Integrated impedance-matched photonic Dirac-cone metamaterials

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Abstract-We design and fabricate an on-chip Dirac-cone metamaterial with impedance-matched zero index in optical regime. Our metamaterial consists of low-aspect-ratio silicon pillar arrays in an SU-8 matrix clad above and below by gold thin films. This design can serve as an on-chip platform to implement applications of Dirac-cone metamaterials in integrated photonics.

Optical metamaterials have demonstrated many exotic material properties and potential applications over the last decade [1]. Metamaterials with a zero index have been demonstrated in applications of supercoupling and phase-matching for nonlinear optics [2, 3]. However, on-chip zero-index metamaterial has not been demonstrated yet. Here, we design and fabricate an integrated in-plane metamaterial with impedance-matched zero index at 1550 nm by exploiting a Dirac cone at the center of the Brillouin zone [4, 5].

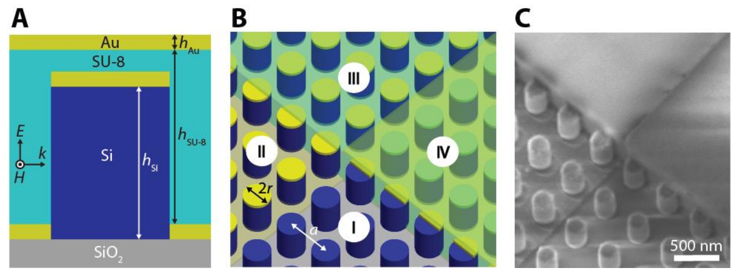

Figure 1: Diagrams and scanning electron microscopy (SEM) image of fabricated Dirac-cone metamaterial. (A) Cross-sectional view of one unit-cell of the metamaterial. The height of silicon pillars is h_{Si} = 500 nm, the SU-8 layer thickness is $h_{SU\text{-}8}$ = 570 nm, and gold layer thickness is h_{Au} = 50 nm. (B) Three-dimensional view of the metamaterial structure in four different fabrication stages: I. Silicon pillars on a silicon-on-insulator (SOI) substrate; II. Silicon pillars with bottom gold layer; III. Silicon pillars in SU-8 matrix with bottom gold layer; IV. Silicon pillars in SU-8 matrix with top and bottom gold layers (completed structure). The period and radius of the silicon pillars are a = 660 nm and radius r = 196 nm, respectively. (C) SEM image of the corresponding metamaterial structure in the same four fabrication stages.

To achieve an in-plane Dirac-cone metamaterial on a photonic chip, we begin with a 2D square array of silicon pillars [4], which have two drawbacks: first, it's challenging to fabricate high-aspect-ratio silicon pillars on chip; second, such a metamaterial has a low coupling efficiency to standard silicon photonics. However, if the silicon pillars are too short, the metamaterial cannot show a reasonable Dirac-cone. To achieve a Dirac-cone with short pillars, we put gold mirrors at top and bottom of the short silicon pillars so that the pillars become, electronically, infinitely tall according to the image theory. To physically support the top gold mirror, we put SU-8 matrix in-between the pillars. Figure 1 shows our design, which is obtained through an optimization procedure with the parameters a and r as well as the figure of merit as the absolute value of the effective index of the metamaterial at the design wavelength, λ=1550 nm. We fabricate the Dirac-cone metamaterial on a SOI wafer using standard lithographic techniques. The fabrication procedure consists of multiple conventional electron-beam lithography and reactive ion etching steps to structure both the pillars and the SU-8 matrix, as well as electron-beam evaporation followed by lift-off to pattern the gold mirrors. Figures 1B and 1C show the metamaterial in different fabrication steps.

