

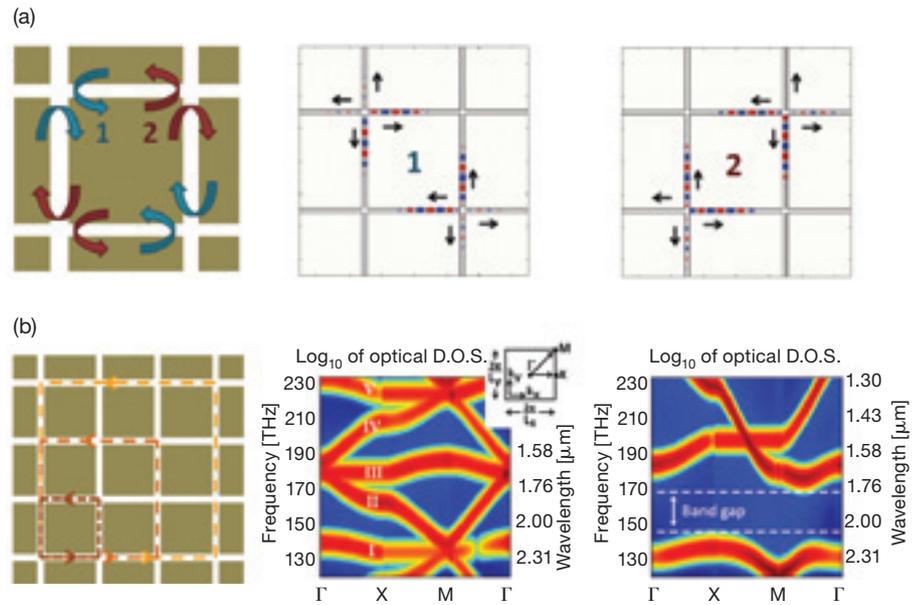
Tuning Wave Dispersion in Resonant Networks

Eyal Feigenbaum, Stanley P. Burgos and Harry A. Atwater

The search for new photonic materials has defined important directions for controlling optical dispersion. The discovery of photonic crystals¹ led to dispersion engineering and also to extremely high quality factor cavities using all dielectric materials based on Bragg diffraction.² The field of metamaterials³ enabled new research areas such as artificial magnetism and transformation optics⁴ based on researchers' ability to locally tune the material electric and magnetic properties with meta-atoms. Resonant guided wave networks (RGWNs) are a new class of artificial photonic material,⁵ distinct from photonic crystals and metamaterials, in which localized waves resonate in closed paths throughout a network of isolated waveguides connected by power-splitting junctions, enabling the wave dispersion to be dependent on the waveguide network layout.

Resonant-guided wave networks can be implemented using two plasmonic components: 1) subwavelength metal-insulator-metal waveguides and 2) junctions consisting of the intersection of two metal-insulator-metal waveguides that act as power-splitting elements in the network. As the insulator thickness is varied, the amplitude and phase of power splitting in the junction can be tuned. Phase is also accumulated during wave propagation in the waveguide segments, and the evolution of phase and amplitude in the network determine the interference and resonance properties of a resonant-guided wave network.

If one appropriately designs the junction and waveguide components as well as the network layout, a small 2×2 resonant-guided wave network, as depicted in (a) of the figure, can be made to function as an ultracompact optical resonator. The resonator quality factor measured by full wave numerical

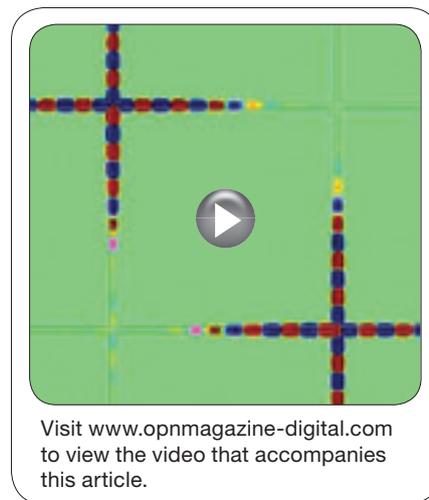


(a) Formation of resonance in a 2×2 RGWN and full wave simulation of resonator turning points in steady state. (b) Schematic of closed loop network resonances and band-structure of two large homogeneous RGWN of different network layouts.

simulations yields $Q \sim 80$ at a wavelength of $1.5 \mu\text{m}$, which is quite a high quality factor for a metallic photonic cavity with wavelength-scale dimensions.

