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On-chip Super-robust All-dielectric Zero-Index Material

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Abstract: The robustness of the modal degeneracy for photonic Dirac-cone can be engineered by designing all-dielectric pillar arrays giving on-chip platform of zero index material for any wavelength regime. We demonstrate this concept for telecom regime.

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1. Zero index material (ZIM) based on "photonic Dirac-cone" at the Γ point

Zero index material (ZIM) has been developed as a platform for novel applications in photonic such as cloaking [1], super coupling [2], and phase-mismatch-free nonlinear optics [3]. Epsilon-near-zero (ENZ) material with infinite impedance behaves like mirrors, which has a poor impedance match to free space and waveguide [2]. Based on "photonic Dirac-cone" at the center of the Brillouin zone (Γ point in the photonic band diagram), ZIM can achieve a finite impedance $(\mu_{\mathrm{eff}} / \varepsilon_{\mathrm{eff}})^{-1/2}$ to optimize the optical coupling with other waveguides [1]. And in order to have compatibility for mass production utilizing CMOS processes, the structure should be as simple as possible. In this work, we demonstrate that a square-lattice Si pillar array can show impedance-matched zero index with unusual structural robustness in terms of the modal degeneracy to form the Dirac-cone, which is significant for the practical applications.

2. Super robustness in All-dielectric ZIM (ADZIM)

We've demonstrated metallic ZIM for telecom band, whose structure is shown in Fig. 1(a) [4]. And, we found that the Dirac-cone is formed by the combination of an electric monopole mode and a transverse magnetic dipole

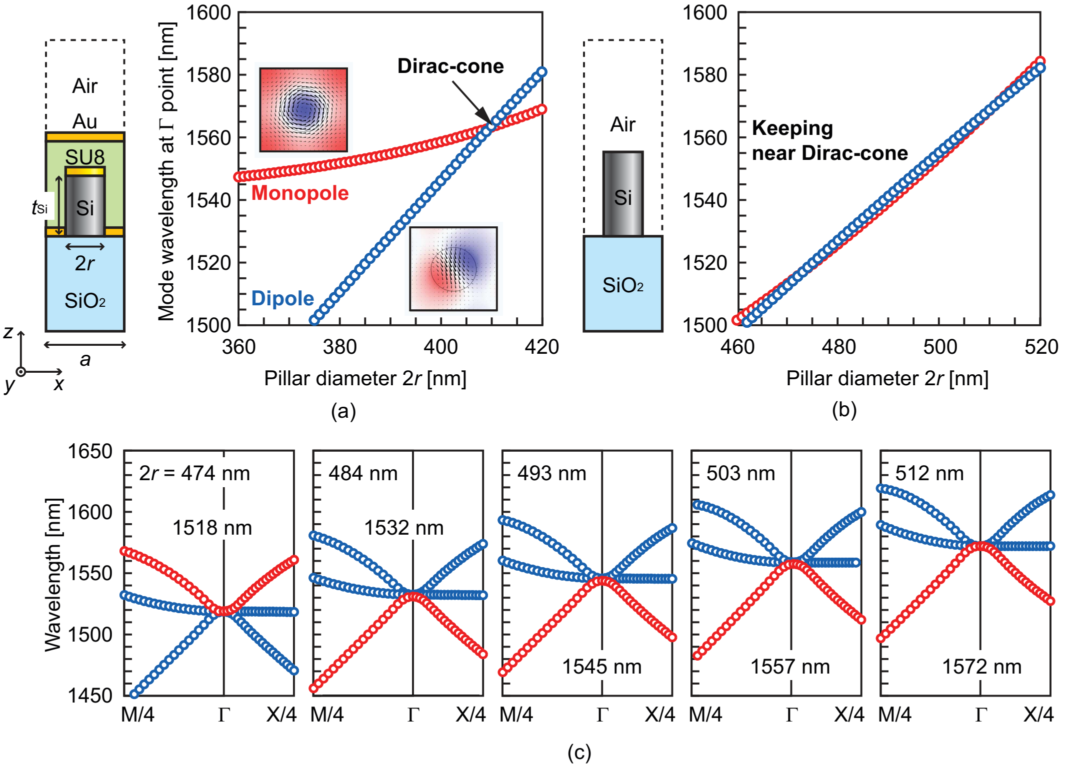

Fig. 1 Comparison of the robustness of the modal degeneracy at the gamma point against the pillar diameter variation between (a) metallic ZIM and (b) ADZIM. The left-side schematics illustrate the cross-section of the unit cell in the simulation. Insets show the top view of the E_z (color) and $H_x + H_y$ (arrow) field for monopole and dipole modes in the unit cell. (c) Photonic band diagrams for ADZIM with different $2r$. Other structural parameters are corresponding to (b).

