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Digital metamaterials shrink integrated photonic devices

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Nanostructured devices with discrete pixels exhibit photonic functions, enabling the smallest polarization beam-splitter to date.

Today's high-bandwidth communications rely on optical signals ferried via optical fibers and processed using discrete optical devices and integrated electronics. Processing these signals on integrated photonic devices, instead, can increase speed and reliability while reducing power consumption and cost. However, compared to integrated electronic devices, integrated photonic devices are large because the wavelength of light is larger than the equivalent wavelength of electrons. For example, a conventional integrated polarization beam-splitter (PBS) can be as large as $100\mu m^2$. These large sizes fundamentally limit the integration density and overall circuit functionality.

Plasmonic designs for smaller PBS devices have been proposed, but absorption reduces their efficiency.[1–3] Devices using photonic bandgaps have also been demonstrated but they are not compatible with standard silicon waveguides.[4,5] Metamaterials—materials engineered with subcomponents smaller than the wavelength of the radiation they are designed to manipulate, providing properties not yet found in nature—offer the potential for new types of very small photonic devices. By discretizing the spatial variation in refractive index via nanostructuring, we have introduced novel 'digital' metamaterials to achieve an extremely small integrated PBS. The geometric distribution of the digital pixels is determined using numerical algorithms. Our designs can be made using standard CMOS processing techniques, which allows them to be manufactured in large volumes and at low cost. Furthermore, our design technique can be generalized to fabricate almost any integrated photonic device. We have previously demonstrated this principle in the design of free-space-to-waveguide couplers[6] and integrated optical diodes.[7]

To demonstrate the possibilities of our digital metamaterials, we have created an integrated polarization beamsplitter (PBS) of area $5.76\mu m^2$ suitable for a 1.5–$1.6\mu m$ wavelength range (see Figure 1).[8] The device is first discretized into square pixels (each 120×120nm) and then an optimization algorithm defines whether each pixel is comprised of silicon or air. The objective is to enable polarization separation with high efficiency and low crosstalk. Our device has one input for either or both of the two linear polarization modes of light, and two outputs each corresponding to one of the two polarization modes.

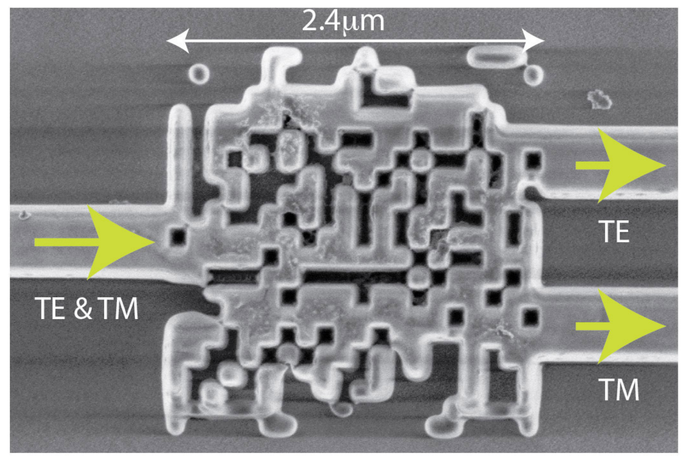

Figure 1. A scanning-electron micrograph of our polarization beam-splitter showing how light of both polarizations enters from the left waveguide and is separated into the two polarizations at the output waveguides on the right. TE: Transverse electric. TM: Transverse magnetic.

We fabricated our PBS using focused-ion-beam lithography on a silicon-on-insulator substrate. The resulting device exhibits a simulated transmission efficiency of more than 80%. We tested the device by measuring the output power at each output waveguide for a given input polarization. This allowed us to measure not only the transmission efficiency but also confirm that the extinction ratio was as low as −12dB. We experimentally confirmed the device performance, and the measurements closely matched the simulated results, with minor discrepancies attributed to fabrication inaccuracies. Our PBS is over two orders of magnitude smaller than equivalent conventional devices, which drastically increases the possible integration density.

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In summary, we applied digital metamaterials to reduce the device size of integrated photonics. The methodology can provide a library of compact integrated photonics devices, which may be strung together to create large-scale integrated photonic circuits. We are currently developing devices that can be integrated into existing CMOS processes and potentially enhance existing photonic chips. Furthermore, digital metamaterials can be extended to active devices for photonic modulation as well as integrated quantum optics. In the realm of active photonics, highly efficient yet ultra-compact modulators, detectors, and other related devices are of extreme practical significance. We are also developing devices for ultra-compact integrated quantum optics, which can exploit the high integration density for complex quantum information processing.

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Rajesh Menon combines expertise in nanofabrication, computation, and optical engineering to impact super-resolution lithography, metamaterials, broadband diffractive optics, integrated photonics, photovoltaics, and computational optics. His research has spawned more than 75 publications, over 30 patents, and three spin-off companies. He is the recipient of NASA's Early Stage Innovations Award, the National Science Foundation's NSF-CAREER Award, and the International Commission for Optics' ICO Prize.

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