

Zero-Spacing Photonic Channels via Perturbation Engineering

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Optical waveguides conventionally rely on wavelength-scale low-index spacing or cladding to isolate neighboring channels, fundamentally limiting photonic integration density. Here, we show that such spatial separation is not a prerequisite for independent waveguiding. By introducing deep-subwavelength metal perturbations ($\sim \lambda_0/25$) onto the surfaces of a dielectric slab, we realize multiple dielectric guiding channels with zero physical spacing. This behavior arises from perturbation-engineered suppression of supermode index splitting, achieved by selectively modifying the symmetric mode while leaving the antisymmetric mode nearly unchanged. We validate this mechanism through full-wave simulations and microwave experiments in both straight and bent geometries. Extending this concept to the optical regime, we design silicon-on-insulator waveguides incorporating hybrid silver-silicon perturbations, achieving ultralong coupling lengths ($L_c \geq 1000\lambda_0$) across a broad bandwidth from 1495 to 1565 nm. Owing to the minimal metal volume, propagation losses remain significantly lower than those of conventional hybrid plasmonic systems. This metal-dielectric hybrid waveguide system enables ultradense photonic integration and provides new insights into controlling optical coupling.

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Low-index spacing or cladding between adjacent waveguides is essential for confining light and suppressing evanescent coupling in conventional photonic circuits. To eliminate crosstalk, wavelength-scale spacing is typically required, fundamentally limiting photonic integration density. To date, a variety of strategies have been devoted to solving this bottleneck, including anisotropic claddings [1–9], superlattices [10–13], periodically curved waveguides [14–21], epsilon-near-zero claddings [22,23] and engineered higher-order waveguide modes [24,25]. However, these methods yield only marginal reductions in spacing. Alternatively, metal-dielectric hybrid plasmonic waveguides offer a route toward higher integration density by exploiting deeply subwavelength-confined plasmonic modes [26–36], yet their practical applicability is severely constrained by ohmic losses. More recently, cladding-free waveguides based on spatial or hyperbolic dispersions [37–40] have been demonstrated, achieving 100% space utilization. Though conceptually elegant, these approaches fundamentally rely on photonic crystals or metamaterials as

new guiding channels, with complexity far beyond dielectric slabs.

In this Letter, we demonstrate a novel zero-spacing waveguide (ZSW) architecture by leveraging perturbation engineering on the surfaces of dielectric slabs. Guided by perturbation theory [41–45], we show that introducing deep-subwavelength metal perturbations onto the surfaces of a bare dielectric slab can selectively engineer the effective refractive index of the symmetric supermode (n_s), while leaving that of the antisymmetric supermode (n_a) unchanged. This allows us to suppress the effective index splitting ($|n_s - n_a| \rightarrow 0$) at any desired wavelength, effectively transforming a single dielectric slab into multiple independent guiding channels with zero spacing. This mechanism is validated through full-wave simulations and microwave experiments on both straight and bent geometries. Furthermore, extending this principle to optical frequencies, we design zero-spacing silicon-on-insulator (SOI) waveguides incorporating a combination of silver and silicon perturbations, which exhibit an ultralong coupling length $L_c \geq 1000\lambda_0$ (λ_0 is the free-space wavelength) from 1495 to 1565 nm, encompassing the entire C band. Crucially, owing to the extremely small metal volume involved, the propagation loss is significantly lower than that of conventional hybrid plasmonic waveguides, enabling propagation lengths exceeding 360 μm at 1550 nm. Our work defines a new category of photonic slab waveguides