mode. However, the degeneracy of those two modes only happens at one specific pillar diameter $2r$ for a given set of pitch a and pillar thickness t_{Si}, Fig. 1(a), which means achieving an exact Dirac-cone is not so practical. This is because the slopes $\Delta\lambda/\Delta 2r$ (structural sensitivity) of both modes are different. But if we make it all-dielectric with simple structure as shown in Fig. 1(b), the slopes can be almost the same since their modal equivalent index in the unit cell can be comparable by choosing a proper combination of the pitch a and pillar thickness t_{Si}. Fig. 1(c) shows photonic band diagrams with different $2r$ to verify that unusual structural robustness. From these diagrams, Dirac-cone is maintained and shifting with $2r$. If we define "near Dirac-cone" whose wavelength difference between the monopole and dipole modes is less than 5 nm, the allowable range of $2r$ can be maximized > ±50 nm. In addition, the tuning of the zero index wavelengths can be achieved with the same a. It is useful for broadband operation without any geometric optimization. Since the operation regime of this robustness is also scalable, it can be called as "*super robustness*" in ADZIM. Although the pillar shape tends to be tapered due to the fabrication error from the dry etching process, we confirmed that ADZIM still keeps its robustness considering the tapered shape. Actually the robustness is improved when the tapered angle is 2 – 4° which is convenient for practical applications.

3. Demonstration of super robust ADZIM

To experimentally confirm this robust behavior, we fabricated the prism devices with different $2r$ thorough e-beam lithography and RIE-ICP dry etching on silicon-on-insulator wafer whose thickness of the Si layer is modified by Si regrowth technique. SEM pictures of the fabricated device are shown in Fig. 2(a) and (b). The prism is coupled to a tapered Si waveguide with 45º tilted angle as the input and to a SU8 semicircular slab waveguide as the output. Tapered Si waveguide is designed to input TM-polarized light (electric field parallel to the pillar axis) into the prism with low radiation loss. When we input the laser light into the tapered Si waveguide, the refracted output beam is scattered onto the edge of the slab waveguide as shown in Fig. 2(c). By observing this refraction angle ϕ according to the center of the scattering point, we can estimate the effective index of the prism n_{eff} using Snell's law ($n_{\mathrm{eff}} \sim n_{\mathrm{SU8}} \cdot \sin\phi / \sin 45°$). Therefore when $n_{\mathrm{eff}} = 0$, we observe the refraction with $\phi = 0°$ (zero index refraction). When we gradually change the wavelength of the input laser, that zero index refraction has been observed at $\lambda_{\mathrm{in}} = 1560$ nm. So we've demonstrated the existence of the zero index in our proposed structure. In order to verify the robustness, the further measurements with different $2r$ are on-going. Those experimental results will be presented in the talk.

4. Summary

We proposed the super-robust ADZIM based on "photonic Dirac-cone" with the simplified structure, and experimentally demonstrated the zero index of ADZIM by using prism geometry. The concept of the robustness can give us an on-chip ZIM platform, which is scalable to any wavelength while keeping its simplicity. By utilizing ADZIM for phase matching, on-chip nonlinear optics will become simpler and more efficient.

5. Acknowledgements

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6. References

[1] X. Huang et al., "Dirac cones induced by accidental degeneracy in photonic crystals and zero-refractive-index materials," Nature materials **10**, 582-586 (2011)
[2] Nader Engheta, "Pursuing Near-Zero Response," Science **340**, 286-287 (2013)
[3] H. Suchowski et al., "Phase Mismatch-Free Nonlinear Propagation in Optical Zero-Index Materials," Science **342**, 1223-1226 (2013)
[4] S. Kita et al., "Demonstration of on-chip double zero index material for planar device application," MRS fall meeting (Boston), L17.02 (2014)

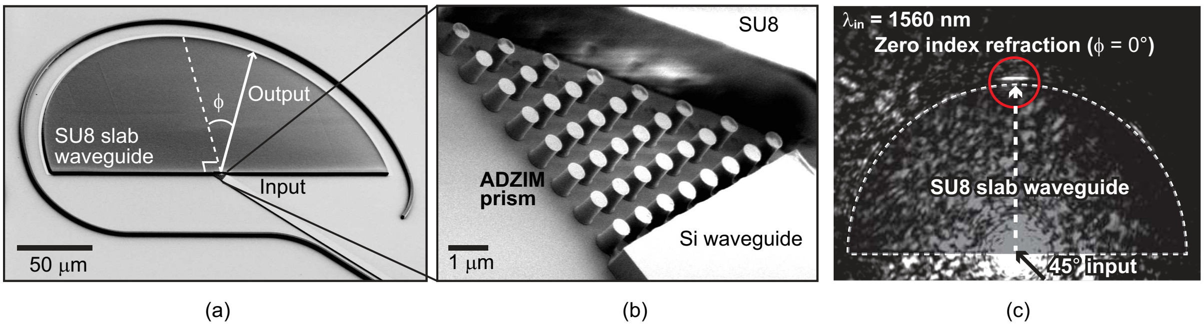

Fig. 2 Demonstration of ADZIM operation. (a) SEM picture of fabricated ADZIM prism with coupling waveguides. White lines and arrow denote the definition of the refraction angle ϕ. (b) Magnified SEM picture around the ADZIM prism. (c) Observed near infrared image around the SU8 slab waveguide when $\lambda_{\mathrm{in}} = 1560$ nm. The white dotted curve indicates the edge of the SU8 slab waveguide.