Exceptional coupling in photonic anisotropic metamaterials for extremely low waveguide crosstalk: supplement

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1. METHODS

A. Numerical simulation

A commercially available software (Lumerical Mode Solution) was used to calculate the effective refractive indices of the coupled symmetric and anti-symmetric modes. For the implementation of an ideal metamaterial cladding, the EMT was used for the $\varepsilon_x = \varepsilon_\perp$ and $\varepsilon_y = \varepsilon_z = \varepsilon_\parallel$, following Eq. 1 of the main manuscript. For the strip-to-eskid adiabatic transition, a full 3D FDTD simulation was used to minimize the cross-coupling efficiency.

B. Coupled mode analysis

For the coupled mode analysis, we calculated the $\kappa_i$ by taking the separate electric fields distributions $E_{1i}$ and $E_{2i}$ of an isolated waveguide 1 and 2, respectively. A dielectric perturbation between the two separate waveguides was obtained for each component $\Delta \varepsilon_i$, which plays a significant role in realizing the exceptional coupling. Each coupling coefficient $\kappa_i$ was added together to form the total coupling coefficient $|\kappa|$, and equation $L_C = \frac{\pi}{2|\kappa|}$ was used to calculate the corresponding coupling length.

C. Device fabrication

The photonic chips were fabricated on an SOI wafer (220 nm thick Si on a 2 µm SiO$_2$) using the JEOL JBX-6300 EBL system, which operated at 100 KeV energy, 400 pA beam current, and 500 µm × 500 µm exposure field. A solvent rinse was done, followed by 5 min of O$_2$ plasma treatment. Hydrogen silsequioxane resist (HSQ, Dow-Corning XR-1541-006) was spin coated at 4000 rpm and pre-exposure baked on a hotplate at 90$^\circ$C for 5 min. Shape placements by the machine grid, the beam stepping grid, and the spacing between dwell points during shot shape writing were 1 nm, 4 nm, and 4 nm, respectively. An exposure dose of 1460 µC/cm$^2$ was used.

The resist was developed in 25% tetramethylammonium hydroxide (TMAH) for 4 min followed by a flowing deionized water rinse for 60 s and an isopropanol rinse for 10 s. Then, nitrogen was blown to air dry. After development of the resist, the unexposed top silicon layer was etched by a Cl$_2$/O$_2$ in a reactive ion-plasma etching tool (Trion Minilock) to transfer the pattern from the resist to the silicon layer.

D. Device characterization

The photonic chips were characterized by a custom-built grating coupler setup. An angle polished (8$^\circ$) eight-channel fiber array was used to couple light in and out of the grating couplers. The fiber array was mounted on a five-axis stage with a high-precision adjuster with 20 nm sensitivity in XYZ direction. A Keysight Tunable Laser 81608A was used as the source and a Keysight N7744A optical power meter with InGaAs sensors was used as the output detector. The wavelength was swept from 1500 to 1580 nm with a step of 100 pm. A polarization controller was used to control the polarization of the input laser light.
2. EFFECTIVE MEDIUM THEORY VS. SUBWAVELENGTH MULTILAYERS

Fig. S1. Ideality of anisotropic metamaterial. Schematics of the (a) ideal eskid with effective medium theory (EMT) and (b) practical eskid with multilayer claddings. Normalized coupling lengths $L_c/\lambda_0$ for the coupled eskid waveguides with (c) EMT and (d) multilayers with different periodicity: $\Lambda = 2$ nm (blue dots), 10 nm (orange dots), 50 nm (yellow dots), and 100 nm (purple dots). The filling fraction is set to $\rho = 0.5$ and the other parameters are $h = 220$ nm, $g = 550$ nm, and $\lambda_0 = 1550$ nm. Note that, as the $\Lambda$ reduces, the exceptional coupling point with multilayers in (d) approaches to that with EMT in (c). This is because the subwavelength-scale multilayer structure approaches an ideal EMT metamaterial as the $\Lambda$ reduces (i.e, $\Lambda \ll \lambda$) [1].

3. STRIP-TO-ESKID ADIABATIC MODE TRANSITION

Fig. S2. Strip-to-eskid interface optimization. (a,b) Schematics of the strip-to-eskid mode transition region: (a) Adiabatic and (b) Direct transitions. The bending radii are $R = 20$ $\mu$m and $r = 15$ $\mu$m, respectively. The core width at the input strip waveguide is fixed to $w_0 = 450$ nm, while the core width of the eskid is varied $w = 400 - 450$ nm. The core width is adiabatically tapered through the bending. $I_{in}$ is the input power at the strip waveguide, whereas $I_0$ and $I_c$ are the powers at the through and coupled ports of the eskid. (c,d) Simulated power coupling efficiencies of (c) $I_c/I_{in}$ and (d) $I_0/I_{in}$ as a function of $w$ for adiabatic (blue) and direct (orange) transitions. Circles indicate the full 3D FDTD simulation results and solid lines are their fitting curves. Notice that the adiabatic transition reduces the coupling efficiency $I_c/I_{in}$ close to $10^{-5}$. This allowed us to measure the extremely low waveguide crosstalk in the experiment.

