Extreme suppression of waveguide crosstalk with all-dielectric metamaterials

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Abstract: We present and demonstrate an exceptional coupling in extreme skin-depth waveguides for the extreme suppression of waveguide crosstalk. The anisotropic dielectric perturbation of metamaterial claddings causes such an exceptional coupling and results in an extremely long coupling length.

OCIS codes: (130.0130) Integrated optics, (230.7370) Waveguides, (160.3918) Metamaterial

Dense integration of photonic integrated circuits (PICs) is one of the biggest challenges in the photonic industry due to the prominent crosstalk between the waveguides. Separation distances between the waveguides need to be large enough to avoid the crosstalk and this limits the integration density of photonic chips. To revolve this issue, several approaches have been proposed, for example, using the waveguides super-lattice [1], inverse design [2], plasmonic hybrid structures [3], and all-dielectric metamaterials [4]. Recently, an extreme skin-depth (eskid) waveguide configuration has been proposed that utilizes highly anisotropic metamaterial claddings for the suppression of evanescent waves to reduce the crosstalk [4]. Subwavelength-scale multilayers effectively work as an anisotropic metamaterial cladding and approximately 30 times longer coupling length has been demonstrated on an silicon-on-insulator (SOI) platform compared to the case of standard strip waveguides. However, even with the reduced evanescent waves, there still is waveguide crosstalk and a further question remains as to the limit of the waveguide crosstalk. In this work, we show that there exists an exceptional coupling point in the coupled eskid waveguides where the crosstalk can be suppressed completely in an ideal case. Our coupled mode analysis reveals that the anisotropic dielectric perturbation of the metamaterial cladding causes a non-trivial coupling regime, where the modal index of the anti-symmetric mode is higher than that of the symmetric mode. An exceptional coupling appears at the transition point to this non-trivial coupling regime and results in an infinitely long coupling length, i.e., complete suppression of the waveguide crosstalk.

Figure 1(a) shows the schematic cross-section and geometric parameters of the coupled eskid waveguides with multilayer claddings. The coupled eskids are designed on an SOI platform, i.e., silicon (Si) and silica (SiO_2) as the core and cladding, respectively. We explore the coupling of the fundamental quasi-TE (TE_0) mode, and its modal field profiles are also plotted in Fig. 1(a); from top to bottom, the real component of E_x for symmetric and anti-symmetric modes and imaginary component of E_z for symmetric and anti-symmetric modes. Geometric parameters are set to $h = 220$ nm, $\Lambda = 100$ nm, $\rho = 0.5$, and $N = 4$, considering the minimum feature size of 50 nm for the practical fabrication. Figure 1(b) shows the simulated effective refractive indices of the coupled symmetric n_s (yellow solid) and anti-symmetric n_a (blue dashed) modes as a function of core width w, and Fig. 1(c) shows the corresponding normalized coupling length (blue dots), following

