Out-of-plane resonances in dielectric and metallo-dielectric photonic quasi-crystal slabs

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Abstract

In this paper, we present a summary of recent results from our studies on out-of-plane resonances in dielectric and metallo-dielectric nanostructured photonic quasi-crystal slabs, with specific reference to the Ammann-Beenker (octagonal, quasi-periodic) tiling geometry. Our experimental results at infrared wavelengths are in good agreement with the numerical predictions from full-wave simulations based on a supercell approximation.

1. Introduction

"Photonic quasi-crystals" (PQCs) are artificial structures based on *aperiodic-tiling* [1] lattices which may exhibit *long-range* order and *high-order* (e.g., eight-fold, twelve-fold) weak rotational symmetries not bounded by the crystallographic restriction.

During the past decade, such structures have elicited a growing attention (see, e.g., [2-4] for recent reviews) in view of their capability of providing similar properties as those exhibited by standard (periodic) photonic crystals, with significant potential improvements attainable via a judicious exploitation of the additional degrees of freedom inherently available in aperiodic structures. In this framework, attention has mostly been focused on *in-plane* propagation effects (e.g., bandgap, field localization, negative refraction and superlensing, etc.), with the *out-of-plane* investigations essentially limited to *metallic* structures (e.g., arrays of sub-wavelength holes/particles [5-7]).

In an ongoing series of numerical [8-11] and experimental [12] investigations, we have focused on out-of-plane propagation effects in *dielectric* and *metallo-dielectric* nanostructured PQC slabs based on the Ammann-Beenker (octagonal, quasi-periodic) tiling geometry shown in Fig. 1(a). In what follows, we provide a compact summary of the salient results.

2. Main results

In a series of preliminary full-wave numerical studies [8-11], we considered *free-standing* structures composed of holey dielectric slabs (with the holes placed at the tiling vertices), as shown in Fig. 1(b). More specifically, in [8,9], we showed that supercell-based *periodic approximants* of PQC slabs may exhibit, under normal-incidence plane-wave illumination, sharp, asymmetrical, Fano-like *guided resonances* (GR) in their transmittance/reflectance spectra (see, e.g., Fig. 1(c)), similar to what observed in standard (e.g., square, triangular) PC slabs [13].

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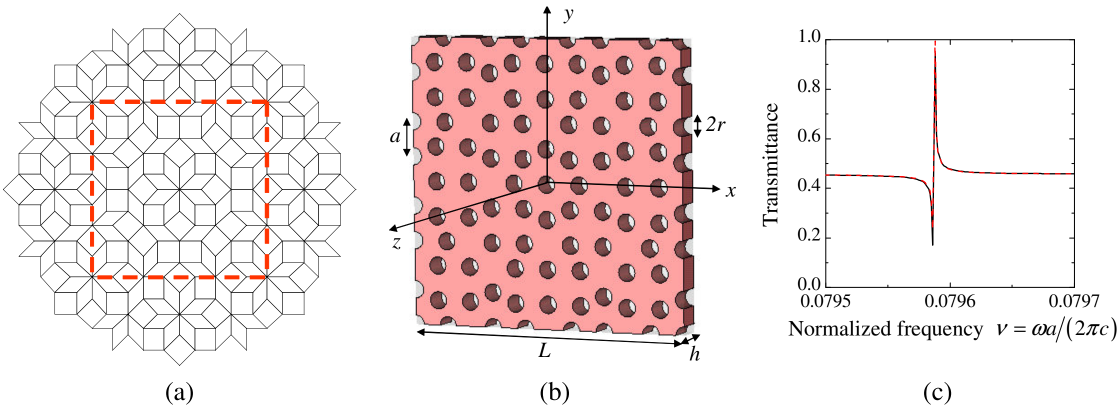


Fig. 1: (From [8]) (a) Ammann-Beenker tiling (red-dashed square delimits the chosen supercell). (b) 3-D view of the PQC slab (supercell). (c) Full-wave-computed (black-solid) and Fano-fitted (red-dashed) transmittance spectra (hardly distinguishable on the plot scale) for a silicon structure (refractive index=3.418), with r=0.25a and h=0.75a.