To measure the waveguide crosstalk at the extremely low power level, the interface crosstalk at each port should be lower than the waveguide crosstalk. When measuring waveguide crosstalk above $-40$ dB, one may use a direct strip-to-eskid coupling as shown in...
Fig. S2(b) [2, 3]. However, in our case, the power level of the waveguide crosstalk due to the exceptional coupling is below ~40 dB and an additional transition scheme is required. Figures S2(a) and S2(b) show the strip-to-eksid interface schemes with adiabatic and direct transitions, respectively. R is the bending radius of the waveguide core and r is the bending radius of the metamaterial multilayers. The powers at the input strip, through port ekisd, and coupled ekisd waveguides are denoted by \( I_m, \lambda_0 \), and \( L_e \), respectively. We fixed the core width at the input strip waveguide to \( w_0 = 450 \) nm and the core width of ekisd waveguide \( w \) is varied from 400 nm to 450 nm. Through the bending, the core width is tapered adiabatically. Figures S2(c) and S2(d) are the full 3D FDTD simulation results showing the coupling efficiencies for \( L_e / I_m \) and \( L_o / I_m \), respectively, with the banding radii of \( R = 20 \mu m \) and \( r = 15 \mu m \). Blue and orange circles are the coupling efficiencies of the adiabatic and direct transition schemes, respectively, and solid lines are their fitting curves. Since the exceptional couplings are observed at the power level below ~40 dB, the coupling efficiency \( L_e / I_m \) should be less than \( 10^{-4} \). With the direct transition, the coupling efficiency \( L_e / I_m \) is at the border-line of \( 10^{-4} \) and the exceptional coupling phenomena were not seen clearly (i.e., too shallow dips). However, with the adiabatic transition as in Fig. S2(c), the coupling efficiency \( L_e / I_m \) has been suppressed further down to \( \approx 10^{-5} \) and the exceptional coupling phenomena were observed clearly as shown in Fig. 3 of the main manuscript.

4. PARAMETRIC STUDIES ON THE EXCEPTIONAL COUPLING

As the exceptional coupling exists near the \( |x_c| \approx |x_s| \), which is determined by the anisotropic dielectric perturbation and the modal overlap, changing the filling fraction \( \rho \) and geometric parameters \( w, g, \) and \( h \) shift the exceptional coupling point. In other words, these parameters would work as tuning knobs to engineer the exceptional coupling points. To explore the engineering capability of the exceptional coupling, full parametric simulations were conducted on the coupled ekisd configuration with EMT. Figures S3(a–c) show the calculated \( L_c / \lambda_0 \) map plots as functions of \( w \) and \( g \), \( w \) and \( h \), and \( w \) and \( \rho \), respectively. Other parameters are set to \( h = 220 \) nm, \( g = 550 \) nm, and \( \rho = 0.5 \), unless otherwise specified. In Fig. S3(a), it is noted that, as the \( g \) reduces, the exceptional coupling appears at a wider \( w \). This is due to the similar trend in \( g \) and \( w \) for the modal overlap; as the \( g \) reduces, there will be more modal overlap due to the proximity, while there will be less modal overlap as the \( w \) increases due to the higher light confinement. The reduced modal overlap due to the increased \( w \) compensates for the increased modal overlap due to the reduced \( g \), shifting the exceptional coupling point. Changing the \( h \) of the scheme would show a similar effect as the \( g \) and \( w \), as increasing the \( h \) allows for a higher confinement, thus less modal overlap. To compensate for the reduced modal overlap due to the increased \( h \), the \( w \) should be narrower. This trend is clearly shown in Fig. S3(b). Changing the \( \rho \) is more complex than changing other parameters, as it simultaneously modifies both \( \varepsilon_x \) and \( \varepsilon_z \). However, within the range of our evaluation, the anisotropy increases as \( \rho \) increases and the effect of anisotropic dielectric perturbation becomes more dominant. Thus, the \( \kappa_s \) with a higher \( \rho \) can compensate for the \( \kappa_s \) at a larger modal overlap, which is a narrower \( w \). This trend is also clearly shown in Fig. S3(c).