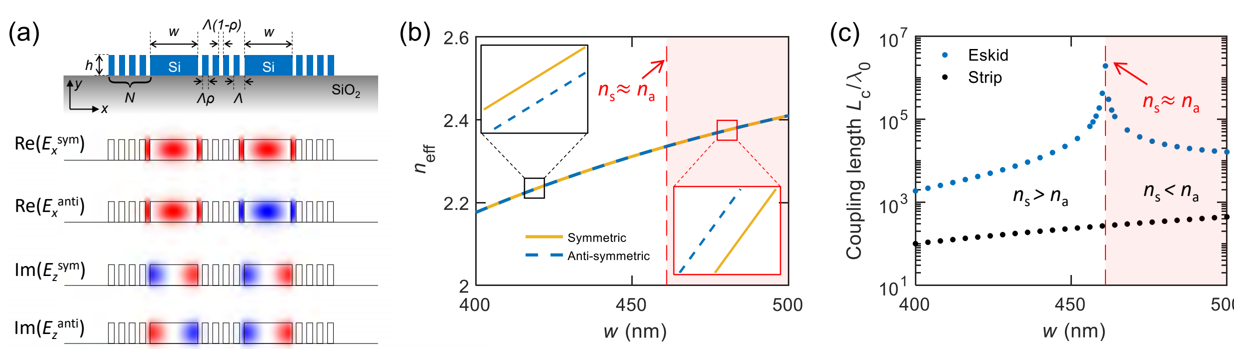

Fig. 1: (a) Schematic cross-section and electric field profiles (real E_x and imaginary E_z of the symmetric and anti-symmetric modes) of the coupled extreme skin-depth (eskid) waveguides with subwavelength multilayer claddings. Geometric parameters are $h = 220$ nm, $\Lambda =$ 100 nm, $\rho = 0.5$, and $N = 4$, unless otherwise specified. The free-space wavelength is $\lambda_0 = 1550$ nm. (b) Numerically simulated effective refractive indices of the symmetric n_s (yellow solid) and anti-symmetric n_a (blue dashed) modes and (c) corresponding normalized coupling length $L_c/\lambda_0 = 1/(2|n_s - n_a|)$. The inset boxes of (b) show the zoomed-in view of the symmetric and anti-symmetric modes. The red-shaded regions in (b) and (c) show the non-trivial coupling regimes, where $n_s < n_a$. The red dashed lines in (b) and (c) indicate the exceptional coupling points, where $n_s \approx n_a$ resulting in an infinitely long coupling length (i.e., $L_c \to \infty$). The black dots in (c) is the case of coupled strip waveguides without metamaterial multilayers for a comparison.

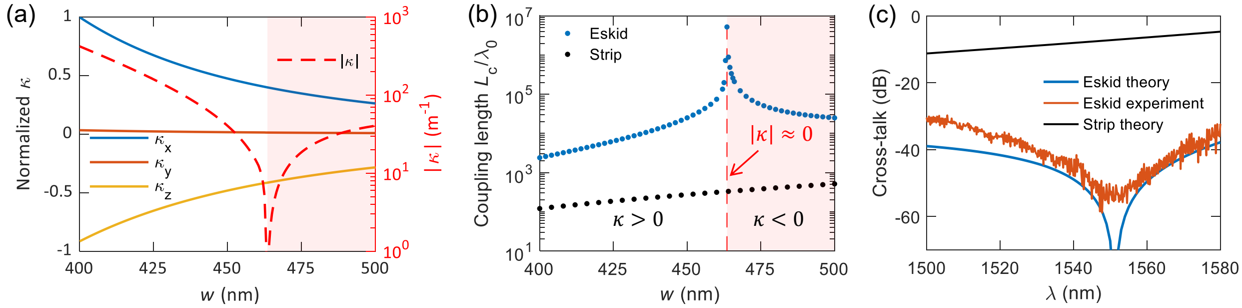

Fig. 2: (a) Normalized coupling coefficients κ_x (blue), κ_y (orange), and κ_z (yellow) of the coupled eskid waveguides (left y-axis) and the corresponding magnitude of the total coupling coefficient $|\kappa| = |\kappa_x + \kappa_y + \kappa_z|$ (red dashed, right y-axis). (b) Normalized coupling lengths $L_c/\lambda_0 = \pi/(2|\kappa|\lambda_0)$ (blue dots). The red-shaded regions show the non-trivial coupling regimes where $\kappa < 0$. The red vertical dashed line indicates the exceptional coupling where $|\kappa| \approx 0$ and $L_c \to \infty$. Geometric parameters are the same as in Fig. 1. (c) Crosstalk of the coupled eskid waveguides as a function of wavelength ($w = 460$ nm and $L = 100\ \mu$m): experiment (orange) and theory (blue). Black solid line is the case in coupled strip waveguides for a comparison.

