PHYSICAL REVIEW B **84**, 085135 (2011)

# Evidence of guided resonances in photonic quasicrystal slabs

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(Received 25 July 2011; published 29 August 2011)

We report on the experimental evidence of Fano-type *guided resonances* (GRs) in aperiodically-ordered photonic quasicrystal slabs. With specific reference to the Ammann-Beenker (8-fold symmetric, quasiperiodic) octagonal tiling geometry, we present our experimental results on silicon-on-insulator devices operating at near-infrared wavelengths, and compare them with the full-wave numerical predictions based on periodic approximants. Our results indicate that spatial periodicity is not strictly required for the GR excitation, and may be effectively surrogated by weaker forms of long-range aperiodic order which intrinsically provide extra degrees of freedom (e.g., higher-order rotational symmetries, richer defect states and phase-matching conditions, etc.) to be exploited in the design and performance optimization of nanostructured dielectric slabs operating in the out-of-plane configuration. The essential spectral features may be qualitatively understood in terms of phase-matching conditions derived from approximate homogenized models, and turn out to be effectively captured by full-wave modeling based on suitably-sized periodic approximants.

DOI: 10.1103/PhysRevB.84.085135 PACS number(s): 42.70.Qs, 41.20.Jb, 61.44.Br

The discovery, in 1984, of "quasicrystals" in solid-state physics[1,2] has triggered a growing interest in the study of aperiodically-ordered structures (based, e.g., on aperiodic tilings[3]) in many branches of physics and engineering.[4] In particular, *photonic quasicrystals* (PQCs) have been widely investigated,[5–7] with the main focus on in-plane electromagnetic (EM) propagation effects in two-dimensional structures constituted of aperiodically-ordered arrangements of cylindrical inclusions (or holes) in a host medium. In this framework, certain effects observable in periodic photonic crystals (PCs), such as band gap, field localization, negative refraction and super-focusing, directive emission, etc., have been reproduced numerically and experimentally (see, e.g., Refs. 5–7 and references therein). The related studies provided useful insights in the influence of higher-order rotational symmetries, Bragg-type and multiple scattering, and short-range interactions.[8] Moreover, they also envisaged some potential advantages inherently tied to aperiodic order, such as easier achievement of phase-matching conditions,[9] higher isotropy and tradeoff between (lower) dielectric contrast and (higher) rotational symmetry,[10] richer and more wavelength-selective defect states,[11] field-localization capabilities even in the absence of lattice defects,[12] etc. In this framework, novel design strategies especially tailored to exploit the peculiar aspects and further degrees of freedom inherent of aperiodic order have been developed (see, e.g., Refs. 13 and 14).

Much less attention has been devoted to *out-of-plane* propagation effects, with the notable exceptions of arrays of subwavelength holes in metallic films,[15–18] and arrays of metallic nanoparticles.[19,20] In particular, these latter results indicated the possibility of exciting broad resonances with enhanced spatial localization, higher density of the enhanced field states, and distinctive scattering fingerprints.

So far, no results are available in connection with the so-called "guided resonances" (GRs)[21] in penetrable structures such as PQC slabs consisting of holey dielectric films. In periodic PC slabs, this phenomenon can be observed under out-of-plane illumination, due to the excitation of "leaky" modes that can couple with the continuum of radiative modes in the surrounding environment, giving rise to sharp, asymmetrical Fano-type resonances, typical of wave-coupling mechanisms between discrete and continuum states. This phenomenon finds important practical applications in contemporary photonic research. Specifically, GRs have been extensively exploited to create optical and photonic devices such as filters,[22] mirrors,[23] beam-splitters,[24] nanoelectromechanical tunable lasers,[25] focusing elements,[26] and polarizers.[27] Also, in photovoltaics, GR-based back-reflectors have been proposed in order to increase absorption in thin-film solar cells.[28] Moreover, the GR sensitivity (in terms of spectral shift) to changes in the surrounding environment has been exploited in connection with displacement[29] and biological[30,31] sensors.

Extension of the GR effects to PQC geometries would bring along the aforementioned aperiodic-order-induced advantages and design perspectives to be exploited in the engineering of the GR phenomenon. However, obtaining a convincing evidence of such extension is a rather challenging task, since the lack of spatial periodicity, with the consequent unavailability of Bloch-type concepts typical of periodic PCs, poses severe limitations in the theoretical and numerical predictive modeling.