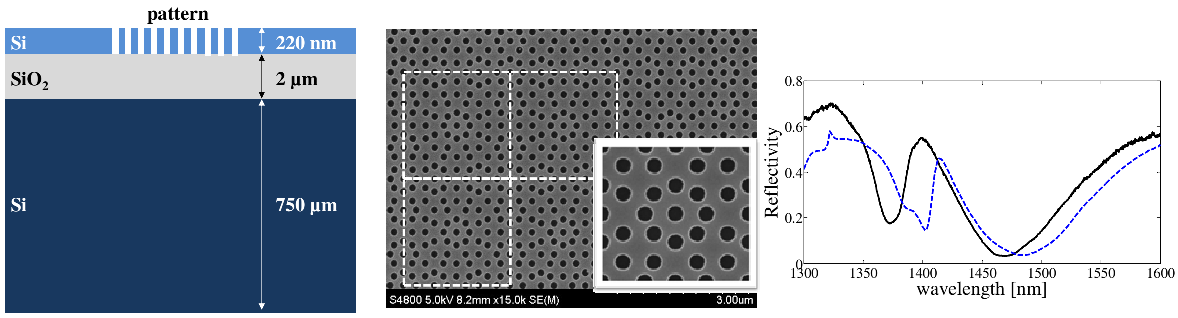
Such resonances, due to the excitation of "leaky" modes that can couple with the continuum of radiative modes in the surrounding environment, are of great interest form the application viewpoint, in view of their inherent suitability to sensing schemes (see, e.g., [14]). In [10], we showed that, capitalizing on the inherent wealth of *inequivalent* point-defect states in (even relatively small sized) supercells, it was possible to selectively excite *uncoupled* GRs, by suitably breaking the lattice symmetry. In [11], we investigated the sensing/tuning efficiency of the above GRs with respect to variations in the refractive index of the holes, and showed that the lattice geometry may indeed play a key role in enhancing the sensitivity.

Building up on the above results, in [12], we found the first experimental evidence of GRs in periodic approximants of PQC slabs, in connection with nanostructured prototype structures fabricated via standard electron-beam-lithography on silicon-on-insulator (SOI) wafers (see Figs. 2(a) and 2(b)), and experimentally characterized at infrared wavelengths via a standard reflection setup, in good agreement with the numerical prediction (see Fig. 2(c)). Preliminary results on *globally-aperiodic* PQC slabs confirm the existence of GRs, and a substantial agreement with the numerical prediction based on suitably-sized supercells.

We are currently working on metallo-dielectric PQC structures composed of low-contrast polymeric nanostructured slabs laid on metallic (aluminium, gold) films, similar to those proposed in [15]. These *hybrid* structures can support both plasmonic-type resonances (*surface plasmon polaritons* – SPPs) due to coherent oscillations of the surface charge density bound at the metal surface, and GRs. In this scenario, the patterned dielectric layer plays a two-fold role, acting both as a diffraction grating for the excitation of SPPs and, at the same time, as a guiding layer supporting GRs. Preliminary (numerical and experimental) results indicate the possibility of exciting multiple GRs and plasmonic resonances, with sensing/tuning efficiencies of interest for practical bio-sensing applications.

3. Conclusions

To sum up, our results indicate the possibility of exciting out-of-plane resonances in dielectric and metallo-dielectric PQC slabs, with good numerical predictions from supercell-based full-wave modeling. Current and future investigations are aimed at the full exploitation of the inherently richer spatial spectra and the additional degrees of freedom (e.g., multiple phase-matching conditions, inequivalent defect states, etc.) available in aperiodic-tiling geometries in order to engineer and optimize the resonant phenomena for application to bio-sensing scenarios.



(a) (b) (c)

Fig. 2: (From [12]) (a) Schematic of the patterned SOI wafer. (b) Scanning-electron-microscope image (zoomed in the inset) of the patterned area, with the white-dashed lines delimiting the supercells. (c) Measured (black-solid) and numerically-computed (blue-dashed) reflectivity spectra for a=300 nm and r =115 nm.

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