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PARAMETRIC STUDY OF GUIDED RESONANCES IN OCTAGONAL PHOTONIC QUASICRYSTALS

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ABSTRACT: *In this article, following up on our previous investigations on guided resonances (GRs) in photonic quasicrystal slabs based on octagonal (quasiperiodic) tilings, we present the salient results from a parametric study of the GR properties, varying the air/dielectric fraction, and the slab refractive index and thickness. Our results, obtained via full-wave simulations, show similar qualitative trends as those observed in the literature for periodic photonic crystal slabs.* © 2009 Wiley Periodicals, Inc. Microwave Opt Technol Lett 51: 2737–2740, 2009; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.24721

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1. INTRODUCTION

Recently, a large body of studies have been devoted to the defect and bandgap engineering of photonic crystal (PC) slabs, mainly aimed at designing micro- and nano-sized optical devices for integrated photonic circuits (see, e.g., [1–7] for a sparse sampling).

In most applications of interest, PC slabs made of air hole arrays in a host dielectric medium typically support "guided modes," which, in a band diagram, are represented below the light line; these modes are completely confined within the slab (because of total internal reflection [8, 9]), and unable to couple to any external radiation. However, PC slabs can also support the so-called "*leaky* modes," represented, in a band diagram, above the light line, and characterized by finite lifetimes, electromagnetic (EM) power strongly confined within the slab, and yet the ability to couple to the continuum of free-space modes; for this reason, these modes are known as "guided resonances" (GRs) [10]. Illuminating the PC slab with a normally incident (with respect to the plane of crystal periodicity) plane wave, the interference between the directly transmitted/reflected wave and the waves originating from the excited GRs can generate in the transmittance/reflectance spectra narrow Fano-like resonant line shapes [11, 12] (whose center frequencies and linewidths depend on the geometric and physical parameters of the PC structure, as well as on the direction and polarization of the incident wave [13]) superimposed on a smoothly varying background resulting from the Fabry-Perot effect associated to the light interaction with an effectively-homogeneous dielectric slab. The reader is referred to [14–21] (and the references therein) for a sparse sampling of recent studies addressing the properties and potential applications of GRs.

In a series of ongoing investigations [22], we have been concerned with the study of GRs in aperiodically-ordered "photonic quasicrystal" (PQC) [23] slabs, intrinsically tied to the concept of "quasicrystal" in solid-state physics [24]. We showed that, in spite of the seemingly necessary spatial periodicity [21], GRs could also be observed in a quasiperiodic geometry based on the Ammann-Beenker (octagonal) tiling [24].

In this article, following up on the above study, we present the results of a parametric study aimed at exploring the role of key parameters, such as the air/dielectric fraction, and the slab refractive index and thickness. Accordingly, the rest of the letter is laid out as follows.

In Section 2, we briefly summarize the key results from our previous study. In Section 3, we illustrate the problem geometry and parameters. In Section 4, we present some representative results from our new parametric studies. Finally, in Section 5, we provide some concluding remarks and hints for future work.

2. SUMMARY OF PREVIOUS STUDIES

Our study in [22] relied on the so-called "supercell" approximation, which had already been successfully utilized in many PQC studies [23]. Our investigation involved the full-wave study of the transmittance response of a large supercell, as well as the band-structure and modal analysis. We showed the possibility, in agreement with what observed in the periodic case, of achieving sharp, asymmetrical Fano-like resonant line shapes in the transmittance response, exploiting the coupling with degenerate modes of the PQC slab with suitable spatial symmetry. To assess to what extent the observed features were indicative of genuine aperiodic-order-induced phenomenologies, and not arising from artifacts attributable to the artificial periodic truncation, we also tried to simulate finite-size structures considering composite supercells featuring air layers of various thickness placed around the usual PQC sample. Increasing the air layer thickness, and hence progressively reducing the coupling effects among adjacent periodicity-induced slabs replicas, we were still able to observe Fano-like resonant line shapes amenable to GRs.

To the best of our knowledge, our study provided the first evidence of GRs in PQC slabs, and, complementing certain results in the topical literature pertaining to randomly disordered geometries (see, e.g., [21]), indicated that perfect spatial periodicity is not strictly required for their excitation.