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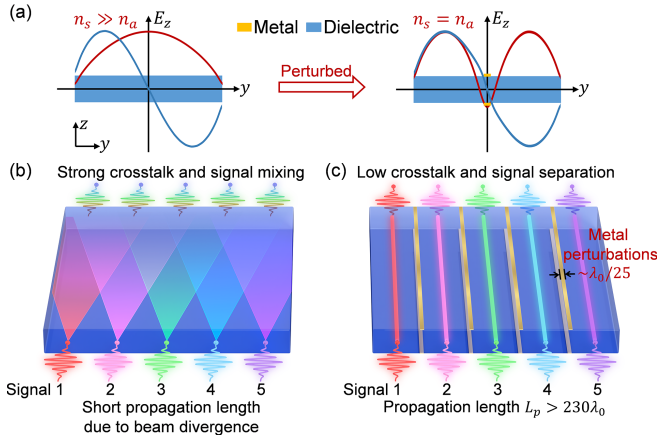


FIG. 1. (a) E_z distributions of the symmetric (red) and anti-symmetric (blue) supermodes in the waveguide without (left panel) and with (right panel) metal perturbations as a function of y . (b) A bare dielectric slab. Optical signals rapidly delocalize across the entire space, causing strong mode mixing and severe interchannel crosstalk. (c) Proposed ZSWs. Deep-subwavelength metal perturbations ($\sim \lambda_0/25$) are introduced on the slab surfaces, suppressing interchannel coupling and effectively segmenting the slab into multiple independent photonic channels with zero spacing.

exhibiting near-zero crosstalk with zero spacing, paving the way for ultrahigh-density photonic integration.

The left panel of Fig. 1(a) shows the case of a bare dielectric slab, where the difference between n_s and n_a implies severe interchannel crosstalk, leading to delocalization (see Fig. S1 in Supplemental Material [46]) of all optical signals launched from different input ports, as shown in Fig 1(b). Conventionally, this problem is mitigated by partitioning the slab into isolated waveguides using low-index cladding to confine modes. In order to suppress evanescent coupling between waveguides, this spacing is usually wavelength-scale. In stark contrast, our approach eliminates the need for any low-index spacing. As shown in Fig. 1(c), we periodically integrate deep-subwavelength metal strips ($\sim \lambda_0/25$) onto the top and bottom surfaces of the dielectric slab. Remarkably, these metal perturbations turn the dielectric slab into multiple optically isolated channels, with negligible crosstalk between adjacent channels. Attributing to influences of metal perturbations, we can significantly change field distributions of the symmetric supermode, and realize $n_s = n_a$, as illustrated in the right panel of Fig. 1(a). Once this supermode degeneracy is achieved, optical energy can be localized within a single channel, preventing any crosstalk to the neighboring channel even under zero-spacing conditions.

To uncover the physical mechanism underlying ZSWs, we first consider a microwave slab waveguide consisting of a suspended alumina slab (relative permittivity $\epsilon_r = 9.6$, width $w = 28$ mm, and height $h = 4$ mm), whose cross section is depicted in Fig. 2(a). To transform this dielectric slab into two ZSWs, two narrow copper strips (electrical conductivity $\sigma = 5.998 \times 10^7$ S/m, width

