Mode confinement in photonic quasicrystal point-defect cavities for particle accelerators

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In this letter, we present a study of the confinement properties of point-defect resonators in finite-size photonic-bandgap structures composed of aperiodic arrangements of dielectric rods, with special emphasis on their use for the design of cavities for particle accelerators. Specifically, for representative geometries, we study the properties of the fundamental mode (as a function of the filling fraction, structure size, and losses) via two-dimensional and three-dimensional full-wave numerical simulations, as well as microwave measurements at room temperature. Results indicate that for reduced-size structures, aperiodic geometries exhibit superior confinement properties by comparison with periodic ones. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2999581]

A promising approach to the development of new types of compact, efficient microwave particle accelerators is to realize structures having higher frequencies of operation since this can increase the accelerating field gradient and reduce the power consumption.[1] Unfortunately, in a particle accelerator, the higher the frequency, the stronger the excitation (by the wakefield effect) of higher order modes (HOMs), with a significant reduction in the beam stability. Nowadays accelerators operate at frequencies $\lesssim 1$ GHz, and they usually rely on waveguide-based HOM dampers in order to efficiently suppress the wakefields. However, at higher ($\gtrsim 10$ GHz) working frequencies, the standard configurations used for HOM damping become rather cumbersome or even technically unfeasible.

In the past, open metallic photonic-crystal (PC) cavities, based on periodic arrangements of inclusions, have been proposed as candidates for a new generation of accelerating cells since they exhibit electromagnetic (EM) responses that can be highly selective in frequency. This property (and others related) arises from the formation of photonic bandgaps (PBGs), whereby multiple scattering of waves by periodic lattices of inclusions acts to prevent the propagation of EM waves within certain frequency ranges. In these structures, an open resonator can be easily created by introducing a lattice *defect*, e.g., by removing one inclusion. Unlike conventional closed cavities, such a *point-defect* PBG cavity can be designed to support only one bound mode (strongly *localized* within the defect region), and *mostly extended* HOMs. This suggests the possibility of using PBG-based cavities for effective HOM wakefield suppression, without the need for mode couplers or detuning. Indeed, a prototype of a large-gradient accelerator that relies on a metallic PBG structure has been successfully fabricated and experimentally characterized.[2] Superconducting prototypes have been also tested at 4 K, showing quality factors up to $\sim 10^5$, limited by radiation losses only.[3] *All-dielectric* or *hybrid-dielectric* PBG structures could also be used, thereby eliminating or reducing the characteristic metallic losses at the frequency of operation, even if at the expense of an increased radiative contribution.[4]

Moreover, it should be observed that spatial periodicity is not an essential ingredient for obtaining PBG and related confinement effects. During the past few years, following up on the discovery of "quasicrystals" in solid-state physics,[5] similar effects have been found in *aperiodically ordered* structures too (see, e.g., Ref. 6 for a recent review). Such structures, commonly referred to as "photonic quasicrystals" (PQCs), are typically based on the so-called aperiodic-tiling geometries,[5] characterized by weak (local or statistical) rotational symmetries of "noncrystallographic" type (e.g., of orders 5, 8, and 12). In PQCs, the EM response can be strongly dependent on the lattice short-range configuration and on multiple interactions,[7] and yet almost independent of the incidence angle, and can be engineered/optimized via judicious exploitation of the additional degrees of freedom endowed by aperiodicity (see, e.g., Ref. 8). Moreover, in view of their many nonequivalent sites, PQCs exhibit a number of possible different defects useful for field confinement,[9] as well as intrinsic localized modes.[10,11] In this connection, PQC-based optical microcavities have already been successfully fabricated, with the ability of strongly confining the light with both high quality factors and small modal volumes.[12,13]

In this letter, we present a comparative study of the confinement properties of different point-defected PBG cavities made of cylindrical dielectric rods arranged according to representative aperiodic PQC geometries. The study is aimed at highlighting the potential advantages offered by PQC dielectric structures in the design of PBG-based accelerating resonators, with respect to their periodic PC counterparts. In this framework, we present a body of results from numerical full-wave simulations to compare the confinement properties of the various configurations (including a reference periodic one) as a function of the structure size, filling fraction, and losses. In addition, for experimental verification, we present the results of measurements at room temperature on cavity prototypes operating in the microwave region (~ 16.5 GHz).