In this paper, we pursue the two-fold objective of i) providing proof-of-concept experimental evidence of GRs in a globally aperiodic PQC slab, and ii) assessing the applicability of computationally-affordable predictive modeling schemes based on suitably-sized periodic approximants. The problem geometry is illustrated in Fig. 1. Our structures are based on

 

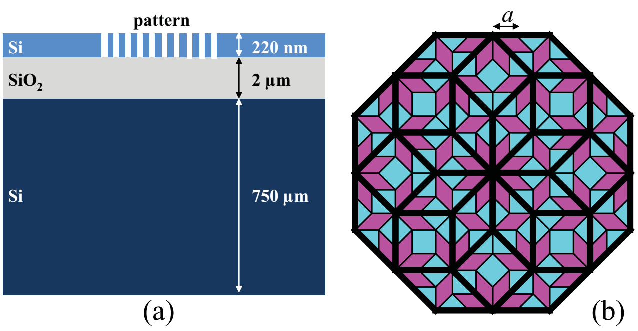


FIG. 1. (Color online) (a) Schematic (not in scale) of the SOI-based PQC slab (details in the text). (b) Initiator (thick black lines) and first stage of inflation rules (shaded tiles) to be iterated for generating the Ammann-Beenker tiling.

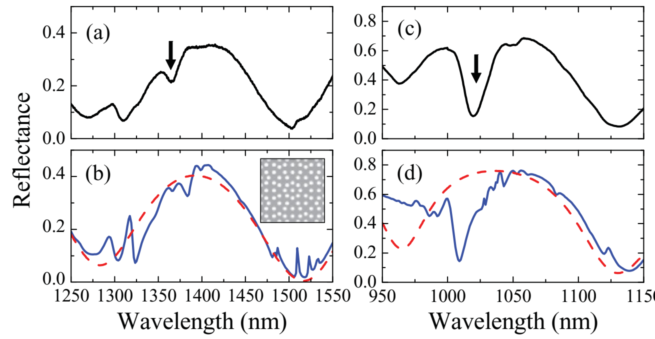


FIG. 3. (Color online) (a) Measured near-infrared reflectance spectrum of a SOI-based globally-aperiodic PQC slab sample with $a = 500$ nm and $r = 140$ nm (cf. Fig. 2), with the thick arrow marking the main GR dip. (b) Numerically-computed response [blue (solid) line] of a periodic approximant obtained by replicating a square supercell (shown in the inset) of sidelength $L = (4 + 3\sqrt{2})a$, compared with the response [red (dashed) line] of an effective homogenized structure. (c), (d) As in (a) and (b), respectively, but for $r = 120$ nm (note also the different axis scales).

a silicon-on-insulator (SOI) wafer featuring a 220-nm-thick top silicon layer, a 2-$\mu$m-thick layer of buried oxide ($SiO_2$), and about 750 $\mu$m of bulk silicon [Fig. 1(a)]. Using standard electron-beam-lithography, a $400 \times 400$ $\mu m^2$ area of the top silicon layer is patterned with holes of radius $r$ placed at the vertices of the Ammann-Beenker octagonal tiling, characterized by an 8-fold-symmetric, quasiperiodic arrangement of square and rhombus tiles of sidelength $a$ (lattice constant), and iteratively generated via the inflation rules illustrated in Fig. 1(b).[32] Figure 2 shows the scanning-electron-microscope (SEM) image (a close-up view is shown in the inset) of a globally-aperiodic sample pattern characterized by a lattice constant $a = 500$ nm and hole radius $r = 140$ nm.

For the experimental characterization at near-infrared wavelengths, we relied on a standard reflection setup.[33] First, we characterized the device in Fig. 2, obtaining the results shown in Figs. 3(a) and 3(b). Specifically, Fig. 3(a) shows the measured reflectance spectrum of the PQC slab within the wavelength range 1250–1550 nm, while Fig. 3(b) shows the numerically-computed response based on the finite-element simulation[34–36] of a suitably-sized *periodic approximant* ("supercell" shown in the inset) as in Refs. 37 and 38, superimposed on the reference Fabry-Perot-type response of an effective