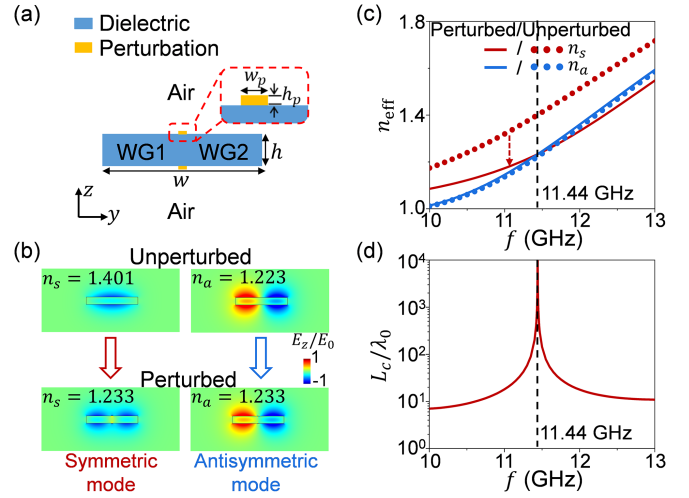


FIG. 2. (a) Cross section of the proposed ZSW, comprising a dielectric strip waveguide with tiny copper perturbations placed on its top and bottom surfaces. (b) Simulated E_z distributions for the fundamental symmetric and antisymmetric TM supermodes at 11.44 GHz, without (upper) and with (lower) perturbations. (c) Calculated effective refractive indices for the fundamental symmetric (n_s , red) and antisymmetric (n_a , blue) TM supermodes as a function of frequency f , without (dots) and with (lines) perturbations. The noncoupling condition ($n_s = n_a$) occurs at 11.44 GHz (black dashed line). (d) Normalized coupling length L_c/λ_0 for the fundamental TM modes as a function of f .

$w_p = 1$ mm, and height $h_p = 35$ μ m) are placed at the centers of the top and bottom surfaces. Since these copper strips are substantially smaller than both the waveguide dimensions and the operating wavelength, they can be treated as perturbations.

We consider transverse-magnetic (TM) modes, dominated by the electric field components E_x and E_z . The upper panel of Fig. 2(b) shows the simulated E_z distributions for the lowest-order symmetric (upper) and antisymmetric (lower) supermodes in this dielectric slab at 11.44 GHz, obtained by using the finite-element software COMSOL Multiphysics. The symmetric and antisymmetric supermodes exhibit effective refractive indices of $n_s = 1.401$ and $n_a = 1.223$, respectively, revealing the mode splitting characteristic of the system's supermodes.

Subsequently, we investigate the effect of copper perturbations on these supermodes. Perturbation theory [41–45] suggests that strategically positioned perturbations in regions of a strong electric field can significantly modify the modal characteristics. These modifications can be quantitatively described by the change in the propagation constant [41,43],

$$\Delta\beta = \frac{k_0^2}{2\beta} \frac{\int (\tilde{\epsilon}(\mathbf{r}) - \epsilon(\mathbf{r})) |\phi(\mathbf{r})|^2 dS}{\int |\phi(\mathbf{r})|^2 dS}, \quad (1)$$

where $\epsilon(\mathbf{r})$ and $\tilde{\epsilon}(\mathbf{r})$ denote the relative permittivity distributions without and with the perturbation, respectively.

$\phi(\mathbf{r})$ is the unperturbed modal field, β is the unperturbed propagation constant, and k_0 is the free-space wave number. For TM modes, the corresponding change in the effective refractive index becomes

$$\Delta n_{\text{eff}} = \frac{\Delta\beta}{k_0} = \frac{1}{2n_{\text{eff}}} \frac{\int \Delta\epsilon(y, z) |E_z(y, z)|^2 dy dz}{\int |E_z(y, z)|^2 dy dz}, \quad (2)$$

where n_{eff} is the unperturbed effective refractive index and $\Delta\epsilon(y, z) = \tilde{\epsilon}(y, z) - \epsilon(y, z)$. Equation (2) indicates that a nonzero $\Delta\epsilon(y, z)$ directly induces a change in Δn_{eff} , providing an effective route to control Δn_{eff} and thus to realize the ZSWs.

The E_z distribution in Fig. 2(b) reveals that $|E_z(y, z)|$ at the perturbation location is large for the symmetric supermode, but vanishingly small for the antisymmetric supermode. According to Eq. (2), this yields $\Delta n_s \ll 0$ ($\Delta n_a \approx 0$) for the symmetric (antisymmetric) supermode, with Δn_s controllable through the geometry of the metal perturbations. The lower panel of Fig. 2(b) presents the simulated E_z distributions for the symmetric (upper) and antisymmetric (lower) supermodes at 11.44 GHz. The metal perturbations indeed reduce n_s to 1.233, while leaving n_a almost unchanged, making the two indices nearly equal. The frequency dependence of n_s and n_a is further explored in Fig. 2(c). The results match well with the predictions from the perturbation theory, as discussed in Fig. S2 in Supplemental Material [46].