$L_c/\lambda_0 = 1/(2|n_s - n_a|)$ [5]. Coupling length defines the minimum length that fully transfers optical power from one waveguide to another and quantifies the crosstalk; i.e., a shorter coupling length means higher crosstalk, and it's the opposite for a longer coupling length. The inset boxes in Fig. 1(b) show the zoomed-in views of n_s and n_a. Notice that, there is a non-trivial coupling regime (red-shaded) where the effective index of the anti-symmetric mode is higher than that of the symmetric mode (i.e., $n_s < n_a$). The red dashed line indicates the transition point to the non-trivial coupling regime, and the indices of the symmetric and anti-symmetric modes cross each other at this point (i.e., $n_s \approx n_a$). Note that, the coupling length is inversely proportional to the index difference between the symmetric and anti-symmetric modes, and the coupling length approaches infinity at this transition point as shown in Fig. 1(c). For a comparison, the normalized coupling length of coupled strip waveguides without metamaterial multilayers is also plotted with black dots.

To fundamentally understand this non-trivial coupling and the exceptional coupling phenomenon, we performed anisotropic coupled mode analysis. As the eskids mode is a quasi-TE$_0$, there exist E_y and E_z components as well even though E_x is dominant. Thus, we should consider all the anisotropic coupling coefficients κ_x, κ_y, and κ_z for an accurate analysis and each coupling coefficient κ_i is given by [5],

$$\kappa_i = \frac{\omega\varepsilon_0}{4} \iint \Delta\varepsilon_i(x,y) E_{1i}(x,y) E_{2i}^*(x,y)\, dxdy \tag{1}$$

where, the subscript $i = x, y$, and z indicate each component, and E_{1i} and E_{2i} are the normalized electric fields at each side of the waveguide without coupling. $\Delta\varepsilon_i$ is the dielectric perturbation between the two modes. Figure 2(a) shows the normalized coupling coefficients κ_x (blue solid), κ_y (orange solid), and κ_z (yellow solid) for the same geometries of Fig. 1. Note that, due to the anisotropic nature of metamaterial claddings, dielectric perturbations are different for each component (i.e., $\Delta\varepsilon_x \neq \Delta\varepsilon_y = \Delta\varepsilon_z$) and $|\kappa_z|$ can be greater than $|\kappa_x|$ (red-shaded). Since E_z is purely imaginary while E_x is purely real, the sign of κ_z is the opposite of κ_x and counteractive in determining the overall coupling coefficient $|\kappa| = |\kappa_x + \kappa_y + \kappa_z|$. The red dashed line in Fig. 2(a) shows the overall $|\kappa|$ (right axis, unit: m^{-1}) and there is an exceptional coupling point where κ_z compensates for κ_x to achieve $|\kappa| \approx 0$. The coupling length of the coupled mode analysis can be obtained by $L_c = \pi/(2|\kappa|)$ [5] and is plotted with blue dots in Fig. 2(b). The black dots are the case of strip waveguides as a comparison. Again, the coupling length of the coupled eskid waveguides approaches infinity ($L_c \to \infty$) at the exceptional coupling point. The exceptional coupling results in Fig. 2(b) through the coupled mode analysis match well with those in Fig. 1(c) from the full numerical simulations. We also experimentally demonstrated the exceptional coupling in Fig. 2(c); the blue and orange lines are the simulated and experimentally measured crosstalk spectrum, respectively, and the dips in the crosstalk near the $\lambda \approx 1550$ nm correspond to the exceptional coupling. The black line is the case of coupled strip waveguides.

In summary, we have presented and experimentally demonstrated an exceptional coupling phenomenon in coupled eskid waveguides that can extremely suppress the waveguide crosstalk. Our coupled mode analysis shows that the anisotropic dielectric perturbation of eskid causes such a non-trivial coupling regime and an exceptional coupling point at transition. Our scheme can be realized on an SOI platform and should increase the photonic chip integration density drastically.

References

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