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Complete spectral gap in coupled dielectric waveguides embedded into metal

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We study a plasmonic coupler involving backward (TM01) and forward (HE11) modes of dielectric waveguides embedded into an infinite metallic background. The simultaneously achievable contradirectional energy flows and codirectional phase velocities in different channels lead to a spectral gap, despite the absence of periodic structures along the waveguide. We demonstrate that a complete spectral gap can be achieved in a symmetric structure composed of four coupled waveguides. © 2010 American Institute of Physics. [doi:10.1063/1.3458694]

Negative index metamaterials (NIMs) are artificial materials which have simultaneously negative permittivity and negative permeability.1–4 In NIM waveguides, modes are backward when more energy flows in the NIM than in other channels. Coupling of a forward propagating mode in a conventional dielectric waveguide with a backward mode in a NIM waveguide has been investigated theoretically in both linear and nonlinear regimes.4,5 The coupling of a forward mode and a backward one results in the formation of spectral gaps without periodic structures along the waveguide. This feedback mechanism may play an important role in nanophotonics, as it could significantly simplify complex geometries that are required for subwavelength optical manipulation and concentration. However, due to the fabrication complexity and high losses of NIM, coupling involving NIM is currently not experimentally feasible and therefore this mechanism has not attracted significant attention.

There has been a surging interest in the field of plasmonics, as it offers one of the most promising approaches for subwavelength optical concentration and manipulation (for a comprehensive review, see e.g., Refs. 6–9). In some plasmonic structures, backward modes exist in regimes when more energy flows in the metal than in the dielectric.10–14 These structures are much simpler and more fabricable than those involving NIM. In this letter, we propose a design of plasmonic coupler involving the coupling between the backward TM01 and the forward HE11 modes of dielectric waveguides embedded into metal [see Fig. 1(a)]. We find a polarization dependent spectral gap in a structure of two coupled waveguides and a complete polarization independent gap in a C3v structure with four coupled waveguides.

It was recently reported15 that taking experimental data of bulk metal16 in numerical calculations of plasmonic modes may lead to losses which are much higher than real losses observed in experiments. In our study, we use the Drude model to simulate the optical properties of a metal as follows: $\varepsilon_m(\omega) = 1 - \omega_p^2/\omega(\omega + i\omega_L)$, where $\omega_p$ is the plasma frequency and $\omega_L$ is the collision frequency. At this time, we define two normalized quantities as follows: loss $\gamma = \omega_L/\omega_p$ and size parameter $\alpha = R \omega_p/c$, where R is the radius of the dielectric core and c is speed of light in vacuum.

Figure 1(a) shows the two-waveguide structure we study: two dielectric rods of the same radius $a = 1.21$ (corresponding R is about 25 nm for silver) with $\varepsilon_1 = 9$ and $\varepsilon_2 = 4$ are embedded into infinite metal. First, by analyzing the dispersion of a single waveguide, we find that the backward TM01 mode for $\epsilon = 9$ intersects with the forward HE11 mode for $\epsilon = 4$ at $\omega/\omega_p = 0.3856$ [see Fig. 2(a)]. This point corresponds to $\lambda = 400$ nm for silver. For the TM01 mode, more energy flows in the metal than in the dielectric, which is similar to the backward SPP on metallic wires.10,17 It should be emphasized that the directionality of TM01 and HE11 modes are radius dependent as follows: the TM01 mode can become forward when the radius increases and the HE11 mode can become backward when the radius decreases.12 However, the HE11 mode has linear polarization inside the dielectric [see Fig. 2(c), which could be excited directly with a normal incident wave] whereas the TM01 mode has radial polarization [see Fig. 2(d)] with much higher losses in the coupling region [see Fig. 2(b)].