The structures of interest are composed of sapphire (relative permittivity $\varepsilon_r = 9.2$, and typical loss tangent of 10^{-6}) circular rods of radius $r = 0.15$ cm and height $h = 0.6$ cm,

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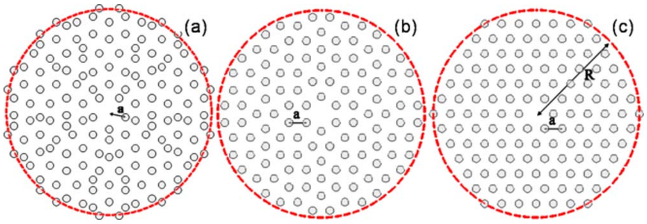

FIG. 1. (Color online) Point-defect PBG cavity geometries for Penrose (a), dodecagonal (b), and periodic (triangular) (c) lattices, with structure radius $R=7a$ and filling fraction $r/a=0.2$.

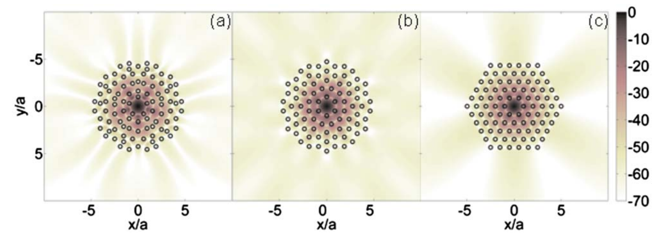

FIG. 3. (Color online) Normalized electric field intensity maps (in dB) of the fundamental resonant TM mode for Penrose (a), dodecagonal (b), and periodic (c) configurations, with $R=5a$ and $r/a=0.2$.

placed at the vertices of a periodic or aperiodic tiling with lattice constant $a=0.75$ cm. The structure is sandwiched between two metallic plates, and presents a bore radius of 0.2 cm for the particle beam transit. Specifically, as shown in Fig. 1, we consider two representative (aperiodic) PQC geometries based on the Penrose [fivefold symmetric, Fig. 1(a)] and on the dodecagonal [12 fold symmetric, Fig. 1(b)] tilings (see, e.g., Refs. 5 and 14 for details about their generation), and a reference periodic (triangular) PC geometry [Fig. 1(c)].

The structures are obtained by cutting, from suitably large lattices with same rod properties and lattice constant, a circular area of radius R, and finally removing the central rod, as shown in Fig. 1, in coincidence with the beam transit aperture. We assume time-harmonic $[\exp(-i2\pi ft)]$ excitation and transverse magnetic (TM) polarization (electric field parallel to the rods axis).

Our full-wave numerical study of the EM response of the structures is based on the combined use of a commercial three-dimensional (3D) simulator (CST Microwave Studio) based on finite integration in the time domain and an in-house two-dimensional (2D) code based on a Bessel–Fourier multipole expansion.[15] The two main loss mechanisms are related to radiation (in view of the open character of the structure) and Ohmic dissipation in the metallic plates, the sapphire dielectric losses being actually negligible. Assuming the metallic plate separation smaller than half a wavelength so that the field distribution is rather uniform in the direction along the rods axis, the radiation losses can be efficiently modeled using the 2D code (which assumes the dielectric rods infinitely long). This renders a parametric study computationally affordable.

