Properties and principles of resonant optical lattices

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***Abstract*— The physical properties of resonant photonic lattices are reviewed. This includes the dynamics of the resonance modes and band structure explaining the characteristics of the leaky (radiant) and nonleaky (closed) band edges. An application primer is presented.**

Keywords—guided-mode resonance, leaky-mode resonance, metamaterials, Bloch modes, leaky-band dynamics, metasurfaces, subwavelength gratings, applications

I. INTRODUCTION

In general, optical lattices are three-dimensional (3D) as are their crystalline counterparts. However, important variants in the form of 2D or 1D patterned films exist in the optical domain. Even though the basic periodic element, namely the diffraction grating, has been known for 100+ years, new solutions and applications based on periodic modulations continue to appear. In recent literature, corresponding assemblies and devices are called metamaterials or metasurfaces. Current lithographic technology enables fabrication of spatial modulations on subwavelength scales in one, two, or three dimensions even at visible or UV wavelengths. The resulting diffractive optical elements (DOE) or metasurfaces may support waveguide modes with proper refractive indices and element dimensions. Waveguide modes that are guided or quasi-guided in waveguide gratings experience stopbands and passbands as the light frequency is varied. Nano- and microstructured lattices with subwavelength periodicity support guided-mode resonance effects and represent fundamental building blocks for a host of device concepts on account of the diversity of spectral expressions mediated by the resonance effect. For many applications, 1D and 2D photonic lattices exhibit attractive features such as compactness, minimal interface count, high efficiency, and potential monolithic fabrication with attendant robustness under harsh conditions. The governing resonance effects hold across the spectrum, from visible wavelengths to the microwave domain, by simple scaling of wavelength to period and proper materials choice.

Here we discuss the physical principles of resonant leaky-mode lattices. We review elementary facts related to diffractive optical elements as these constitute the original basis for metamaterials. We show that perfect reflection is obtainable in 1D and 2D lattices and that its occurrence is immune to particle shape. We review the leaky-mode band structure and emphasize that its origin lies in the periodic assembly as opposed to particle resonance. The state of related technology is briefly summarized.

II. RESULTS AND DISCUSSION

A. Resonance principle

Guided-mode resonance (GMR) occurs when an incident wave is phase-matched to a leaky waveguide mode supported by an optical lattice [1 ,2]. Excitation at normal incidence yields counterpropagating lateral modes producing a standing wave. Such lattices operate at the second stopband. These bands differ from 3D photonic crystal Bragg-type stop bands in that there exists an out-of-plane radiative energy-coupling channel. Therefore, the leaky mode resides above the light line in the Brillouin zone. The physical and spectral properties of the resonance lattice depend critically on its symmetry. A symmetric lattice yields a single resonance and corresponding radiation at one edge of the second (leaky) stopband whereas both edges resonate and radiate the light for asymmetric lattices.

Figure 1 depicts common geometry and key processes at resonance.

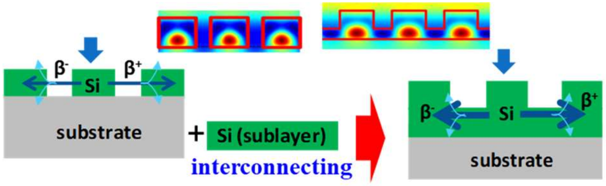

Fig. 1. Schematic cross section of a 1D or 2D planar optical lattice. The resonant layer can be composed of discrete particles or have a connective subfilm. Indicated are Bloch mode wavenumbers β and typical standing wave field patterns at resonance.

B. Application in bio- and chemical sensing

Optical sensors are needed in many high-value fields including medical diagnostics, biomarker discovery, drug development, food safety, industrial process control, and environmental monitoring. The guided-mode resonance sensor operates with quasi-guided waveguide modes induced in periodic layers by a beam of light [3]. The resonance is enabled by one- or two-dimensional nanopatterns that can be fabricated in large formats in a reliable, repeatable, and cost-effective manner making this method commercially viable. We invented and experimentally demonstrated the guided-mode resonance biosensor more than two decades ago. Since then, there have been steady developments in technology and implementation as exemplified in Fig. 2. Label-free photonic sensors are immune to electromagnetic interference and permit effective light input and output which is key to achieving compact architectures. These sensors are economic due to material sparsity and simple interrogation with unpolarized light.

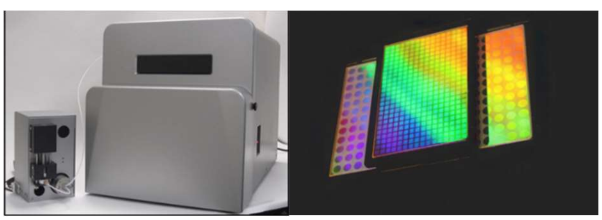

Fig. 2. Commerialized GMR sensor system example with imprinted multi-well plates containing the resonant sensor layer at the bottom of each well. Courtesy of Resonant Sensors Incorporated.

C. Application in LWIR technology

The principle of guided-mode, or lattice, resonance enables creation of diverse spectral expressions such that a single-layer component can behave as a reflector, filter, or polarizer. This architectural sparsity contrasts strongly with the venerable field of multi-layer thin-film optics that is basis for most optical components on the market today. Whereas lattice resonance can be similarly exploited in all spectral regions with appropriate low-loss materials, important targets of the technology are components operating in the long-wave infrared spectral region spanning a key atmospheric transparency window in the long-wave infrared (LWIR) region. At such long wavelengths, traditional thin-film methods largely fail to provide acceptable solutions because the quarter-wave films foundational to that approach become excessively thick. The technology provided by the GMR principle has strong potential to enable transformative, economic solutions for advanced optical component applications with a particularly favorable competitive advantage at long wavelengths. Figure 3 depicts representative fabricated and characterized LWIR devices [4].

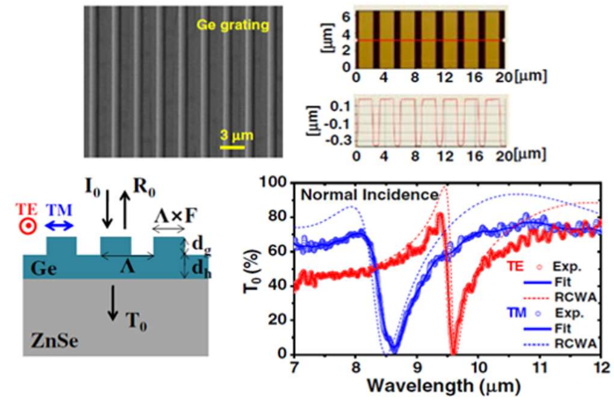

Fig. 3. Representative results in LWIR technology development including device model, AFM data, and measured and computed transmission spectra.

III. Conclusions

The fundamental physical processes generating the lattice resonance signatures discussed here are well understood. The physical cause is guided-mode resonance mediated by lateral Bloch modes excited by evanescent diffraction orders in the subwavelength regime. This point has been emphasized in in recent publications with detailed explanations [5, 6]. Therein, local resonances, including Mie resonance and Fabry-Perot resonance, are shown to be non-causal in the lattice resonance generation. Potential applications grounded in this resonance effect have been summarized.

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