing technology to plasmonic systems. This naturally leads to investigation on plasmonic structures capable of playing the role of wavelength multiplexers and demultiplexers.

A variety of plasmonic multiplexers [2, 3] and demultiplexers [4–11] have been proposed in the literature. Many of them use resonant cavities to select the required wavelength [2, 4–9], while a few designs have been proposed without such cavities [3, 10, 11].

In this paper, we propose a structure with two subwavelength slits to couple free-space waves onto unidirectional SPP modes of a MIM waveguide. This unidirectional coupler [12–14] is then converted into a dual-wavelength multiplexer through an appropriate selection of spacing between the slits and angle of incidence. We consider circular wave front and plane wave front for demonstration of the functioning of our structure. Simulations are carried out using COMSOL Multiphysics. We feel that since in our design there are no cavities used to differentiate the wavelengths, there will be lesser losses. Also, as mentioned above, our design is based on only two slits which will considerably reduce the structure footprint.

Principle and design

In this section, we develop the design of the proposed dual-wavelength multiplexer. We begin with the design of a simple unidirectional coupler. The construction of the coupler is illustrated schematically in Fig. 1a. The bus

✉ M. Sathish Kumar
  sathish.kumar@manipal.edu

1 Electronics and Communication Engineering Department,
   Manipal Institute of Technology, Manipal Academy of
   Higher Education, Manipal, Karnataka 576104, India

Fig. 1 **a** Schematic structure of the proposed unidirectional coupler, **b** illustration of free-space wave propagating from a point source towards the slits
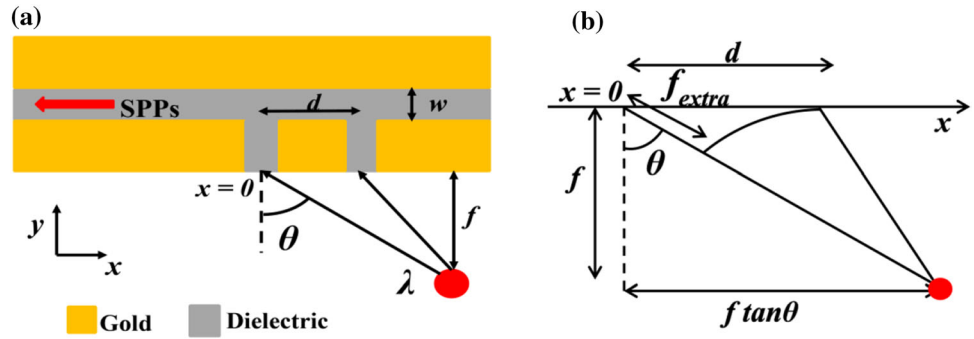
waveguide is composed of a metal–dielectric–metal structure with two nanoslits carved on it. The width of the slits as well as that of the bus is w, and both are filled with identical dielectric material. To achieve unidirectional coupling, we fix the position of one of the slits at say, $x = 0$, and the position of other slit relative to this slit is arrived at so that the desired interference effects could manifest.

A p-polarized light of a particular wavelength λ from a point source located at a distance of f from the structure is assumed to fall on the structure. The width w of the MIM waveguide is chosen such that it can support only the fundamental plasmonic mode (TM$_0$) for this wavelength. The propagation constant β of this mode can be calculated using the dispersion relation given as follows [1]:

$$\tanh\left(k_1 \frac{w}{2}\right) = -\frac{\varepsilon_d k_2}{\varepsilon_m k_1} \tag{1}$$

with $k_1 = \sqrt{\beta^2 - k_0^2 \varepsilon_d}$ and $k_2 = \sqrt{\beta^2 - k_0^2 \varepsilon_m}$, where k_0 is the free-space propagation constant and ε_d and ε_m are the dielectric constants of insulator and metal, respectively.

SPPs excited in the slits will permeate into the bus waveguide and propagate in both the directions of the waveguide. In order to realize a directional excitation, SPP propagating in the desired direction must be enhanced and the one propagating in the opposite direction must be suppressed. This implies the phases of the coupled SPP from each of the slits add up constructively in the desired direction and destructively in the opposite direction.

