Principles and applications of guided-mode resonant photonic lattices

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INTRODUCTION

A photonic lattice is a periodic assembly of arbitrarily shaped particles. These particles can be made of metals, dielectrics, and semiconductors or their hybrid compositions. The lattice is, in general, three-dimensional (3D) with important variants in the form of 2D or 1D patterned films. The lattice operates in fundamental ways on incident light with ability to control and manipulate amplitude, phase, spectral distribution, polarization state, and local mode structure. Thus, nano- and microstructured films with subwavelength periodicity represent fundamental building blocks for a host of device concepts. For many real-world applications, attractive features of this device class include compactness, minimal interface count, high efficiency, potential monolithic fabrication, and attendant survivability under harsh conditions. The fundamental operational modality is available across the spectrum, from visible wavelengths to the microwave domain, by simple scaling of wavelength to period and pertinent materials selection.

Here, we address the physical basis behind the resonance effects inherent in the fundamental lattice, discuss the observed behavior, and provide example applications. The guided-mode resonance (GMR) concept refers to quasi-guided waveguide modes induced in periodic layers or thin films [1-3]. Whereas the canonical physical properties of the resonance are fully embodied in a one-dimensional (1D) lattice, the final device constructs are often patterned in a two-dimensional (2D) slab or film in which case we commonly refer to them as photonic crystal slabs or metasurfaces. These surfaces are capable of supporting lateral modes and localized field signatures with propagative and evanescent diffraction channels critically controlling the response. Local Fabry-Perot and Mie mode signatures are observable via computations within the structural geometry. It can be convincingly argued that such local modes have no causal impact with lateral Bloch modes generating all key effects [4]. The subwavelength restriction of periodicity is usually maintained for efficient devices; however, it is also possible to generate interesting spectral behavior when this is not satisfied leading to unexpected device concepts.

The dominant second, or leaky, stop band exhibits many remarkable physical properties including band-edge transitions and bound states in the continuum. The Fourier harmonic content of the spatial modulation is key to understanding the band dynamics of these lattices. Multi-resonance effects are observed when Bloch eigenmodes are excited with more than one evanescent diffraction channels with the resulting spectral response clearly understood by invoking this process. We have shown how materially sparse leaky-mode photonic lattices may be nearly completely invisible to one polarization state while being opaque to the orthogonal polarization state with this property existing over significantly wide spectral bands. Device concepts with experimental prototypes verifying theoretical predictions including wideband reflectors, nonfocusing spatial filters, ultra-sparse reflectors and polarizers, single-layer bandpass filters, and multiparametric resonant sensors were demonstrated by the UT-Arlington Nanophotonics Device Group in the past.

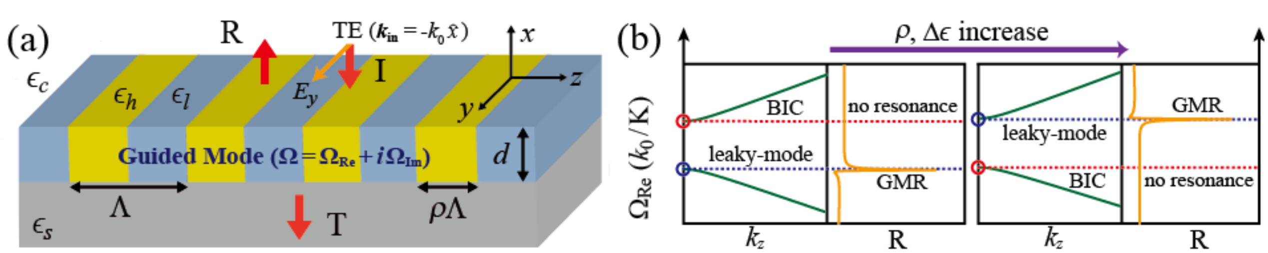

Figure 1. Band flip in a leaky-mode resonant photonic lattice. (a) Schematic of a resonant lattice with a normally-incident TE-polarized plane wave. (b) Conceptual illustration of the band flip phenomenon. When the values of ρ and Δε are small, GMR (BIC in a red circle) occurs at the lower (upper) side of the second stop band. Here, ρ = F =fill factor, $\Delta\varepsilon = \varepsilon_h - \varepsilon_l$ is the dielectric contrast in the period, and Ω denotes complex frequency. Adapted from reference [5].

THE BAND STRUCTURE OF THE LEAKY-MODE LATTICE

The fundamental properties of the photonic band structure of resonant leaky-mode metamaterials are of key importance. The band possesses a leaky edge and a non-leaky edge for each supported resonant Bloch mode if the lattice is symmetric. The non-leaky edge is associated with what is now called a bound state in the continuum (BIC), or embedded eigenvalue, currently of considerable scientific interest. It is possible to control the width of the leaky band gap by lattice design [5]. In particular, as a modal band closes, there results a quasi-degenerate state—this state is remarkable as it is possible to transit to it by parametric and material choice. The transition to, and across, this point executes a band flip. The leaky-mode band dynamics are summarized in Fig. 1.

OPTICAL COMPONENTS

Guided-mode resonance nanophotonics constitutes an applications platform with numerous useful outcomes. Optical components of various sorts constitute a subclass of the application domain. In Fig. 2 we show a wideband reflector example that may be considered as a complimentary solution to traditional thin-film reflectors. The noteworthy aspect is that the device applies only a single resonant film but achieves a wideband response.

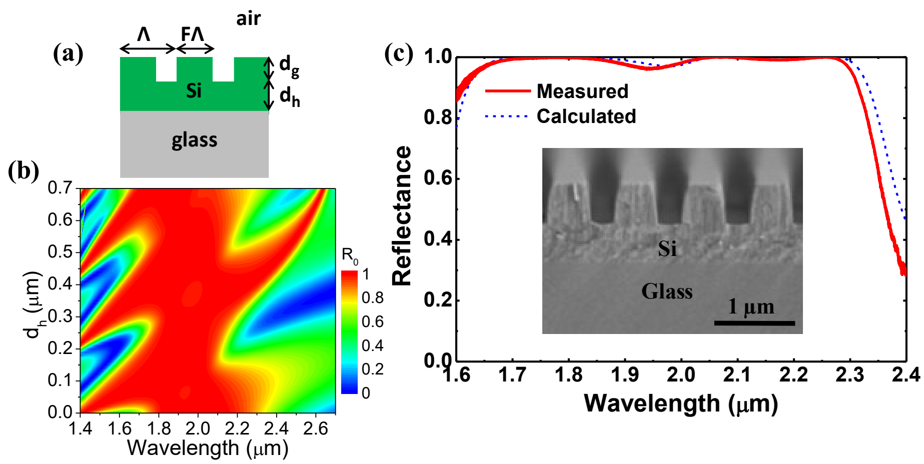

Figure 2. (a) An illustrative schematic of a Si-based zero-contrast grating (ZCG) on a glass substrate with typical grating parameters. (b) RCWA simulated zero-order reflectance R_0 map as a function of an interconnecting sublayer thickness (d_h) where the grating parameters are d_g = 565 nm, Λ = 858 nm, and F = 0.55. The device is illuminated at normal incidence under TM (magnetic field vector normal to the plane of incidence) polarization. (c) Calculated and measured R_0 spectra of a corresponding device where d_h is 410 nm. The inset in (c) is a cross-sectional SEM image of the fabricated device.

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