When $n_a = n_s$, crosstalk between the two ZSWs (denoted as WG1 and WG2) vanishes [50]. As shown in Fig. 2(c), this condition arises at 11.44 GHz. The coupling length L_c between adjacent waveguides, which is inversely proportional to crosstalk strength, is given by [32,51]

$$L_c = \frac{\lambda_0}{2|n_s - n_a|}. \quad (3)$$

Figure 2(d) shows the normalized coupling length L_c/λ_0 as a function of frequency f . It diverges ($L_c/\lambda_0 \rightarrow \infty$) at 11.44 GHz, indicating zero crosstalk under zero-spacing conditions. Notably, the copper strip perturbation has a deep-subwavelength width $w_p \sim \lambda_0/25$ ($\lambda_0 \approx 26.2$ mm), orders of magnitude smaller than conventional cladding width ($\sim 1.1\lambda_0$, see Fig. S3 in Supplemental Material [46]).

To validate the functionality of ZSWs, we perform full-wave simulations and proof-of-principle microwave experiments. We first investigate the transmission characteristics of either WG1 or WG2 with a propagation distance $L \approx 63\lambda_0$ ($\lambda_0 \approx 26.2$ mm) [Fig. 3(a), inset], under fundamental TM mode excitation. The model is identical to that in Fig. 2(d). The transmission can be derived from [4,6,8]

$$T = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{1}{\tan^2\left(\frac{\pi L}{2L_c}\right) + 1}, \quad (4)$$

where the coupling length L_c is obtained from Fig. 2(d). Excellent agreement is observed between the theoretical

results (line) and full-wave simulations (dots), both showing near-unity transmission around 11.44 GHz.

The ZSW behavior is further validated through microwave experiments. Figure 3(b) shows the fabricated sample and the experimental setup. The waveguide system consists of an alumina strip ($240 \times 28 \times 4$ mm) sandwiched between two flexible printed circuits with copper strips ($240 \times 1 \times 0.035$ mm). The alumina strip is placed on a foam (relative permittivity ~ 1). A monopole antenna is inserted into an alumina channel ($50 \times 14 \times 4$ mm) to excite the fundamental TM mode of the channel. A probe antenna measures the E_z distribution on the xy plane, at a distance of 1 mm above the alumina strip. Figure 3(c) presents the simulated (11.44 GHz) and measured (11.14 GHz) $|E_z|$ distributions in the waveguide with (lower panels) and without (upper panels) metal perturbations. Attributed to the modulation of the copper perturbations, the transmitted waves are clearly tightly confined to the lower channel, with negligible coupling into the upper channel. By contrast, in the absence of copper perturbations, severe waveguide crosstalk occurs [Fig. 3(c), upper panels]. These experimental results agree well with the simulations, further confirming the effectiveness of the ZSW.