For excitation in the desired direction (left side) and cancellation in the opposite direction, the following two equations will have to be satisfied simultaneously

$$\beta d = k_0 f_{\text{extra}} + 2N\pi \tag{2}$$

$$\beta d = -k_0 f_{\text{extra}} + (2M + 1)\pi \tag{3}$$

where d is the separation between the two slits, N and M are integers and f_{extra} is as shown in Fig. 1b and given by

$$f_{\text{extra}} = f \sec\theta - \sqrt{(f \tan\theta - d)^2 + f^2} \tag{4}$$

where θ is the angle of incidence measured with respect to normal to the surface of the structure.

Based on the above theory, for a given wavelength of incident light and distance f of the light source, d and θ have to be arrived at appropriately. It is worth mentioning that since both the slits are identical, the phase accumulated in these slits need not be considered in the above design.

The above discussion can be specialized to the case of a plane wave by simply letting $f \to \infty$. This transforms Eq. (4) into,

$$f_{\text{extra}} = d \sin\theta. \tag{5}$$

The rest of the design procedure remains the same.

The simple unidirectional coupler discussed above can be converted to a dual-wavelength multiplexer if we choose d, angles of incidence of the two light waves as well as their wavelengths intelligently. Assume the presence of a second source emitting at a different wavelength. Let this second source be located such that it defines as angle θ_2 with respect to the normal to the structure as shown in Fig. 2. A multiplexer is realized using the above designed structure so as to couple two different free-space wavelengths to propagating SPP in the same direction (left of the slits) in the MIM waveguide. Note that the angle is defined for both the sources with reference to the slit at $x = 0$. Further, both the sources are located on a straight line parallel to x-axis at a distance of f.
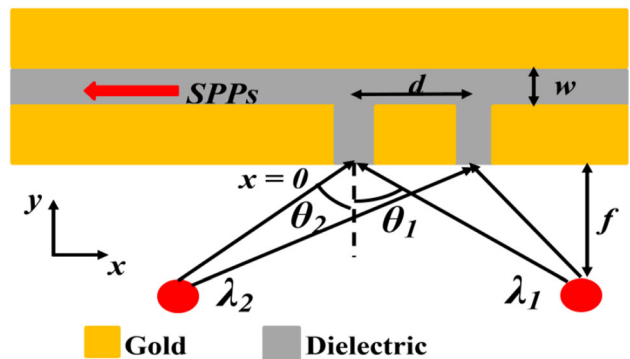

Fig. 2 Schematic structure of proposed multiplexer

Using the interference conditions as earlier, it can be shown that propagation of SPP excited by this second source towards the left is guaranteed if the following set of equations are satisfied simultaneously.

$$\beta d = -k_0 f_{extra} + 2N\pi \qquad (6)$$

$$\beta d = k_0 f_{extra} + (2M + 1)\pi \qquad (7)$$

where

$$f_{extra} = \sqrt{(f \tan\theta + d)^2 + f^2} - f \sec\theta. \qquad (8)$$

Needless to say, by making $f \to \infty$ the dual-wavelength multiplexer theory that is being developed is applicable to plane waves also.

Before moving on to "Results and discussion", the theory discussed above may be consolidated as follows. Equations 2, 3, 6, and 7 should hold for the same value of d and f. However, Eqs. 2 and 3 will hold for the wavelength λ_1 of source 1 and angle of incidence θ_1 and Eqs. 6 and 7 will hold for the wavelength λ_2 of source 2 and angle of incidence θ_2 (Fig. 2). Due to this complexity, the equations have to be solved iteratively using appropriate numerical/graphical methods.

Results and discussion

The proposed dual-wavelength multiplexer is simulated using FEM technique (COMSOL Multiphysics).The width of the bus waveguide w is fixed as 100 nm, and the sizes of both the slits are fixed as 100 nm × 100 nm. The metal in the structure is assumed to be gold, and the dielectric within the waveguide is assumed to have a refractive index of 1.2. Permittivity of gold is computed using Drude model [15]. Light illuminating the structure is assumed to be p-polarized.

For the case of point source, we chose $\lambda_1 = 650$ nm and $f = 2.5$ μm. Having chosen these values, we obtain d and θ_1 as 523 nm and 23°, respectively. Next, we solve Eqs. 6 and 7 with the values of d arrived at as above and f as mentioned earlier for obtaining the second-source emission wavelength λ_2 as 980 nm and angle of incidence θ_2 as 18°. For completeness of discussion, we would like to mention that the above solutions are for N and M as 1 at 650 nm for Eqs. 2 and 3 and N as 1 and M as 0 at 980 nm for Eqs. 6 and 7.