Figure 2 shows, for the three geometries of interest, the

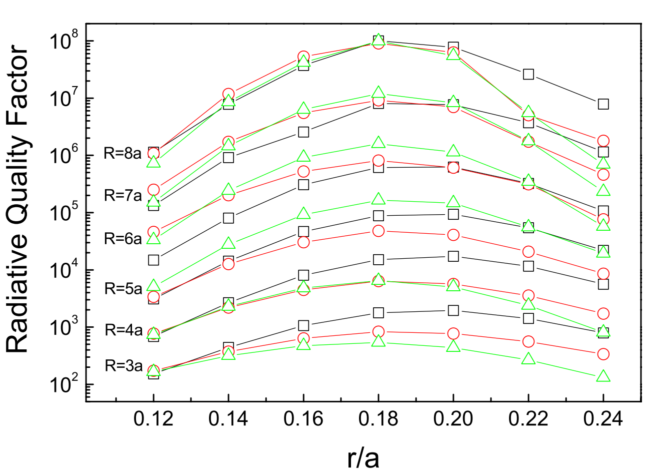

FIG. 2. (Color online) Radiative quality factor of the fundamental TM mode, for Penrose (triangles), dodecagonal (squares), and periodic (circles) geometries, as a function of the filling fraction r/a, and for different values of the structure radius R.

radiative quality factor ($Q_r=f_c^{(r)}/2f_c^{(i)}$, with $f_c^{(r)}+if_c^{(i)}$ denoting the complex eigenfrequency obtained by solving a source-free problem)[15] dependence on the filling fraction r/a and the structure size R. We observe that for all geometries, a maximum Q_r is achieved for r/a ranging between 0.18 and 0.20. Differences among the geometries emerge when considering the dependence on the structure size R. Specifically, dodecagonal PQC cavities outperform the periodic ones for small to moderate structure sizes, and become eventually comparable for $R \gtrsim 8a$. Particularly intriguing is the behavior of the Penrose PQC cavities, which exhibit the lowest Q_r for smaller sizes ($R \lesssim 4a$), and the highest for moderate cavity sizes. Similar indications emerged from the study of the electric field spatial distribution of the resonant modes, shown in Fig. 3 for a moderate structure size $R=5a$, so as to better visualize the power radiated outside the cavity.

For modeling the conducting losses of the metal plates, which become dominant for larger-size structures, we use the commercial (CST Microwave Studio) 3D simulator, whose eigenmode solver option also allows the computation of all the main parameters (shunt impedance, conducting and dielectric loss contributions) of interest for accelerating cavities, with the exception of the radiation losses.

Table I summarizes, for the cases under test and for the fundamental TM mode, the resonance frequency, the Ohmic, and radiative quality factors Q_c and Q_r, respectively, and the shunt impedance per unit length r_s, defined as $V_o^2/(2Ph)$, where V_o is the voltage "seen" by the incoming particle and P is the EM power lost in the PBG cavity. In the simulation analysis, conducting losses are computed at 300 K assuming the metal plates as made of high-purity copper (electrical conductivity $\sigma=5.8\times10^7$ S/m).

The r_s values well compare with data previously reported on PBG metallic cavities,[2] and suggest that hybrid-dielectric structures can be successfully exploited for the design of high-gradient accelerators.

For experimental verification, we fabricated prototypes of the simulated structures, by suitably placing single crystal

TABLE I. Simulated characteristic parameters for the fundamental TM mode of point-defect midsized cavities ($R=4a,5a$) having Penrose (PEN), dodecagonal (DOD), and periodic triangular (PER) geometries, and filling fraction $r/a=0.2$.

	$R=4a$			$R=5a$		
	PEN	DOD	PER	PEN	DOD	PER
f_c(GHz)	16.788	16.424	16.556	16.770	16.429	16.561
Q_c	11 400	11 800	11 900	12 200	11 900	11 900
Q_r	5000	17 200	5700	147 000	93 000	40 800
r_s[MΩ/m]	60	180	100	280	280	240

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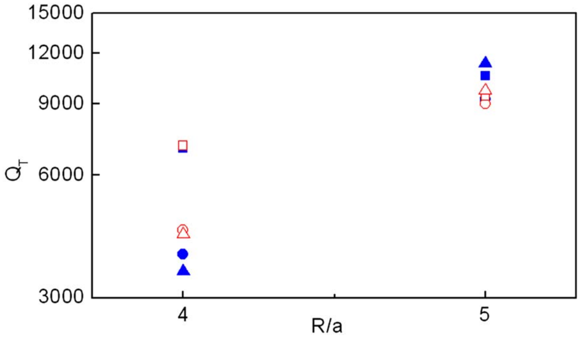