3. GEOMETRY AND PARAMETERS

In this article, we consider the same geometry as in [22]. Figure 1 illustrates the generation of the PQC slab supercell of interest, which, starting from the aperiodic (Ammann-Beenker, octagonal) tiling sample shown in Figure 1(a), entails the selection of a sufficiently large

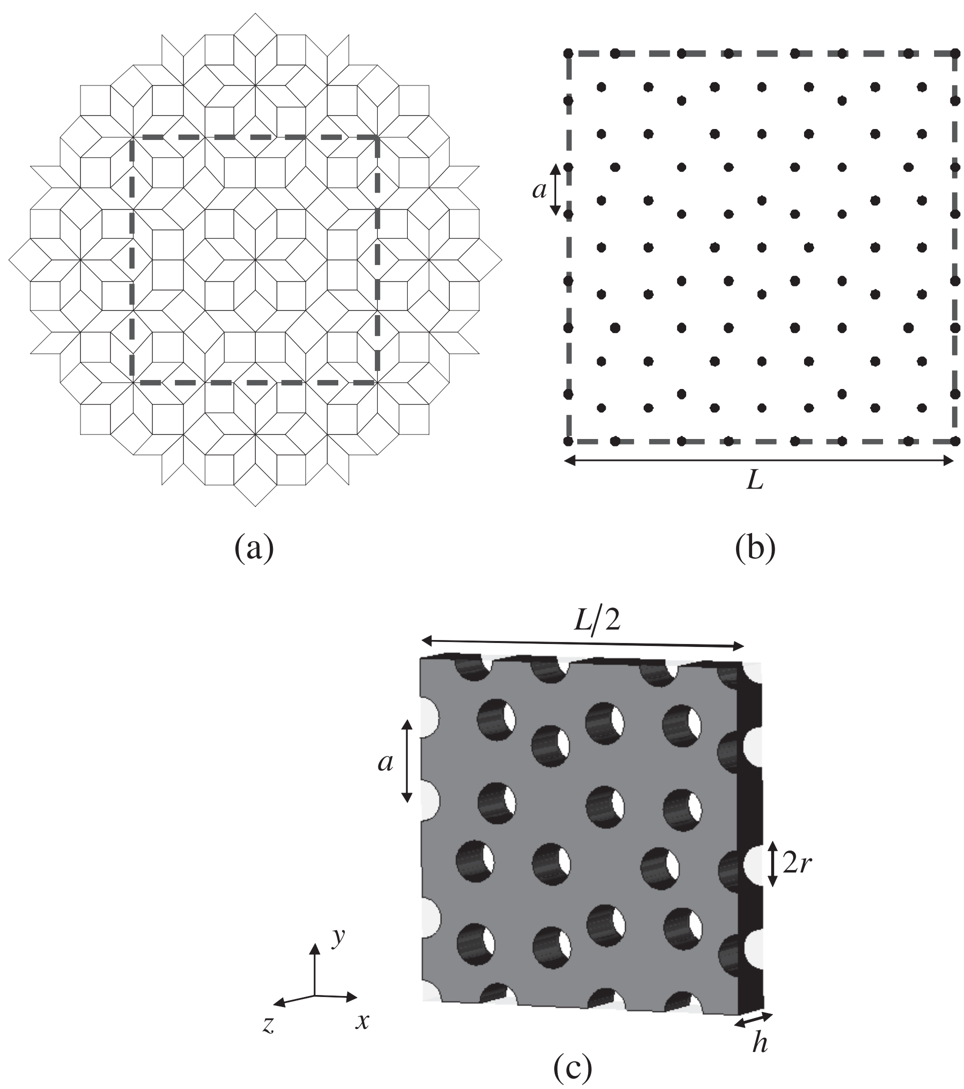

Figure 1 (a) Sample of the octagonal tiling (the gray dashed square delimits the portion cut for obtaining the supercell). (b) Supercell cut from the tiling with the detail of the tiling vertices, with a denoting the lattice constant and L the total size. (c) Final supercell obtained by placing air holes at the tiling-vertice positions in the slab, in the associated three-dimensional Cartesian reference system, and with indications of the parameters involved in the simulations

square portion (gray dashed square). Next, as shown in Figure 1(b) (where a is the lattice constant, that is, the square/rhombus tile sidelength, and L denotes the total sidelength), the tiling vertices falling in the selected portion are considered as the centers of circular air holes in a dielectric slab immersed in air. Actually, in view of the mirror symmetry exhibited by the tiling around the horizontal and vertical axes passing through its center [see Fig. 1(a)], the computational burden can be minimized by considering only one quarter (e.g., the upper-right), leading to the final 3-D structure in Figure 1(c), where r is the hole radius and h the slab thickness. Such a structure, with sidelength $L/2 = (4 + 3\sqrt{2})a/2$, is representative of a PQC-slab supercell composed of 97 holes (or fractions of them), with electric size (in the frequency range of interest) that is compatible with our current computational resources.