Figures 3 and 4 show the simulated magnetic field intensity $|H_z|^2$ and magnetic field H_z plots for 650-nm and 980-nm point source and plane wave source, respectively. Figures 3a, b and 4a, b show the simulated $|H_z|^2$ and H_z

Fig. 3 Plots of **a** and **c** magnetic field intensity ($|H_z|^2$), **b** and **d** magnetic field (H_z) for the designed multiplexer with 650-nm and 980-nm wavelength point sources, respectively
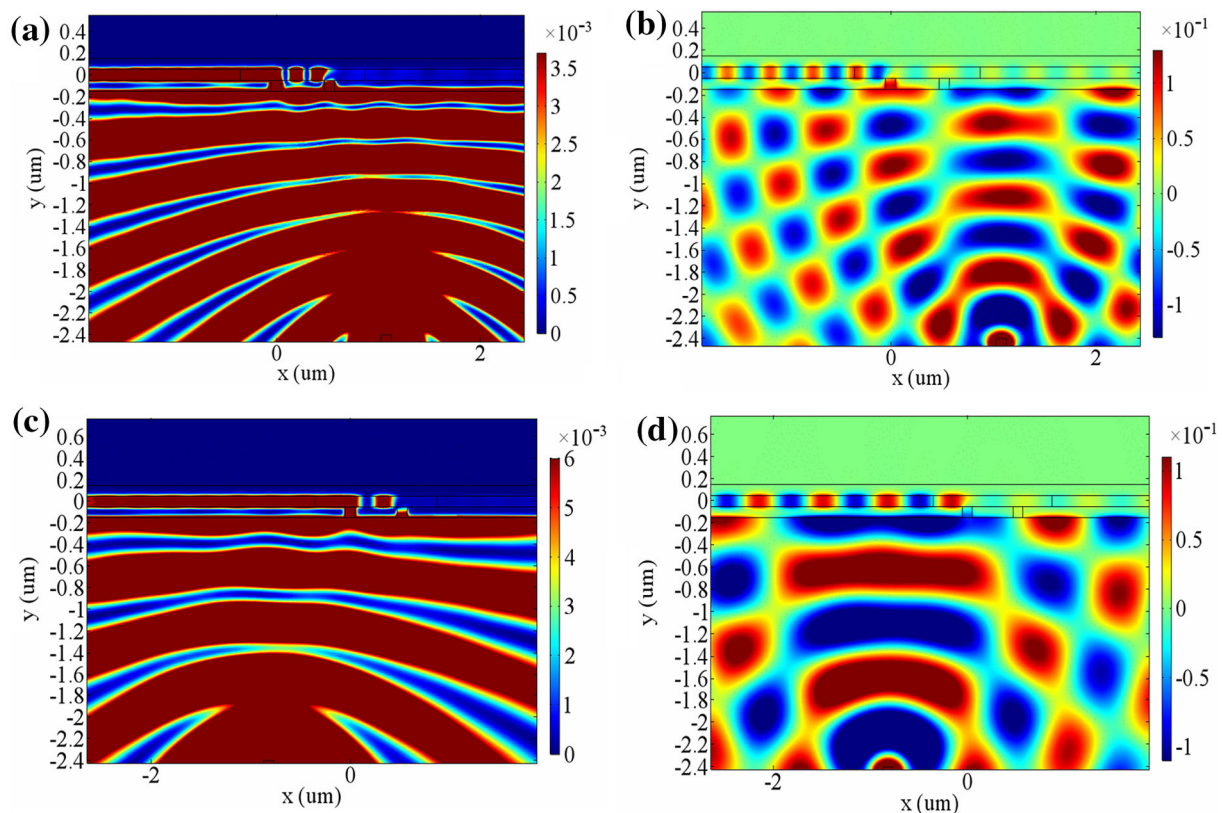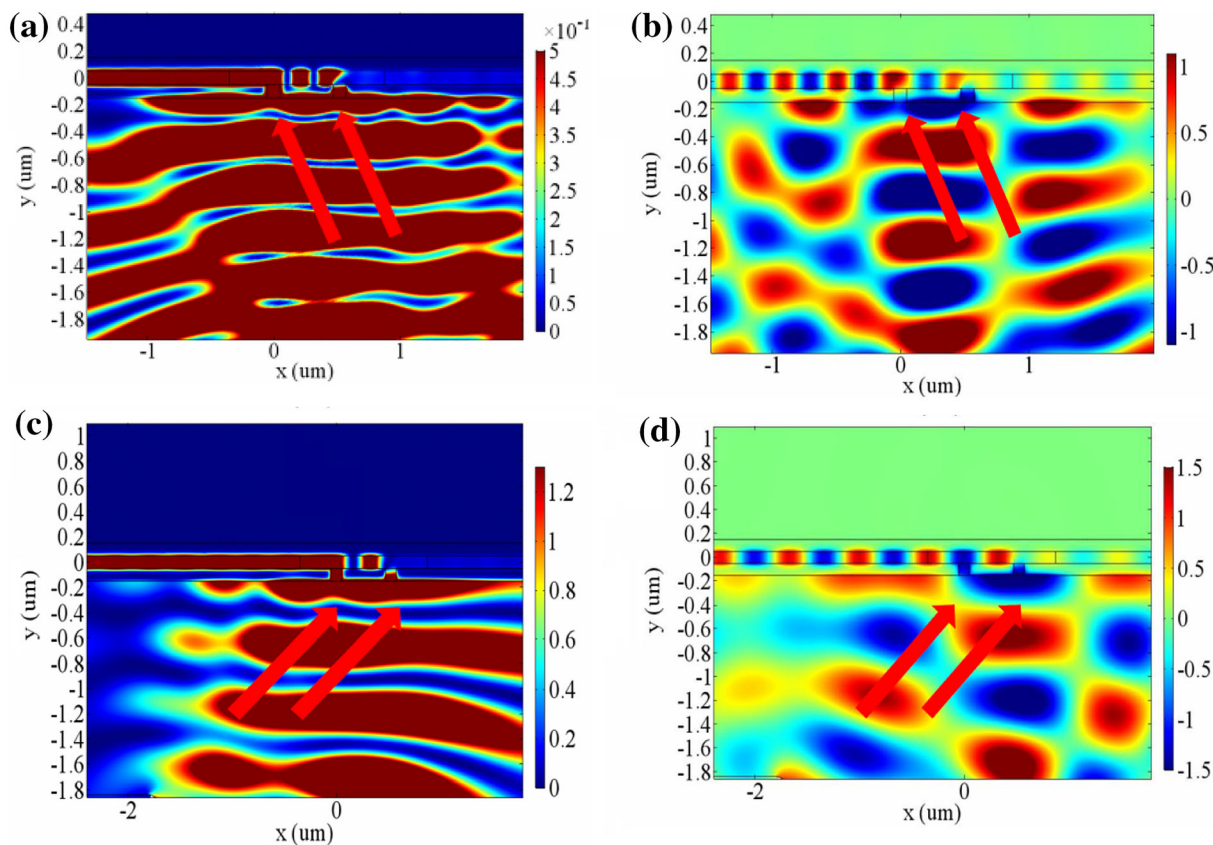
Fig. 4 Plots of **a** and **c** Magnetic field intensity ($|Hz|^2$), **b** and **d** magnetic field (Hz) for the designed multiplexer with 650-nm and 980-nm wavelength plane wave sources

