Integrated super-couplers based on zero-index metamaterials

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Zero-refractive-index metamaterials have been proposed as potential candidates for super-coupling applications, where light is confined to sub-diffraction limited length scales on-chip. Such a device allows for efficient coupling between disparate modes and compact 90 degree bends, which are challenging to achieve using dielectric waveguides. We discuss the simulation and fabrication results of all-dielectric on-chip zero-index metamaterial-based couplers. We observe transmission normal to all faces, regardless of the structure's shape, highlighting an unexplored feature of zero index metamaterials for integrated photonics.

There has been strong interest in the confinement of electromagnetic energy in sub-diffraction limit waveguide configurations. Such an achievement would offer applications in telecommunications, subwavelength imaging, optical memory storage, and on-chip photonic processes. Materials with a refractive index of zero have been considered as strong contenders for such "super-coupling" applications.[1,2] Though ε-near-zero and μ-near-zero metamaterials, where zero index is obtained by tuning the effective electric permittivity or permeability to zero, have been proposed as a possible candidate, their infinite or zero impedance causes large reflections which pose a challenge for coupling applications.

Recently, metamaterials with simultaneously zero effective permittivity and permeability have been demonstrated in both out-of-plane and on-chip configurations.[3,4] Both of these configurations take advantage of an accidental Dirac cone at the center of the Brillouin zone and an all-dielectric design that offers both impedance-matching and low losses.[5] An on-chip implementation of such an ε-and-μ-zero metamaterial offers a suitable platform for exploring supercoupling. This design consists of an array of silicon pillars fabricated using a standard CMOS-compatible process. We have previously fabricated a prism consisting of this material (Fig. 1) through which we are able to observe an unambiguous demonstration of zero effective index.[3]

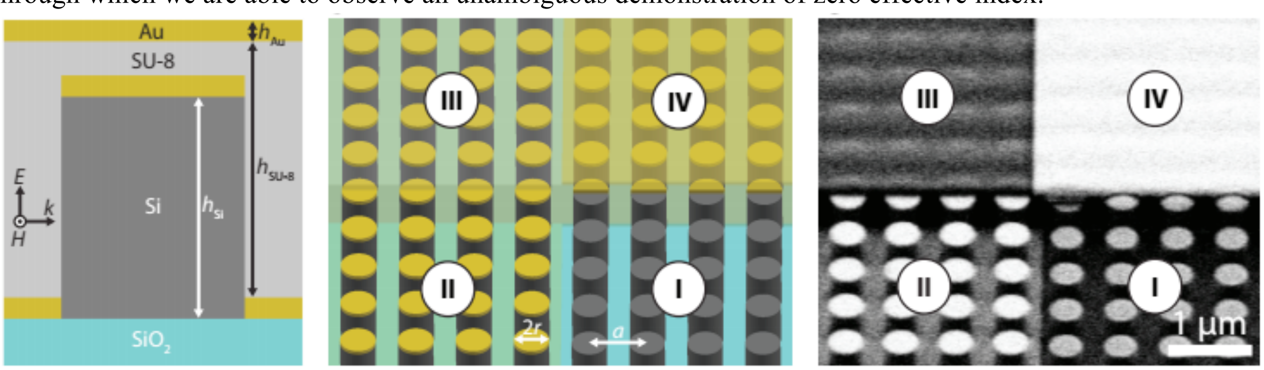

Figure 1: Schematic showing the design and SEM of the fabricated ε-and-μ-zero metamaterial. The first panel shows the cross-section of a unit cell. The second and third panel show a rendering and corresponding SEM of the metamaterial at different fabrication stages: I) Silicon pillars on silicon-on-insulator (SOI) substrate, II) After deposition of first gold mirror, III) After backfilling of SU-8 matrix, IV) After deposition of top gold layer.

In this work, we use an ε-and-μ-zero metamaterial to achieve demonstrable super-coupling. Using two-dimensional FDTD simulations, we explore S-bend and power splitter configurations of super-coupling structures between two separate waveguides for wavelengths within the telecom regime (Fig. 2). The results are challenging to explain using conventional photonics. First, we observe full transmission through a pair of 90 degree bends (Fig. 2a); second, we find that the power exiting the ε-and-μ-zero metamaterial through multiple output waveguides scales with the size of the corresponding waveguide cross-section. These are both representative features of zero-index propagation and indicate a great potential for successful super-coupling demonstration.

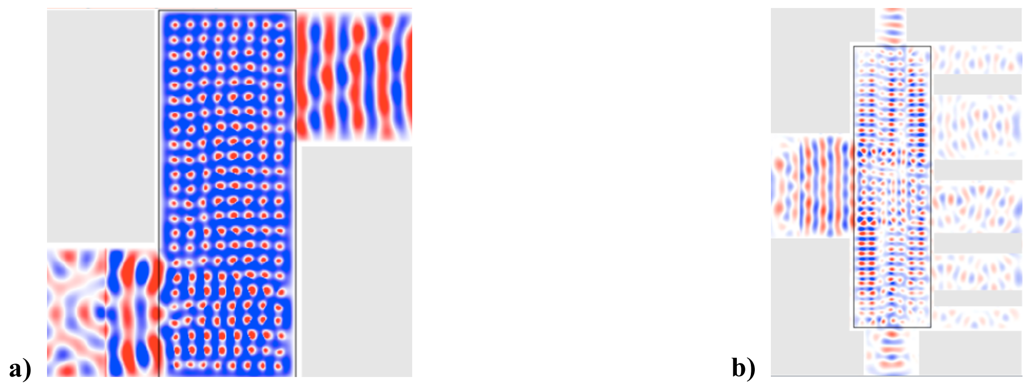

Figure 2. a) Electromagnetic energy propagating in an S-bend configuration. **b)** Electromagnetic energy through a power splitter configuration. In both figures, ε-and-μ-zero metamaterial is represented as the region within the black box and photonic bandgap material is represented as the grey shaded area.

To experimentally demonstrate super-coupling, we fabricate an optimized low-loss ε-and-μ-zero structure with subwavelength cross section coupled to an input and output silicon waveguide. The measured transmission is compared to comparable silicon waveguide structures. We expect that these devices will demonstrate the future significance of ε-and-μ-zero metamaterials for silicon photonics.

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