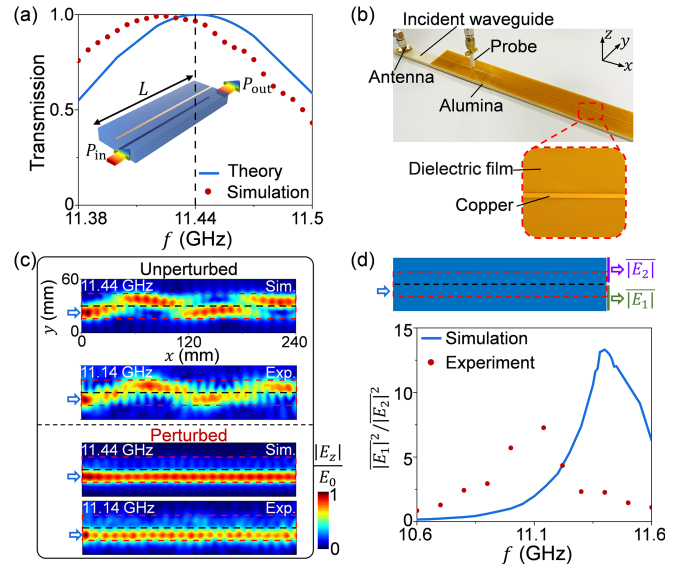


FIG. 3. (a) Theoretical (line) and simulated (dots) transmission through waveguides of length $L \approx 63\lambda_0$ ($\lambda_0 \approx 26.2$ mm) under fundamental TM mode excitation (inset). (b) Photographs of the waveguide sample and the experiment setup. (c) Simulated (11.44 GHz) and measured (11.14 GHz) $|E_z|$ distributions in the waveguide of length $L = 240$ mm. The upper and lower panels correspond to the unperturbed and perturbed slabs. (d) The square of the ratio of simulated (blue line) and measured (red dots) average electric field ($|E_1|^2/|E_2|^2$) at the initial channel's output to that at the adjacent channel's output as a function of the operating frequencies f . The upper panel in (d) shows the schematic for extracting the output average electric fields (i.e., $|E_1|$ and $|E_2|$).

To make a quantitative comparison, we extract the average electric fields (i.e., $|\overline{E}_1|$ and $|\overline{E}_2|$) at the output facets of both channels in simulation and experiment, as illustrated in the upper panel of Fig. 3(d). As shown in the lower panel of Fig. 3(d), the square of the simulated (blue line) electric field ratio ($|\overline{E}_1|^2/|\overline{E}_2|^2$) reaches its maximum near 11.44 GHz, while the experimental (red dots) peak occurs around 11.14 GHz. The trend of these two curves matches the transmission curve in Fig. 3(a) very well.

Next, we show that the working bandwidth of ZSWs can be expanded by combining metal and dielectric perturbation engineering. We now consider the practical design of a broadband zero-spacing SOI waveguide array in the optical regime. The system is modeled as an infinite waveguide array using periodic boundary conditions [Fig. 4(a)].

We first consider a waveguide with only metal perturbations [Fig. 4(a), left panel]. Rectangular silver (Ag) perturbations ($w_p \times h_p$) are introduced on the top and bottom surfaces of a silicon (Si) slab ($w = 1800$ nm, $h = 220$ nm). By optimizing the Ag perturbation dimensions ($w_p = 68$ nm, $h_p = 30$ nm), the condition $n_s \approx n_a$ is achieved near 1550 nm, as depicted in Fig. 4(c) for the case of $h_0 = 0$. However, this configuration exhibits a narrow bandwidth of approximately 3 nm for $L_c \geq 1000\lambda_0$. Here, we use silver instead of copper due to its lower ohmic loss in the near-infrared band (see Sec. 13 in Supplemental Material [46]).

To broaden the bandwidth, we introduce additional dielectric perturbations. As shown in the right panel of Fig. 4(a), rectangular Si perturbations (width w_0 , height h_0) are placed above and below the Si slab. According to Eq. (2), the magnitude of the effective refractive index shift is proportional to the electric field intensity within the perturbed region. We find that for the symmetric supermode, the electric field in the silicon perturbed region is stronger at shorter wavelengths than at longer wavelengths (see Fig. S8 in Supplemental Material [46]), leading to a larger increase in n_s at shorter wavelengths. In contrast, for the antisymmetric supermode, the field strength in the perturbation region remains nearly constant over the wavelength range, resulting in a wavelength-independent shift in n_a . This different dispersion behavior makes the dispersion curves of the symmetric and antisymmetric supermodes nearly parallel, yielding $n_s \approx n_a$ over a broad spectral range and thereby realizing a broadband zero-spacing SOI waveguide array. Details are provided in Sec. 7 in Supplemental Material [46]. Here, the dispersions of Ag, Si, and SiO₂ are all taken into account. Figure 4(b) shows the bandwidth $\Delta\lambda$ for $L_c/\lambda_0 \geq 1000$ as a function of width w_0 and height h_0 of the Si perturbations. Concurrently, we fine-tune the Ag perturbation dimensions (w_p and h_p) to ensure an infinite coupling length near $\lambda_0 = 1550$ nm. By balancing bandwidth performance with fabrication feasibility, we identify a set of optimal parameters: $w_0 = 350$ nm, $h_0 = 80$ nm, $w_p = 44$ nm, and $h_p = 30$ nm, as indicated by the red star in Fig. 4(b).