Prior to preforming a fully numerical study, we use temporal coupled-mode theory18,20 (TCMT) to get a qualitative understanding of dispersion relation in the lossless case. The eigenmodes of a coupled system are expressed as a superposition of individual waveguide modes as follows: $\mathbf{E} = \sum_m A_m(z, t) \mathbf{E}_m(x, y)e^{i(k_mz + \omega_m t)}$, where $\omega_m = \omega_m$ at $k = k_0$

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and $\kappa_{mn}$ is the self-coupling coefficient. For the two coupled waveguides, three modes can couple to one another as follows: two forward HE$_{11}$ modes of preferred $x$ and $y$ polarizations, which could be approximately reconstructed by two orthogonal eigenmodes of circular polarizations $A_{1,2}(z,t)$ and one backward TM$_{01}$ mode $A_3(z,t)$. The coupled-mode equations in time domain are as follows:

$$i\frac{\partial A_{1,2}(z,t)}{\partial t} + i v_g \frac{\partial A_{1,2}(z,t)}{\partial z} + \kappa A_3(z,t)e^{i2\delta} = 0,$$

$$i\frac{\partial A_3(z,t)}{\partial t} + iv_g \frac{\partial A_3(z,t)}{\partial z} + \kappa \sum_{m=1}^{2} A_m(z,t)e^{-i2\delta} = 0,$$

where $\delta = (1/2)(\kappa_{31} + \omega_0 - \kappa_{11} - \omega_{10}) = (1/2)(\kappa_{31} + \omega_0 - \kappa_{22} - \omega_{20})$ is the asymmetry parameter of two waveguides; $A_{1,2}$ are normalized envelopes: $v_{g1}', v_{g2}' = v_g > 0, v_{g3} < 0$ are the group velocities at $\omega_0 = \omega(k_0); \kappa_{12} = \kappa_{21} = 0$ (mode 1 and 2 are orthogonal); and the other mutual coupling coefficients are identical; $\kappa_{ij} = \kappa_i (i = 1, 2; j = 3)$. In the coupling region we ignore the dispersion of group velocities and assume that $v_{g1,3}$ and $\kappa$ are constants. By introducing the following variables: $a_1(z,t) = A_1(z,t)e^{-i\delta}, a_2(z,t) = A_2(z,t)e^{-i\delta}, a_3(z,t) = A_3(z,t)e^{i\delta}$, and applying the Fourier transform, we obtain the propagation constants of three eigenmodes:

$$k_{1,2} = (\alpha \pm i\sqrt{-8v_g v_3 v_k^2 - \beta^2})/2v_g v_3, \quad k_{3} = (\omega + \delta)/v_g$$

where $\alpha = v_g(\omega + \delta) + v_3(\omega + \delta)$ and $\beta = v_g(\omega - \delta) - v_3(\omega + \delta)$. When $-8v_g v_3 v_k^2 \geq \beta^2$, $k_{1,2}$ is a conjugate pair, indicating the existence of a spectral gap, while $k_3$ corresponds to the eigenmode $a(k,\omega) = \tilde{a}_1(k,\omega) + \tilde{a}_2(k,\omega)$, where $\tilde{a}_1(k,\omega)$ and $\tilde{a}_2(k,\omega)$ denote orthogonal circularly polarized modes. Thus, $k_3$ corresponds to a linearly polarized HE$_{11}$ mode, which is not coupled to the TM$_{01}$ mode. This mode makes the gap dependent on the polarization. Figure 1(b) shows the results obtained using TCMT of $\delta = 0$ when values with $v_{g3}$ are taken from Fig. 2(a).