plots for 650-nm point source and plane wave source, respectively. Figures 3c, d and 4c, d show the same for the second point source and plane wave source emitting at a wavelength of 980 nm, respectively. These figures clearly show that both the wavelengths excite mainly a left propagating SPP in the waveguide, which is as per the design of the structure. Further, a considerable suppression of fields on the opposite (right) direction also is observed. High ER [16] of 14.4 dB and 17.66 dB, respectively, could be recorded for the wavelengths 650-nm and 980-nm point source, and an ER of 19.25 dB and 14.59 dB is recorded for 650-nm and 980-nm plane wave source, respectively. As reported in [13, 14, 16], destructive interference will not completely extinguish the field in the opposite direction because the additional phase shift due to scattering and coupling effects of the slits is not considered in the design.

To get a measure of the selectivity of the designed structure, we plot the ER as a function of wavelength for fixed incidence angle θ and d in Fig. 5a. An acceptably sharp selectivity can be observed from this figure. The ER peaks around the desired wavelength and stays at a value of 10 dB and above over a range of wavelengths $\Delta\lambda_{1-} = 47$ nm and $\Delta\lambda_2 = 410$ nm for 650-nm and 980-nm point source, respectively, whereas for plane waves,

$\Delta\lambda_1 = 36$ nm and $\Delta\lambda_2 = 290$ nm for 650 nm and 980 nm, respectively. ER as a function of angle of incidence as well as spacing between the slits for fixed wavelengths is also shown in Figs. 5b, c. A high selectivity is obvious from these figures as well. For 650-nm point source, the ER stays above 10 dB for incident angles ranging from 15° to 26°, while for 650-nm plane waves, this angular range is from 15° to 24°. Similarly for 980 nm, this angular range is from 13° to 35° and 22° to 40°, respectively, for point source and plane waves. Another point is that carving tiny corrugations on either side of the slits which couple light into the MIM waveguide can result in an increase in the coupling efficiency.

Though we have presented the results of the two wavelengths that get coupled onto SPP modes propagating in the same direction, it should be possible to design this structure such that the two coupled wavelengths propagate in opposite directions. Such a structure may be visualized as a 2 × 2 mode converter. Also, attempts can be made to extend this principle so as to achieve an NX1 wavelength multiplexer.

Before we conclude, we would like to mention that there are a few deviations in the simulated results when compared to what is expected based on the theoretical design. One such deviation is that though the design is for the ER

Fig. 5 Plots of ER versus
a wavelength, **b** angle and
c spacing for point source
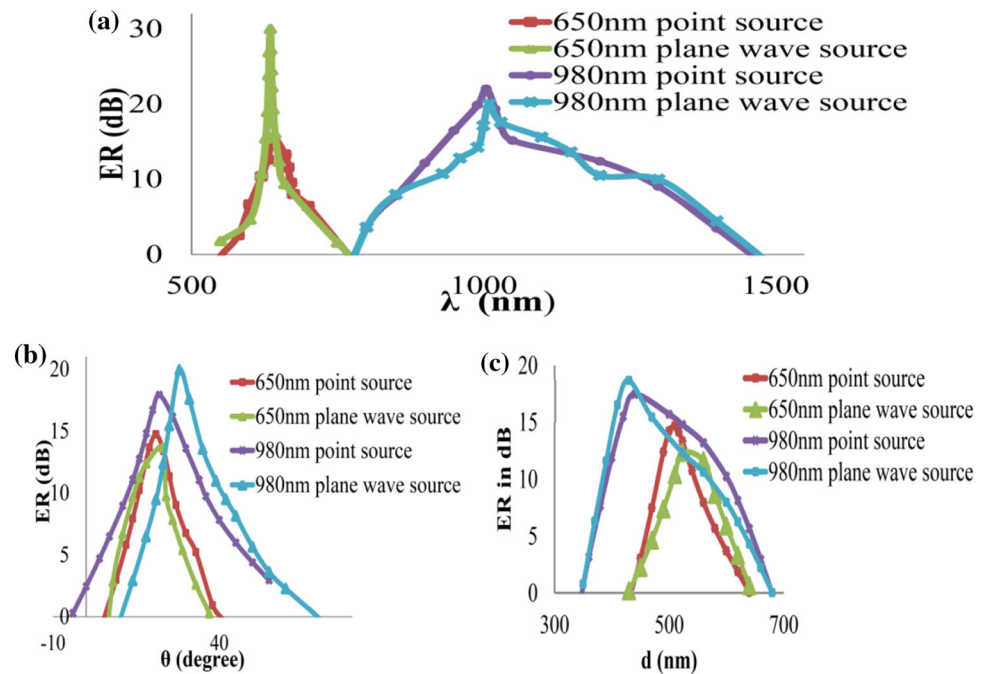
to peak at 650-nm and 980-nm wavelengths, it is observed that the ER actually peaks at wavelengths that are slightly offset from these. As mentioned earlier in the context of ER being not infinity, this could be due to ignoring the scattering and coupling effects.

Conclusion

We have proposed a novel dual-wavelength plasmonic multiplexer which can couple two different wavelengths onto SPP modes supported by an MIM waveguide. Direction of propagation of the coupled SPP waves can be controlled through appropriate selection of the parameters of the proposed structure. The proposed structure is essentially based on an unidirectional coupler composed of two slits which is converted to a multiplexer through an intelligent choice of spacing between the slits and angle of incidence. Simulated results using COMSOL Multiphysics for circular and plane wave fronts incident on the structure are in accordance with what is predicted by the design. A high ER of greater than 10 dB is obtained in all the cases. The proposed structures will have wide applications in plasmonic-based nanophotonic systems.

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