To theoretically verify our design, we computed the bandstructure of the Dirac-cone metamaterial (Fig. 2A) for the transverse-magnetic (TM) mode with electric field parallel to the pillar axis (Fig. 1A). At the design wavelength, λ=1550 nm, two linear dispersion bands intersect at the Γ point, forming a Dirac-like cone at the center of the Brillouin zone. These two linear bands correspond to a combination of an electric monopole and a transverse magnetic dipole at the Dirac-point wavelength (inset of Figure 2B), which confirms that the scattering from the pillars is dominated by the monopole and dipole terms in Mie series [4]. Because only the scattering of an electrically small scatter can be approximated with the first a few terms of the Mie series, the pillars are electrically small near the Dirac point. Considering this fact and the effective wavelength λ_{eff} approaches infinite in the vicinity of the Γ point, the homogenization criterion ($\lambda_{\text{eff}} \gg a$, where a is the period of the silicon pillar arrays as shown in Fig. 1) is met in this region so that the metamaterial can be treated as a homogeneous bulk medium with effective constitutive parameters in the vicinity of the Dirac point [4, 5]. We can extract the effective relative permittivity $\varepsilon_r^{\text{eff}}$ and permeability μ_r^{eff} of this metamaterial from the simulated reflection and transmission coefficients (Fig. 2B). We designed the metamaterial such that $\varepsilon_r^{\text{eff}}$ and μ_r^{eff} cross zero simultaneously and linearly at the Dirac-point wavelength 1550 nm, which corresponds to an effective impedance around 1.42. The isofrequency contours of this metamaterial are almost circular, especially in the region close to the Dirac point, as shown in Figure 2C. All of these properties indicate that this metamaterial possesses a relatively isotropic zero index that has good impedance matching to free space.

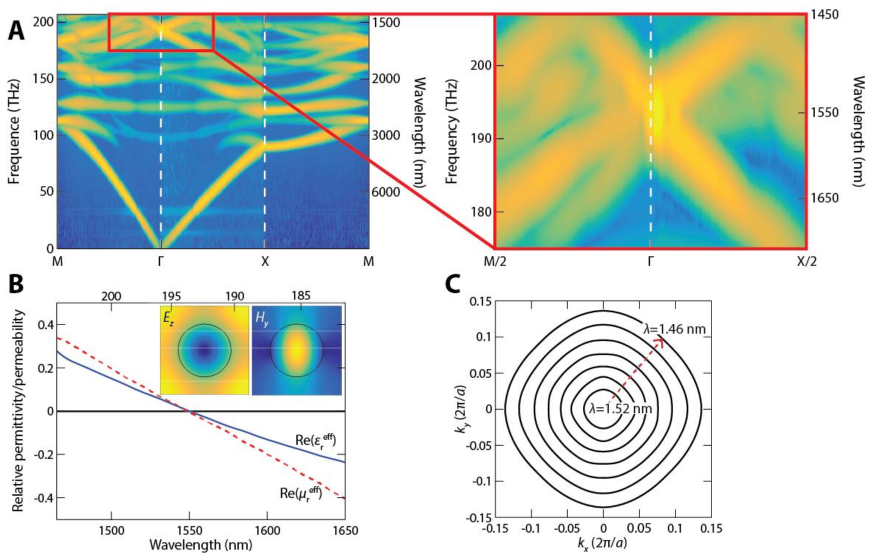

Figure 2: Material properties of the Dirac-cone metamaterial. (A) Photonic bandstructure of the 3D Dirac-cone metamaterial (Fig. 1) for TM mode. Two linear dispersion bands intersect at the Γ point at λ=1550 nm, forming a Dirac-like cone. (B) Effective relative permittivity and permeability of the metamaterial retrieved from numerically calculated reflection and transmission coefficients (finite-difference time-domain method, FDTD). Inset: electric and magnetic fields in a unit-cell at the Dirac-point wavelength, depicting an electric monopole and a transverse magnetic dipole behavior. (C) Isofrequency contours of the Dirac-cone metamaterial. These nearly circular contours indicate that the index is nearly isotropic near Γ point.

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