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 ≤1 GHz, and they usually rely on waveguide-based HOM dampers in order to efficiently suppress the wakefields. However, at higher (≥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 ~105, 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, 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, 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 εr = 9.2, and typical loss tangent of 10−6) circular rods of radius r = 0.15 cm and height h = 0.6 cm.
placed at the vertices of a periodic or aperiodic tiling with
lattice constant $a=0.75$ cm. The structure is sandwiched be-
 tween 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 ge-
ometries 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 par-
allel to the rods axes).

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. 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. Assum-
ing the metallic plate separation smaller than half a wave-
length so that the field distribution is rather uniform in the
direction along the rods axis, the radiation losses can be ef-
ciently modeled using the 2D code (which assumes the di-
electric rods infinitely long). This renders a parametric study
computationally affordable.

Figure 2 shows, for the three geometries of interest, the
radiative quality factor $Q_r=a^2/2\pi f_c$ (with $f_c$ denot-
ing the complex eigenfrequency obtained by solving a source-
free problem) 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 con-
sidering the dependence on the structure size $R$. Specifi-
cally, dodecagonal PQC cavities outperform the periodic ones
for small to moderate structure sizes, and become eventually
comparable for $R\approx 8a$. Particularly intriguing is the behavior
of the Penrose PQC cavities, which exhibit the lowest $Q_r$ for
smaller sizes ($R\leq 4a$), and the highest for moderate cavity
sizes. Similar indications emerged from the study of the elec-
tric 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 di-
electric loss contributions) of interest for accelerating cavi-
ties, 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 $Q_r$ and $Q_c$, respectively, and
the shunt impedance per unit length $r_s$, defined as $V_s^2/(2Ph)$,
where $V_s$ 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 re-
ported on PBG metallic cavities, 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

\begin{table}[h]
\begin{center}
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
 & $R=4a$ & & & $R=5a$ & & & \\
\hline
 & PEN & DOD & PER & PEN & DOD & PER & \\
\hline
$Q_r$ & 11 400 & 11 800 & 11 900 & 12 200 & 11 900 & 11 900 & \\
$Q_c$ & 5000 & 17 200 & 5700 & 147 000 & 93 000 & 40 800 & \\
$r_s$[M$\Omega$/m] & 60 & 180 & 100 & 280 & 280 & 240 & \\
\hline
\end{tabular}
\end{center}
\end{table}

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. 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 $R$.

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 $r/a=0.2$. 

\[ \frac{\text{Q}}{\text{c}} = \frac{\text{r}}{\text{a}} \approx 5 \times 10^{17} \text{ S/m} \]
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 $\approx -40$ 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 [$Q_T=(Q_T^g+Q_T^r)^{-1}$], 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 ($\approx 4 \times 10^3$) of similar size and resonance frequency ($\approx 17.1$ GHz). This is due to the combined reduction in both Ohmic and radiative losses, by using dielectric inclusions and exploting 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. Moreover, it is worth noting that, in principle, breakdown and charging can be strongly reduced or avoided in a dielectric accelerating structure.

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 PQC, which at variance with the periodic PC case, are not necessarily related to long-range interactions. With specific reference to Penrose-type PQC, 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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