4. REPRESENTATIVE RESULTS

Our numerical studies of the time-harmonic $[\exp(-i\omega t)]$ transmittance response, under plane-wave excitation propagating along z (i.e., normally-incident on the slab) with y-polarized (vertical) electric field, rely on the use of a commercial software package (CST MICROWAVE STUDIO® [25]) based on the finite-integration technique. The structure is placed in a "waveguide simulator" composed of two horizontal perfectly-electric-conducting walls and two vertical perfectly-magnetic-conducting walls, whose fundamental mode is a transverse-electromagnetic nondispersive field; within the single-mode range of the waveguide simulator (bounded by the cut-off frequency of the first transverse-electric higher-order mode), this mimics the desired plane-wave excitation. Moreover, air layers of thickness $40h$ are placed at each side of the slab along the z axis, and the structure is discretized using a hexahedral mesh of at least 25 lines per wavelength (corresponding, in the frequency range of interest, to roughly 1.38 million mesh cells [25]).

In what follows, we illustrate the salient results from our parametric studies, pertaining to the transmittance ($|T^2|$) response as a function of the normalized frequency $\nu = \omega a/(2\pi c)$ (c being the speed of light in vacuum), within the single-mode range ($\nu < a/L \approx 0.12$) of the waveguide simulator.

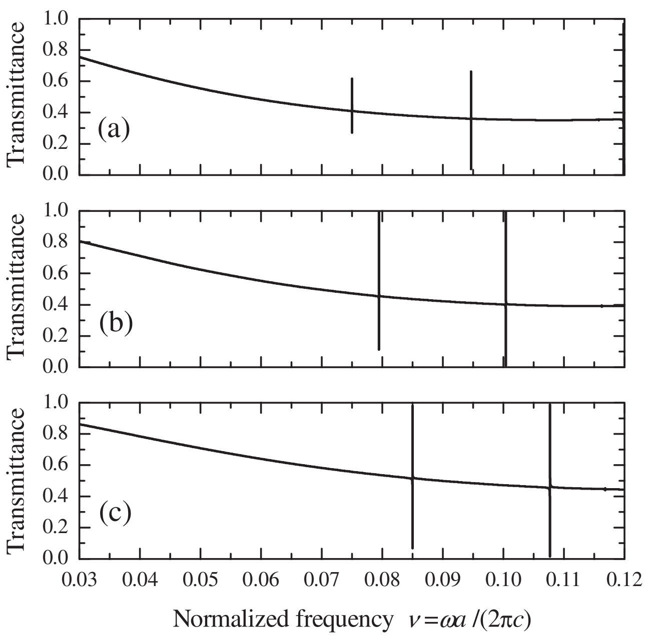

Figure 2 Transmittance spectrum (for normal plane-wave incidence, with y-polarized electric field) of the PQC slab, with $h = 0.75a$, $n = 3.418$, and different values of the hole radius: (a) $r = 0.2a$, (b) $r = 0.25a$, (c) $r = 0.3a$

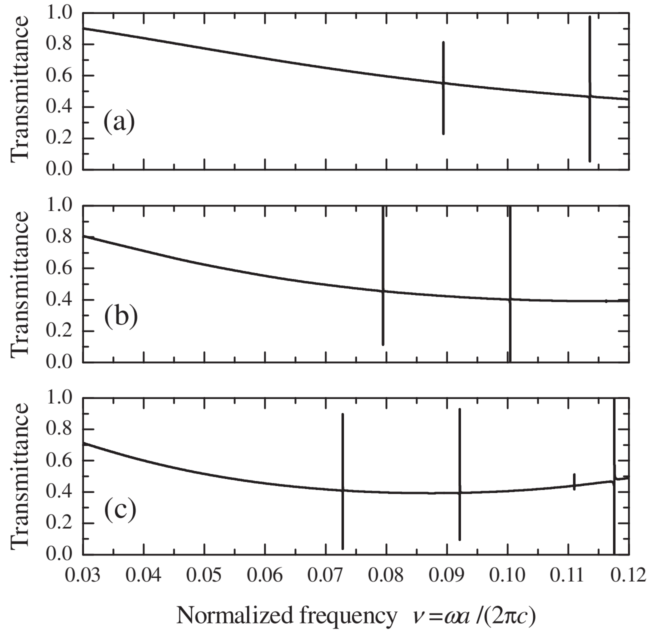

Figure 3 As in Figure 2, but with $r = 0.25a$, and different values of the slab thickness: (a) $h = 0.5a$, (b) $h = 0.75a$, (c) $h = a$

4.1. Varying the Air/Dielectric Fraction

Starting from the parametric configuration in [22], we first considered variations in the air/dielectric fraction, by varying the hole radius r, while keeping fixed the slab refractive index ($n = 3.418$, i.e., silicon) and thickness ($h = 0.75a$). In the periodic case [19], besides the changes in the Fabry-Perot background (in view of the changes in the effective refraction index), increasing the air/dielectric fraction (i.e., increasing the hole radius) was found to produce a shift of the GRs towards higher frequencies.

