PBG CAVITIES FOR SINGLE-BEAM AND MULTI-BEAM ELECTRON DEVICES*

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Abstract

PBG cavity having one or six defects is studied in the frequency domain. External Q-factors are found numerically for different portal configurations. A new type of hybrid HOMs with coupled monopole and multipole field patterns is found. A novel radial transmission line method is introduced to evaluate the external Q-factor of modes with quasi-absorbing external boundary. A flat-field, rectangular cavity loaded with linear arrays of rods and defects is designed and compared with the planar barbell cavity. Loss-factor and modal spectra are compared with conventional cavities for both circular and planar PBG cavities.

INTRODUCTION

Photonic Band Gap (PBG) structures for accelerator applications have been studied in the last few years by several research groups [1,2,3,4,5]. We consider the rod-loaded configurations as a new class of microwave structures having periodic boundary in the transverse dimensions. The PBG acronym for such generalized rod-loaded structures may better stand for Periodic Boundary in a Gap. For most classical accelerator physics applications, an infinite lattice is not required, and the essence of such structures is the fields defined by the metallic (or dielectric) rods in discrete modes useful to the specific application. They can be cavities (usually a single-gap) or waveguides (multi-gap in the longitudinal direction). We present some of the new features found for metallic single-defect and 6-defect cavities as well as novel multi-cell [6] and planar designs.

SINGLE- AND 6-DEFECT CAVITIES

The common property of the PBG structures is that the modal spectrum is much denser than that for the conventional pillbox structure. Along with trapped (defect) and global (non-local) modes [4], we have found and identified new hybrid modes for the metal PBG cavities. These hybrid modes are a result of the coupling between monopole and multipole modes in the lattice.

In Figure 1 we compare the modal spectrum (TM modes) and bunch energy loss for a single-defect PBG cavity with those of a cylindrical pillbox cavity having about the same gap, fundamental mode frequency and r/Q-value. For the PBG the loss-factor is about the same (or higher) as for the pillbox cavity. This result is in agreement with comparison made for PBG and TESLA cavities [2], and also with the fundamental nature of structure-dominated waveguides and cavities [7].

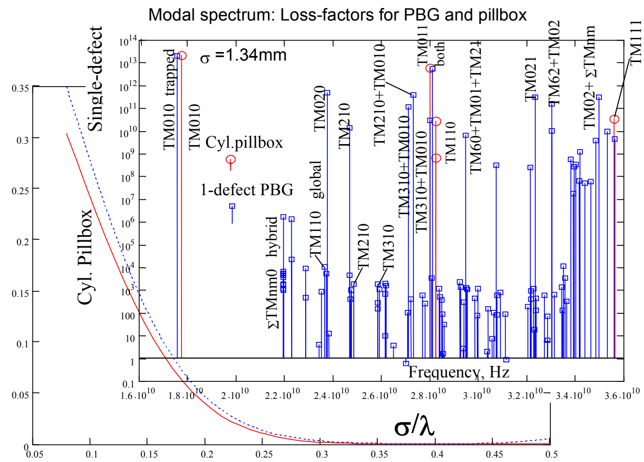

Figure 1: Gaussian bunch TM HOM normalized losses *vs* rms normalized bunch length (solid line: pillbox cavity; dashed: 1-defect cavity). Inset: spectral losses (J-s/C^2) *vs* frequency (Hz) for pillbox (circles) and 1-defect cavity (boxes).

As an example of a multi-defect PBG cavity [6], a 6-defect cylindrical cavity with 55 rods (Figure 2, a) is found to have a high efficiency: r/Q = 5.25 kΩ/m per defect at f = 16.7 GHz, Q = 5491 for a gap of 6.91 mm. Thus in total, r/Q =5.25 × 6 = 31.5 kΩ/m, which is very close to a simple TM_{01} pillbox cavity having an r/Q of 32.2 kΩ/m at f = 17 GHz, and a Q of 5525 for the same gap. Unlike single-defect PBG and most non-PBG structures, a sextupole mode has about the same r/Q as the fundamental one. Moreover, dipole and quadrupole degenerate modes for some of the defects give even higher values of r/Q (by ~1.5 to 2 times, depending on the mode).