FIG. 4. (Color online) Experimental (open symbols) and simulated (full symbols) unloaded quality factor Q_T values for Penrose (triangles), dodecagonal (squares), and periodic (circles) lattices, having filling fraction $r/a=0.2$, and structure radii $R=4a$ and $R=5a$.

sapphire rods between two oxygen-free high-conductivity copper plates. In the experimental setup, input and output tiny dipole antennas are placed on the top plate; the input antenna feeds the cavity near (but not in correspondence of) the defect region, so as to avoid extreme reflection from that port, whereas the output antenna is sufficiently far from the dielectric rods. Both input and output antennas are then connected to a HP8720C Vector Network Analyzer. Careful attention is paid to ensure that measurements are carried out in a weak coupling configuration (insertion losses at the resonance ~−40 dB). From the frequency response of the transmission scattering parameters, we evaluate the resonance frequency f_c and the unloaded overall quality factor Q_T for midsize structures ($R/a=4,5$) featuring each of the geometries under study. Concerning the spectral response, results confirm the intrinsically monomodal behavior of PQC cavities, with the defect mode being the only one transmitted well within the corresponding bandgap. The measured resonance frequencies agree pretty well (within 2%) with the numerical predictions in Table I. There is also a good agreement between the experimentally measured Q_T and the values extracted from simulations $[Q_T=(Q_r^{-1}+Q_c^{-1})^{-1}]$, as shown in Fig. 4.

For $R=4a$, the performance is limited by radiation losses only, and therefore the Q_T factor is strongly dependent on the geometry, as expected from the results shown in Fig. 2. Surprisingly, the measured quality factors are always higher than those predicted by the simulations. Conversely, for $R=5a$, Q_T is almost independent of the dielectric rods arrangement since it is strongly dominated by the conductive losses. The slight discrepancy between measurements and simulations in this latter case should be ascribed to the inherent uncertainty in the copper conductivity values considered in the modeling (see, e.g., Ref. 16).

It is worth mentioning that the quality factors of our hybrid-dielectric aperiodic structures are higher than those found for metallic periodic cavities ($\sim 4\times 10^3$) of similar size and resonance frequency (~17.1 GHz).[2] This is due to the combined reduction in both Ohmic and radiative losses, by using dielectric inclusions and exploiting aperiodic geometries. Additional advantages of hybrid-dielectric resonators include a reduced complexity in the fabrication, and the possibility of operating at higher frequencies using HOMs without mode competition.[4] Moreover, it is worth noting that, in principle, breakdown and charging can be strongly reduced or avoided in a dielectric accelerating structure.[17,18]

To sum up, our comparative study indicates that although in the limit of very large structure size the confinement properties of periodic and aperiodic geometries tend to become comparable, for small to moderately sized structures specific aperiodic configurations (in our case, Penrose and dodecagonal) turn out to outperform the reference periodic one. In particular, for the structure size $R=5a$, we found the Penrose-type geometry to provide a considerable improvement (of nearly a factor 4) in the radiative quality factor, as compared to the periodic (triangular) counterpart (see Table I). The physical interpretation of such observation can be addressed recalling the mechanisms underlying the bandgap formation in PQCs, which at variance with the periodic PC case, are not necessarily related to long-range interactions. With specific reference to Penrose-type PQCs, it was shown in Ref. 7 that the bandgap pertaining to the point-defect mode of interest here is actually attributable to *short-range* interactions. Accordingly, for reduced-size structures, we intuitively expect such a geometry to provide a more effective field confinement than a periodic counterpart.

An improvement in the quality factor, achievable via a simple spatial rearrangement of the inclusions, constitutes indeed an attractive perspective toward the design of cavities for compact, efficient microwave particle accelerators. However, as shown by our numerical and experimental results, such improvement can actually be washed out by conducting losses in the metallic plates. In this framework, current and future studies are aimed at the fabrication and testing of cryogenic hybrid-dielectric prototypes.

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