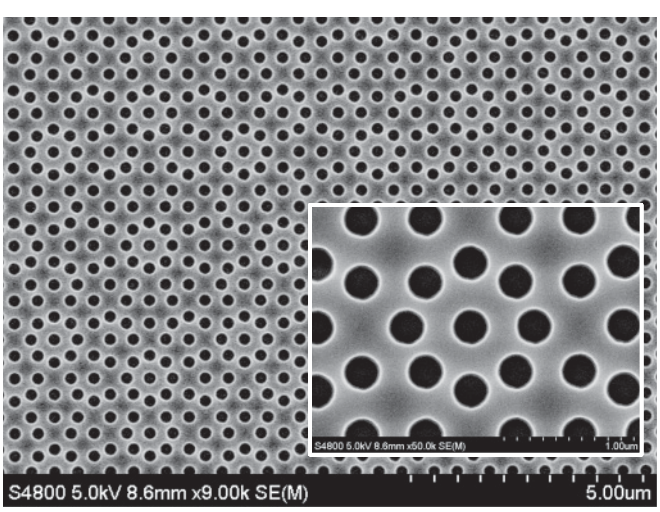


FIG. 2. SEM image (zoomed in the inset) of a globally-aperiodic PQC sample pattern with $a = 500$ nm and $r = 140$ nm.

*homogenized* structure (with the top layer having the same effective refractive index as our patterned PQC slab). From the comparison, we note that the PQC response consists of a smooth Fabry-Perot background (qualitatively similar to that of the homogenized structure) broken by a series of dips/peaks attributable to GRs. In particular, a GR line shape (marked by a thick arrow) is clearly visible around 1370 nm, with good agreement between simulations and measurements. This represents a key result, as it provides the desired experimental evidence of the phenomenon, and also indicates the effectiveness of the periodic-approximant-based numerical modeling (with the chosen supercell size) in capturing the associated spectral features. The moderate disagreement observable for the minor dips/peaks at lower and higher wavelengths may be attributable to the fabrication tolerances (typically $\sim\pm5$ nm in the hole radius and silicon layer thickness) and/or to the fact that such spectral features show up in regions of minimum reflectance, where the signal-to-noise of the experimental setup is lower.

As a further representative example, Figs. 3(c) and 3(d) show the response of a device featuring $a = 500$ nm and $r = 120$ nm at shorter wavelengths (950–1150 nm). Compared with the previous case, a more pronounced GR line shape can now be observed at approximately 1020 nm, with respectable dynamic range (from $\sim$0.6 to $\sim$0.16 reflectance) and very good agreement with the numerical prediction.

For low-contrast configurations, the GR phenomenon may be physically understood and parameterized via simple semi-analytical models (e.g., along the lines of Ref. 39) based on *phase-matching* conditions between the bound modes supported by an effective homogenized slab waveguide and Bragg-type peaks in the PQC spatial spectrum (reciprocal lattice). Although, strictly speaking, our high-contrast SOI configurations fall beyond its range of applicability, the above framework still provides useful physical insight and rules-of-thumb for GR design. For instance, Fig. 4(a) shows the dispersion curves for the fundamental transverse-electric ($TE_0$) bound modes supported by a homogenized asymmetrical slab

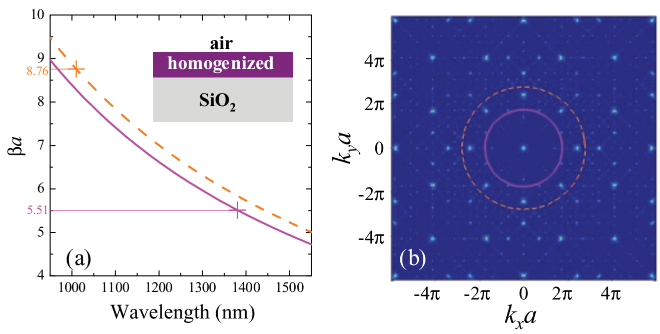


FIG. 4. (Color online) (a) Dispersion curves of the fundamental ($TE_0$) bound mode supported by a homogenized asymmetrical slab waveguide (shown in the inset), for $r = 140$ nm [magenta (solid) line] and $r = 120$ nm [orange (dashed) line]. (b) Spatial spectrum of the PQC, with superimposed circles of radii $\beta a = 5.51$ [magenta (solid) line] and $\beta a = 8.76$ [orange (dashed) line] pertaining to the resonant wavelengths (marked with crosses in the dispersion curves) of 1380 nm (for $r = 140$ nm) and 1010 nm (for $r = 120$ nm). For model consistency, such wavelengths were extracted from the numerical results in Figs. 3(b) and 3(d).