Through appropriate design of structural parameters and correspond-

ing wave dispersion, large resonant guided wave networks can be tuned to exhibit either "flat" continuous photonic bands or photonic bandgaps, as shown in (b). Spatially inhomogeneous and nonperiodic resonant guided wave networks also open the possibility for optical material designs with spatially-varying wave dispersion and propagation across the structure, allowing for the implementation of complex optical functions. \blacktriangle



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Refractive-Index Engineering of Planar Waveguides with Subwavelength Gratings

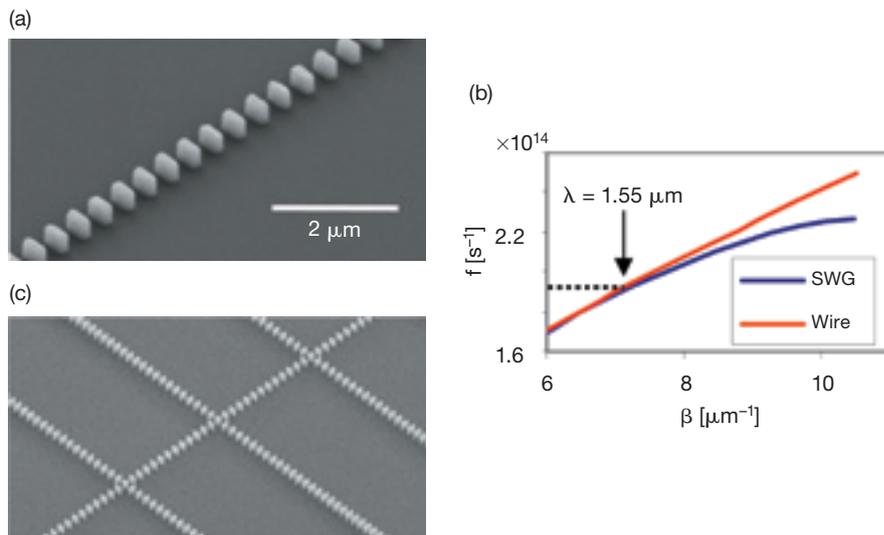
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In integrated photonic circuits, the refractive-index contrast is usually set by the choice of the material platform. For example, for silicon photonic circuits operating at a wavelength near $\lambda = 1.55 \mu\text{m}$, the waveguide core and the cladding indices are given by the material constants of silicon ($n = 3.5$) and silicon dioxide ($n = 1.44$), and waveguide devices must be designed within the constraint of these fixed values.

From free-space optics, we know that periodic dielectric structures with a periodicity smaller than one half of the wavelength do not diffract any light. Instead, such so-called subwavelength gratings (SWGs) act as homogeneous effective media with spatially averaged refractive index.¹ We have recently demonstrated the first use of SWGs for refractive-index engineering in micro-photonic waveguides, providing a powerful method for controlling the refractive index of a waveguide core in any specific location of a photonic chip. Importantly, our method only relies on standard fabrication techniques and can be implemented without any modifications to the chip fabrication process flow.

The structure shown in (a) exemplifies refractive-index engineering of a silicon photonic wire waveguide. By etching periodic gaps of a well-defined width w and pitch Λ into a standard silicon photonic wire, an SWG waveguide is formed with an effective core index determined by the duty ratio w/Λ . Calculation of the dispersion relation of the segmented waveguide and comparison with the dispersion of an equivalent photonic wire waveguide with identical cross section and a core index of $n = 2.65$, as shown in (b) confirms theoretically the concept of spatial refractive-index averaging.

Experimentally, we have observed waveguiding in such SWG structures with a propagation loss as low as



(a) SEM image of an SWG waveguide. (b) Dispersion relation of an SWG waveguide and an equivalent photonic wire waveguide with core refractive index of 2.65 (TE polarization). (c) SWG waveguide crossings.

2.1 dB/cm, comparable to the best photonic wire waveguides reported, and with a low and nearly wavelength-independent group index, as predicted by theory.² Although consistent with Bloch theory, it is fascinating to observe light propagating almost unperturbedly through so many strong discontinuities.³

Among the applications of SWG waveguides⁴ is an SWG slab waveguide structure that simultaneously acts as a lateral cladding for a photonic wire waveguide in a novel microspectrometer design and an efficient in-plane fiber-chip coupling structure. The coupler structure works by gradual modification of the waveguide core index, leading to mode-size transformation between a high-index photonic wire and the low-index optical fiber. Measured coupling loss is 0.9 dB for TE and 1.2 dB for TM polarization. SWG waveguides were also implemented for highly efficient waveguide crossings,⁵ such as those shown in (c).

Having the ability to intersect waveguides with low loss and crosstalk is an important prerequisite for designing complex high-density photonic circuits. SWG waveguide loss per crossing was measured to be as low as 0.02 dB with polarization-dependent loss of less than 0.02 dB and crosstalk less than 40 dB. These applications demonstrate the obvious advantages of having the new degree of freedom in photonic circuit design afforded by SWG refractive-index engineering. ▲

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