Full numerical simulation results using COMSOL (see Fig. 3) qualitatively agree with TCMT. In the lossless case $\gamma = 0$, the spectral gap is defined by a pair of complex conjugated propagation constants [see Figs. 3(a) and 3(b)]. The gap width increases with decreasing the distance $D$ [see Fig. 3(f)], because the coupling coefficient becomes larger. When we incorporate some losses ($\gamma = 0.002$), all modes become complex and the definition of width of the gap depends on how far it is from the observing point to the source. However, the gap width of lossy metal ($\gamma = 0.005$) may still serve as a guide and effective approximation as shown in Figs. 3(a) and 3(b). In addition to the modes of conjugated propagation constants, there exists one more HE$_{11}$ like decoupled mode. The energy flow of this mode is mostly confined inside $\varepsilon \varepsilon = 4$ waveguide [see Fig. 3(e)]. Thus, the gap of the two coupled waveguides is incomplete and polarization dependent.

To make modes of different preferred polarization directions degenerate and obtain a full gap, symmetric structures could be used. One of the options is to utilize four-waveguide $C_{6v}$ structure [see Fig. 4(a)]. We use subscripts $n = 1, 2$ to denote two HE$_{11}$ modes of circular polarizations and $n = 3, 4, 5$ for three TM$_{01}$ modes. Based on the symmetry and energy conservation law in the lossless case, the following relations are satisfied for mutual coupling coefficients: $\kappa_{12} = \kappa_{21} = 0, \kappa_{1m} = \kappa_{m1} = \kappa_{2m} = \kappa_{m2} = \kappa_{i,j}^c$ for $m, n = 3, 4, 5$ and $m \neq n$. Due to the $C_{3v}$ symmetry, eigenmodes $a(k,\omega) = \sum_{m=1}^{3} \beta_{m1} a_m(k,\omega)$ of preferred $x$ polarization ($\beta_1 = \beta_2$) and those of preferred $y$ polarization ($\beta_1 = -\beta_2$) should be degenerate. Using TCMT we can find five eigenmodes of three frequencies: $k_{1,2} = (\alpha \pm i\sqrt{-12v_g v_3 v_k^2 - \beta^2})/2v_g v_3$ (corresponding to two degenerate pairs of modes), $\omega = \omega_0(k) + 2\kappa_2$, where $\alpha = v_g(\omega - \delta + \kappa_2) + v_3(\omega + \delta), \beta = v_g(\omega - \delta + \kappa_2) - v_3(\omega + \delta)$ and $\omega_0(k)$ is the dispersion of the individual TM$_{01}$ mode. Again $k_{1,2}$ can be a conjugate pair, indicating the existence of a gap, $\omega = \omega_0(k) + 2\kappa_2$ corresponds to eigenmode (E3 mode) $a(k,\omega) = \sum_{m=1}^{3} \beta_{m2} a_m(k,\omega)$, which is a symmetric combination of TM$_{01}$ modes. The cut-off frequency of E3 mode is shifted by...
2k, compared with individual TM_{01} mode. Numerical results from COMSOL are shown in Fig. 4. This allows us to conclude that the spectral gap indicated by the yellow region of four coupled waveguides becomes polarization independent when the E3 mode is cutoff. For larger losses (metal in deep ultraviolet regime) the spectral gap still exists but the effective width becomes smaller and eventually disappears as increasing losses make the differences between gap and non-gap region smaller. To enable coupling at longer-wavelength regimes, where losses of metal are lower, one could use dielectric waveguides with higher permittivities (GaAs, for example).

In summary, we have studied a coupler based on two dielectric waveguides in metal involving the coupling of backward and forward waves. By using the TCMT we have predicted a spectral gap in such a system without a periodic structure. This result has been verified by direct numerical simulations. Moreover, we have demonstrated that a complete polarization independent gap can be achieved by using four coupled waveguides with C_{3v} symmetry. Similar coupling between surface plasmon polaritons (SPPs) can happen in metallic-wire structures when the radius is small enough to support backward SPPs. However, high losses of backward SPPs on metallic wires prevent them from realistic realizations. We anticipate that by incorporating materials with gain and/or nonlinearities, the proposed structure can be considered as a platform for the study of gap solitons, optical bistability, high-Q cavities, and plasmonic nanolaser in various systems without periodicity.

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