waveguide (i.e., assuming an infinite $SiO_2$ layer), for the two hole-radius values considered, from which we can extract the in-plane propagation constant $\beta$ (normalized to the lattice constant $a$) pertaining to the resonant wavelengths in Fig. 3. Phase-matching conditions can be expressed as $\beta a = |\mathbf{k}_n|a$ (with $\mathbf{k}_n$ denoting a Bragg wave vector in the reciprocal space), and may accordingly be assessed by drawing circles of radii $\beta a$ superimposed on the spatial spectrum of the PQC, as shown in Fig. 4(b). It is observed the the $\beta a$ circles pertaining to the more pronounced GRs in Fig. 3 fall rather close to two (different) orders of spectral peaks, and seem therefore consistent with the associated phase-matching conditions.

In conclusion, we have demonstrated experimentally the possibility of exciting Fano-type GRs at near-infrared wavelengths in SOI-based PQC slabs characterized by an octagonal (Ammann-Beenker) tiling geometry. This constitutes evidence of GRs in globally-aperiodic dielectric PQC structures. Our results fill a gap in the literature, indicating that, similar to what is observed for other typical propagation effects in PCs, the seemingly implied requirement of strict spatial periodicity may be relaxed so as to encompass a weaker form of long-range aperiodic order. Moreover, they also indicate that these GR phenomena may be qualitatively understood in terms of phase-matching conditions derived from approximate homogenized models, and that their essential spectral features may be effectively captured by full-wave numerical modeling based on suitably-sized supercells.

The extension to PQC structures also opens up different perspectives in the GR engineering, especially in terms of richer resonant features and enhanced field-tailoring capabilities. In connection with the first aspect, the nature and spacing of the resonances in a PQC is inherently different from those of a comparable regular periodic structure. This intrinsic difference can be exploited for a number of applications, such as solar cells or nonlinear phase matching. In solar cells, one may want to adjust the density of resonances and their coupling strength to match the spectral profile of the absorbing layer; in nonlinear phase matching, one needs to compensate for material dispersion and hence requires non-evenly-spaced resonances. Both of these important requirements can be met by an aperiodically-ordered PQC of the type we demonstrate here.

An additional feature of these structures is their ability to tailor the optical field and its overlap with either the high-index or the low-index part of the lattice. In our previous numerical studies on the sensing/tuning efficiency (with respect to changes in the hole refractive index) of free-standing structures,[40] we observed that, for a given parameter configuration (slab thickness and refractive index, and filling fraction), and by simply changing the spatial arrangement of holes from periodic (square) to aperiodic (octagonal), it was possible to enhance the field concentration in the holes, thereby increasing the sensitivity to environmental changes by up to a factor of seven (from about 70 nm/RIU to 485 nm/RIU).

These examples clearly highlight the potential for innovation possible with PQCs and the new design opportunities they offer; having now demonstrated a truly nonperiodic and global quasicrystal structure experimentally, we anticipate that corresponding novel devices will soon be realized, with possible applications to a variety of leading-edge multidisciplinary fields, ranging from chemical and biological sensing to nanodevices and photovoltaics (see, e.g., Refs. 22–31). Moreover, in view of the pervasive nature of the involved Fano-type resonant phenomena (ranging from EM and acoustics to atomic and condensed-matter physics; see, e.g., Ref. 41 for a recent review), the photonic-based configuration and results presented here may inspire analogous studies in other wave-scattering scenarios that feature discrete quasibound states (induced by aperiodic order) interacting with a continuum radiation spectrum.

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[33]In our measurement setup, light emitted by a broad-band white light source is coupled directly into an optical fiber bundle (standard reflection probe), consisting of six fibers, and carried to the probe end focused on the sample. The sample is placed on a motorized XYZ positioning stage (enabling a 10 $\mu$m absolute on-axis accuracy), and its surface selectively reflects light back into another fiber connected to an optical spectrum analyzer. The above setup provides direct illumination of the entire patterned area, and a collection spot of radius $\sim$ 200 $\mu$m. A distance of 7 mm between the sample and the probe end was chosen as a tradeoff between the fulfilling of paraxial (quasinormal incidence) conditions and an acceptable signal-to-noise ratio. The measured reflectance spectrum of the sample is finally normalized to that of an aluminum mirror.

[34]We used the COMSOL Multiphysics software package,[35] with the SOI constitutive parameters derived from Ref. 36 (see Refs. 37 and 38 for more details).

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