Guided Resonances in Photonic Crystal Slabs with Aperiodically-Ordered Supercells

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Abstract: We report on the first experimental evidence of guided resonances (GRs) in photonic crystal slabs based on aperiodically-ordered supercells. Using the Amman-Beenker (quasiperiodic, 8-fold symmetric) tiling geometry, we present our study on the fabrication, experimental characterization, and full-wave numerical simulation of two representative structures (with different filling parameters) operating at infrared wavelengths (1300-1600 nm). Our results show a fairly good agreement between measurements and numerical predictions, and pave the way for the development of new strategies (based, e.g., on the lattice symmetry breaking) for GR engineering.

Keywords: Silicon Photonics, Photonic Crystals

1. Introduction

In recent years, defect and bandgap engineering of photonic crystal (PC) slabs have been the subject of many studies aimed at designing micro- and nano-sized optical devices for integrated photonic circuits [1]. For applications that require the light-flow control at a wavelength scale, PC slabs made of air hole arrays in a host dielectric medium support guided modes that are completely confined in the slab and cannot couple to any external radiation because of total internal reflection which results from the refractive index contrast between the PC slab and the surrounding media [2]. In addition to guided modes, PC slabs also support leaky modes, with finite lifetimes inside the slab, that can couple to the continuum of free-space modes. These modes are known as “guided resonances” (GRs) [3], since their electromagnetic power is strongly confined within the slab but, at the same time, they can also couple to the external radiation. In PC slabs, GRs can be excited under normally incident (with respect to the crystal-periodicity plane) plane-wave illumination. In this context, the slab transmission/reflection spectra exhibit Fano-like resonance line shapes [4] (due to the interference between the directly transmitted/reflected wave and those originating from the excited GRs) superimposed on a smoothly varying background that results from the Fabry-Perot effect associated with the light interaction with an effectively-homogeneous dielectric slab. Such resonances have recently attracted considerable research interest in view of the intriguing possibilities of tailoring/engineering their spectral features (e.g., by acting on the incidence angle and on the physical and geometrical parameters of the gratings) as well as their relevance for a number of applications. More specifically, GRs in PC slabs have been exploited to demonstrate mirrors [5], optical filters [6], polarization splitters [7] and displacement sensors [8], just to mention a few. However, it is worth noting that all of these experiments, as well as most of the numerical work, has focused only on periodic PCs. In recent work, Prasad et al. [9] argued that strict periodicity is an essential requirement for the excitation of GRs. However, in some recent studies [10-12], we have already demonstrated by numerical analysis that GRs can be excited in PC slabs based on aperiodically ordered supercells, and have also shown the possibility of controlling GR excitation by introducing ad-hoc point defects [12]. Starting from the periodic-approximant case, for which rigorous full-wave numerical modeling [10-12] is still computationally affordable, here we report the first experimental evidence of GR excitation in PCs with aperiodically ordered supercells.

2. Case of Study

In accordance with our previous papers [10-12], we considered a supercell based on a quasiperiodic (Ammann-Beenker, octagonal) lattice exhibiting eight-fold symmetry [13] and containing 97 elements (or a fraction of them), shown in Fig. 1a.
We chose a silicon-on-insulator (SOI) wafer characterized by a top silicon layer with a nominal thickness $t = 220$ nm, 2 $\mu$m of buried oxide, and about 750 $\mu$m of bulk silicon for the experimental realization. The PQC parameters were chosen on the basis of the design carried out in [10], but taking fabrication constraints into account, e.g., leaving the buried oxide layer underneath the guiding layer for mechanical support and making holes with a radius larger than 90 nm in order to guarantee that the holes are properly etched into the silicon slab. Based on these considerations, as a first attempt for our study, we chose a lattice constant (see Fig. 1a) $a = 300$ nm and a hole radius $r = 95$ nm, corresponding to a filling parameter $r/a = 0.32$. Since the focus of this first study is on providing some generic experimental evidence of the GR phenomenon in PQCs, the design parameters were not optimized for a specific application.

The pattern was first defined in ZEP-520A electron beam resist (by using a ZEISS GEMINI 1530/RAITH ELPHY PLUS electron beam writer) and then transferred into the top silicon layer by using low power, low DC bias, reactive ion etching (RIE) with a combination of SF6 and CHF3 gas (50:50 mix). At the end of the fabrication process, the remaining resist was removed by soaking in dimethylacetamide. Figure 1b shows scanning electron microscope (SEM) images of a fabricated structure. The size of the patterned area was about 300 $\mu$m $\times$ 300 $\mu$m, corresponding to about 14700 supercells.

The fabricated sample was then characterized in reflection using normal incidence illumination through a beamsplitter with the electric field polarized along the side of the supercell. We used a broadband supercontinuum (KOHERAS Super Compact) source. The spot size was about 60 $\mu$m and we normalized the measured reflectivity of the slab to that of a gold mirror. Figure 2 shows the normalized reflectivity in the wavelength range 1300-1600 nm, and compares it with the numerical prediction obtained by finite-element modeling (COMSOL Multiphysics, RF Module [14]). The computational domain (restricted, for symmetry considerations, to one quarter of the supercell) is transversely terminated with two horizontal perfectly-electric-conducting (PEC) and two vertical perfectly-magnetic-conducting (PMC) walls, so as to simulate a normally-incident plane-wave with vertically-polarized electric field. The structural parameters used for the simulation, which closely represented those of the experimental realization as obtained by SEM inspection, are reported in the figure caption. Both losses and dispersion of silicon have been taken into account.

3. Results

The first result is shown in Fig. 2a, where we observe that the classical Fabry-Perot behavior of the SOI slab is broken by a set of Fano-type resonances arising from the coupling of the incident plane wave with degenerate modes of the PC.
Although, at this stage, no effort was made to obtain GR-based cavities characterized by high quality factors, it is refractive index of the slab) results in a shorter life-time of the GR, thus leading to a reduction of the quality factor.

GR occurring in the investigated wavelength range. More specifically, it exhibits a deep broadband resonance at 1373 nm. The response is compared with the numerical prediction. As predicted, this new structure ensures a higher visibility of the GRs in the reflectivity spectrum. To this aim, we fabricated and characterized another structure with the same lattice constant (typ. ± 5%).

In conclusion, we have experimentally demonstrated the evidence of GRs in PC slabs based on aperiodically-ordered supercells. For this particular application, aperiodically-ordered lattice geometries seem to be inherently suited in view of the variety of inequivalent defect sites that they can offer by comparison with periodic PCs. A good agreement between numerical and experimental results has been observed. Demonstrating the robustness of the GR phenomena in spite of the increased complexity of the slab supercell, taking also into account the related fabrication tolerances. These results, which confirm our previous numerical predictions [10,11], may open up new intriguing perspectives on the engineering of GRs.

4. Conclusion
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References