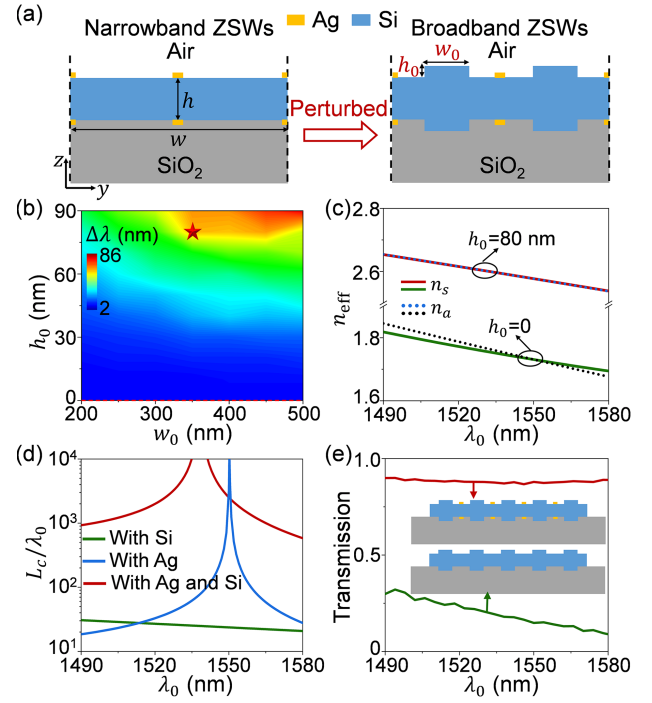


FIG. 4. (a) Cross-sectional schematic of an infinite waveguide array without (left) and with (right) additional Si perturbations, where periodic boundary conditions are applied along the y direction. The waveguide consists of a Si slab (dimension $w \times h$) on a SiO₂ substrate with engineered rectangular Ag (dimension $w_p \times h_p$), and Si perturbations (dimension $w_0 \times h_0$) above and below the Si slab. (b) Calculated bandwidth $\Delta\lambda$ for $L_c/\lambda_0 \geq 1000$ as a function of the width w_0 and height h_0 of Si perturbations. The red star marks the optimal design with $w_0 = 350$ nm and $h_0 = 80$ nm. (c) Effective refractive indices for symmetric (solid lines) and antisymmetric (dotted lines) TM supermodes as functions of λ_0 for the ZSW [right panel in (a)] with ($h_0 = 80$ nm) and without ($h_0 = 0$) Si perturbations. (d) Normalized coupling length L_c/λ_0 as a function of λ_0 in comparison with Si-only (green), Ag-only (blue), and hybrid (red) perturbation configurations. (e) Simulated transmission of the excited channel in a five-channel waveguide array (length 40 μ m) for hybrid (red, upper inset) and Si-only (green, lower inset) perturbations, with the fundamental TM mode excited in the central channel.