As one can gather from Figure 2, showing the transmittance spectra corresponding to three different values of the hole radius $r = 0.2a, 0.25a, 0.3a$ similar qualitative trends are also observed in our PQC case. In particular, two sharp resonances are clearly visible in each case [and a third one is barely visible, at the edge of the range of interest, in Fig. 2(a)], both moving towards higher frequencies as the air/dielectric fraction increases. As already pointed out in [22], the linewidths of these GRs turn out to be considerably narrower than those typically observed in periodic PCs, and a very fine frequency sampling ($\Delta\nu = 10^{-}$) is required in order to resolve them. However, their physical explanation is still rather controversial (see, e.g., the discussion in [22]) and deserves deeper studies.

4.2. Varying the Slab Thickness

Next, we varied the slab thickness, while keeping fixed its refractive index ($n = 3.418$) and the hole radius ($r = 0.25a$). In the periodic PC case [19], besides the changes in the Fabry-Perot background, increasing the slab thickness was found to lower the GR frequencies.

This qualitative trend is observed in the PQC case too, as shown in Figure 3, pertaining to three different values of the slab thickness $h = 0.5a, 0.75a, a$. As an effect of this frequency shift, for the thicker slab case [$h = a$, cf. Fig. 2(c)], two additional GRs appear within the frequency range of interest.

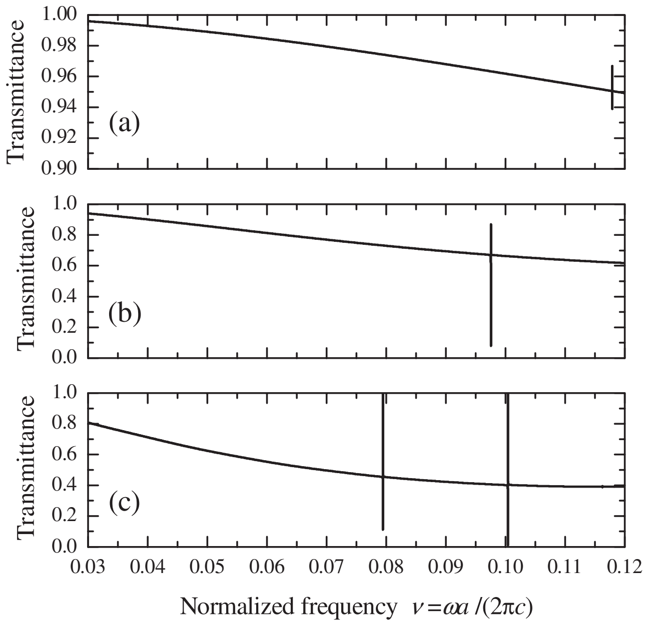

Figure 4 As in Figure 2, but with $r = 0.25a$, and different values of the slab refractive index: (a) $n = 1.5$, (b) $n = 2.5$, (c) $n = 3.418$. Note the different transmittance scale in (a)

4.3. Varying the Slab Refractive Index

Finally, we varied the slab refractive index, while keeping fixed its thickness ($h = 0.75a$) and the hole radius ($r = 0.25a$). In the periodic PC case, besides the changes in the Fabry-Perot background, increasing the refractive index was found to lower the GR frequencies. In this context, it is worth emphasizing that GRs are not directly related to bandgap-type phenomena, and can therefore be excited even in the presence of a relatively low refractive index contrast of the PC slab.

Once again, a similar qualitative trend is observed in the PQC case too, as shown in Figure 4, pertaining to three different values of the slab refractive index $n = 1.5, 2.5, 3.418$ (representative of typical substrate materials: glass, gallium nitride, and silicon, respectively). In particular, GRs turn out to be excitable even in the presence of low-contrast PQCs, although, for the lowest refractive indices [Figs. 4(a) and 4(b)], only one resonance is observed within the frequency range of interest.

To sum up, the above results extend to the PQC case the qualitative trends typically observed for the periodic PC case.

5. CONCLUSIONS

In this article, we have presented the salient results from a parametric study of the transmittance response of a PQC slab supercell. In particular, we have studied the effects of the air/dielectric fraction as well as the slab thickness and refractive index, showing that GRs can be observed over wide parametric ranges, and exhibit similar qualitative trends as those observed in the periodic PC case.

Current and future studies are aimed at a systematic comparative study of the GR mode lifetimes and linewidths in PC and PQC slabs, as well as the experimental validation of the results.

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