5. EXCEPTIONAL COUPLINGS WITH DIFFERENT PARAMETERS

As shown in Fig. S3, the exceptional coupling can be engineered with geometric parameters that determine the modal overlap and the anisotropic dielectric perturbation. In cases of the practical ekisd waveguides with subwavelength-scale multilayers, the number of ekisd layers \( N \) and the periodicity \( \Lambda \) determine the gap \( g \) between the two ekisd waveguides, and the ratio of the multilayer width \( \Delta \rho \) and gap \( \Lambda(1 - \rho) \) define the filling fraction \( \rho \). For the practical implementation of the ekisd waveguide, the minimum feature size limits the gap size of multilayers \( \Lambda(1 - \rho) \) to be larger than 40 nm. Considering these limitations, we also demonstrated exceptional couplings with different sets of \( N \) and \( \rho \). Figures S4(a–d) show the crosstalk map plots as functions of \( w \) and \( g \) for different geometries: (a) \( N = 5, \Lambda = 100 \) nm, \( \Lambda(1 - \rho) = 40 \) nm, (b) \( N = 4, \Lambda = 120 \) nm, \( \Lambda(1 - \rho) = 50 \) nm, (c) \( N = 4, \Lambda = 130 \) nm, \( \Lambda(1 - \rho) = 50 \) nm, and (d) \( N = 3, \Lambda = 130 \) nm, \( \Lambda(1 - \rho) = 50 \) nm. Note that the filling fractions of each case are (a) \( \rho = 0.6 \), (b) \( \rho = 0.583 \), (c) \( \rho = 0.615 \), and (d) \( \rho = 0.615 \). Figures S4(e–h) are the simulation results that correspond to Figs. S4(a–d). Notice that, in Fig. S4(a) (\( \rho = 0.6 \)), the exceptional coupling appears at a narrower \( w \) compared to the case of Fig. 3(h) (\( \rho = 0.5 \)) in the main manuscript. The increased \( \rho \) introduces a higher anisotropic dielectric perturbation, allowing the \( \kappa_s \) to compensate for \( \kappa_s \) at a larger modal overlap, i.e., a narrower \( w \). This trend is consistent with our parametric analysis in Fig. S3(c). A similar trend is shown between Figs. S4(b) and S4(c); the \( \rho = 0.615 \) of Fig. S4(c) is higher than \( \rho = 0.583 \) of Fig. S4(b), shifting the exceptional coupling point to a narrower \( w \). The g of Fig. S4(c)
Fig. S4. Exceptional couplings with different geometric parameters. (a-d) Experimentally measured waveguide crosstalk maps as functions of $\lambda$ and $w$ for different geometric parameters: (a) $N = 5$, $\Lambda = 100$ nm, $\Lambda(1 - \rho) = 40$ nm, (b) $N = 4$, $\Lambda = 120$ nm, $\Lambda(1 - \rho) = 50$ nm, (c) $N = 4$, $\Lambda = 130$ nm, $\Lambda(1 - \rho) = 50$ nm, and (d) $N = 3$, $\Lambda = 130$ nm, $\Lambda(1 - \rho) = 50$ nm. The height is fixed to $h = 220$ nm. (e-h) Simulated crosstalk maps that correspond to (a-d).

is also slightly larger ($\Delta \rho = 40$ nm) than that of Fig. S4(b), having the same effect, i.e., a narrower $w$. To separately observe the effect of $\rho$, we also tested the devices with the $N = 3$ in Fig. S4(d). Note that, between Figs. S4(c) and S4(d), the only difference is $N$ while the other parameters are the same. Thus, we can view the results in Fig. S4(d) as the case of a reduced $\rho$ while fixing the other parameters. It is clearly seen that, with a reduced $N$ (thus, a reduced $\rho$), the exceptional coupling appears at a wider $w$. Reducing the $\rho$ increase the modal overlap, thus a wider $w$ (i.e., a higher confinement) is required to compensate for the increased modal overlap. Again, this is consistent with the parametric studies in Fig. S3(a).

6. CROSSTALK SUPPRESSION WITH DIFFERENT NUMBER OF LAYERS

Fig. S5. Numerically simulated crosstalk suppression between eskid and strip waveguides (i.e., $\Delta$Crosstalk) as functions of wavelength $\lambda$ and number of layers $N$. The waveguide core width is set to $w = 450$ nm, and the other parameters are the same as in Fig. 3 of the main manuscript; the case when $N = 5$ corresponds to the result in Fig. 3. Note that, even without the exceptional coupling, there is $\approx 20$ dB of crosstalk suppression; this is due the reduced skin-depth effect of eskid waveguide [2]. The extreme suppression of crosstalk more then 20 dB can be achieved only with the exceptional coupling, i.e., here the case of $N = 5$. 
7. BANDWIDTH ANALYSIS ON THE EXCEPTIONAL COUPLING

Fig. S6. Bandwidth analysis on the exceptional coupling. The bandwidth \(\Delta \lambda\) versus the crosstalk suppression \(\Delta \text{Crosstalk}\) (i.e., the crosstalk difference between the eskid and strip waveguides) of the experiments (blue dots) and simulations (orange lines) in Figs. 3(d) and 3(f), respectively: (a) \(w = 420\) nm, (b) \(w = 430\) nm, (c) \(w = 440\) nm, and (d) \(w = 450\) nm. The average bandwidth ranges \(\Delta \lambda \approx 62.9 \pm 3.7\) nm for \(\Delta \text{Crosstalk} = 30\) dB and \(\Delta \lambda \approx 16.0 \pm 2.1\) nm for \(\Delta \text{Crosstalk} = 40\) dB.

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