To elucidate the role of Si perturbations, we compare the effective refractive indices of symmetric (n_s , solid lines) and antisymmetric (n_a , dotted lines) supermodes for waveguides with ($h_0 = 80$ nm) and without ($h_0 = 0$) Si perturbations [Fig. 4(c)]. For $h_0 = 80$ nm, the Si perturbations significantly broaden the spectral range over which $n_s \approx n_a$ holds, thereby enabling wideband ZSW operation. Figure 4(d) quantifies this performance by plotting the normalized coupling length L_c/λ_0 as a function of λ_0 for three configurations: Si-only (green), Ag-only (blue), and hybrid Si-Ag (red). The Si-only configuration fails to suppress crosstalk, exhibiting a short coupling length across the spectrum. The Ag-only structure successfully suppresses crosstalk but is limited to a narrow bandwidth of

~ 3 nm. Interestingly, the hybrid Si-Ag design not only achieves zero crosstalk ($L_c/\lambda_0 \rightarrow \infty$ at 1538 nm) but also maintains $L_c/\lambda_0 \geq 1000$ over a 70-nm bandwidth (1495–1565 nm). Furthermore, it sustains $L_c \geq 600\lambda_0$ across an ultrawide spectrum of 169 nm (1410–1579 nm; see Fig. S9 in Supplemental Material [46]), substantially outperforming the narrowband Ag-only case. We then plot the transmission of the excited channel in a five-channel waveguide array (length 40 μm) for hybrid (red) and Si-only perturbations (green) in Fig. 4(e), with the fundamental TM mode launched in the central channel. The hybrid design exhibits substantially enhanced transmission over a broad bandwidth, confirming the effectiveness of perturbation engineering in suppressing crosstalk in this zero-spacing SOI waveguide array. Details of simulated field distributions and simulation settings are provided in Secs. 8 and 18 in Supplemental Material [46], respectively.

These findings reveal the complementary roles of the perturbation types: Ag perturbations yield long coupling lengths, whereas Si perturbations further broaden the operational bandwidth. From the results of both the infinite and five-channel arrays, we obtain a center-to-center distance of just 900 nm between adjacent SOI waveguides. This represents a 29% reduction compared to previous anisotropic-cladding designs (1270 nm) [8] for TM-mode photonic circuits. We also demonstrate a high-transmission 180° -bending ZSW with hybrid Si-Ag perturbations (see Fig. S13 in Supplemental Material [46]).

Notably, in our proposed ZSWs, metal perturbations serve to modify the supermode profiles without exciting surface plasmons. Consequently, the propagation length for this ZSW (exceeding 360 μm at 1550 nm) is substantially larger than that in hybrid plasmonic waveguides (~ 40 μm), which rely on surface plasmons sustained by metals (see Fig. S14 in Supplemental Material [46]). This fundamental difference is also manifested by the tiny volume of the Ag perturbations. We note that the stability in signal transmission is further confirmed (see Fig. S16 in Supplemental Material [46]), and the propagation loss can be mitigated by incorporating gain materials [52–55] or complex frequencies [56–60].

Compared with previous cladding-free designs that adopt complex structures such as photonic crystals or metamaterials [37–40] to construct new guiding channels, the present architecture possesses the distinct advantage of retaining dielectric slabs as guiding channels, enabling compatibility with mainstream photonic circuit platforms. The introduction of metal and dielectric perturbations on the surfaces of a bare dielectric slab establishes a fundamentally new working principle of metal-dielectric hybrid waveguiding. We note that although supermode degeneracy has been exploited for thin-cladding engineering [6,8], such an extraordinary zero-spacing waveguide system has never been proposed or demonstrated before. Furthermore, our method may provide a versatile platform to flexibly control

the coupling length and dynamically tailor waveguide configurations for future photonic applications.

In summary, perturbation engineering establishes a robust route toward ZSWs with negligible crosstalk, transcending the conventional reliance on cladding-assisted confinement. By leveraging mode-selective perturbations to achieve $n_s \approx n_a$, we effectively decouple adjacent channels within a continuous dielectric slab. This framework offers near-arbitrary control over coupling lengths, introducing a critical degree of freedom in the design of ultracompact on-chip devices such as directional couplers and splitters. Looking forward, this approach is readily compatible with tunable platforms such as lithium niobate, enabling dynamically reconfigurable and programmable photonic circuits. Crucially, the metal-only implementation suggests a potentially etching-free fabrication process that requires only patterned metal features on dielectric slabs. These findings open a pathway to ultra-high-density photonic integration and establish a versatile paradigm for engineering scalable, fabrication-efficient on-chip systems through perturbative design.

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Data availability—There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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End Matter

Applicability and limitations of the perturbation theory—It should be noted that the application of Eqs. (1) or (2) is independent of whether the electric field is normalized. Notably, in this waveguide system, dielectric perturbations ($\tilde{\epsilon} \geq 1$) cannot achieve supermode degeneracy, as Eq. (2) dictates that $\tilde{\epsilon} < 1$ is required for the perturbation to yield a negative effective index change ($\Delta n_s < 0$). Furthermore, Eq. (2) only predicts that the relative permittivity of the introduced perturbation must be lower than that of the original medium, but it cannot yield an exact value. Consequently, both the specific relative permittivity and the geometric dimensions of the perturbation still need to be determined through simulations.

Frequency tunability and universality of the ZSW design—The noncoupling frequency where $\Delta n = 0$ can be tuned by perturbation width w_p and height h_p (see Fig. S4 in Supplemental Material [46]). Importantly, this method

also applies to higher-order modes beyond the fundamental TM mode (see Fig. S5 in Supplemental Material [46]), underscoring the universality of the ZSW design.

Applicability of Eq. (4)—The deviation between theory and simulation in Fig. 3(a) likely stems from the applicability of Eq. (4) to conventional waveguides with physical gaps, which differs from our zero-spacing waveguide. However, the overall trends of the transmission calculated by both approaches are in good agreement.

Details of experimental results—In microwave experiment, both antennas are connected to a PNA Network Analyzer N5224B. Here, we establish a direct through-connection between the excitation antenna and the receiving probe antenna to calibrate the S_{21} response. For experimental results in Fig. 3(d), $|\overline{E}_1|$ and $|\overline{E}_2|$ are obtained by taking the line average of the

output field along the upper and lower halves of the evaluation line across the dual-waveguide system, respectively. Furthermore, a 90°-bending ZSW is also validated by both simulations and experiments (see Fig. S6 in Supplemental Material [46]). The results confirm that the ZSW mechanism operates in bent geometries as well, highlighting the universality of the approach. Furthermore, we investigate the impact of fabrication tolerances in copper perturbations on the coupling length in this microwave waveguide (see Sec. 17 in Supplemental Material [46]).

Fabrication feasibility and tolerance analysis—This broadband zero-spacing SOI waveguide in Fig. 4(a) can be realized by using current mainstream nanofabrication technologies, and the detailed fabrication process is provided in Sec. 11 of Supplemental Material [46]. Notably, the proposed zero-spacing SOI waveguide exhibits relatively good robustness against fabrication errors in the silicon and Ag perturbations. Although a shift of the operating wavelength for the infinite coupling length can be observed after introducing

fabrication errors, this issue can be effectively mitigated by appropriately increasing the waveguide width (see Sec. 12 in Supplemental Material [46]).

Propagation length and practical applications—We note that the propagation length of this zero-spacing SOI waveguide is significantly shorter than that of conventional dielectric optical waveguides. Therefore, it is not intended to replace dielectric waveguides for long-distance optical signal transmission. Instead, by leveraging the physical mechanism of this perturbation engineering, we can design ultracompact local functional optical devices that do not require long-distance propagation, such as ultracompact mode converters and directional couplers (see Sec. 15 in Supplemental Material [46]). Furthermore, the propagation distance can be substantially increased by widening the waveguide. For instance, when the waveguide width $w = 2400$ nm, the propagation length at $\lambda_0 = 1550$ nm reaches approximately $2500\ \mu\text{m}$ (see Sec. 16 in Supplemental Material [46]).