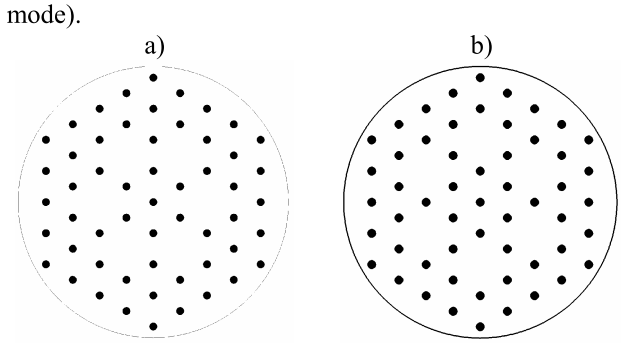

Figure 2: Two lattice configurations for a typical 6-defect, 4th order PBG structure.

Like the 1-defect case, most of the non-trapped HOMS are hybrid in the 6-defect case. The classification of hybrid modes (e.g. those in Figure 3) is more difficult in

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this case since they can combine some of the local and trapped modes along with global modes.

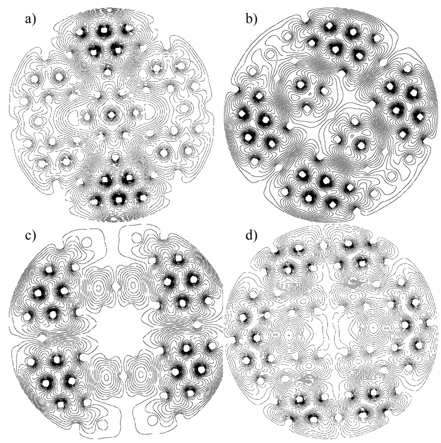

Figure 3: Hybrid modes of a 6-defect PBG cavity: a) coupled monopole and global quadrupole modes; b) global dipole and local sextupole modes; c) trapped and global quadrupole modes; d) sextupole and dipole modes – both global and trapped.

Several coupling schemes for the 6-defect cavity (see Figure 2, b) are considered using frequency detuning methods [8,9]. Calculated outcoupling coefficients β_c for TM_{02} mode in a configuration with two or three rectangular waveguides on the periphery are 1.2 and 1.7, respectively.

Another configuration is a cylindrical pipe of ∅6.6 mm attached to an additional, center defect. From the results given in Table 1 one can see that the TM_{02} mode is suppressed completely, dipole modes are overcoupled, and the fundamental mode is strongly overcoupled.

Table 1: Central coupling characterization.

Mode	f, GHz	Q_{ext}	β_c
TM_{02}, next monopole	18.78	1.71	6130
TM_{31}, sextupole	18.62	10^6	$7.2 \cdot 10^{-3}$
TM_{21}, quadrupole next	18.44	12750	0.544
TM_{21}, quadrupole	18.41	16940	0.4
TM_{11}, dipole next	18.09	1176	7.4
TM_{11}, dipole	18.05	1102	7.8
TM_{01}, fundamental	18.02	347	20

Next we introduce a simple numerical method of calculating the external Q-factor for a cavity with a perfect, peripheral absorber. Instead of performing extensive, time-domain simulations with a real absorber [10], we consider the entire circular periphery as a moveable boundary within the framework of a frequency detuning method [8]. The peripheral boundary is extended to include an outer radial waveguide (radial transmission line) where there are no rods. The results are given in Table 2 for a 4th order lattice with 55 rods (in the brackets); a smaller 3rd order lattice with 31 rods; and a bigger 5th order lattice with 85 rods.

The results show that the lattice order has a dramatic influence on the external Q-factor of the major modes (up to 1-2 orders). This is quite understandable: the group velocity is always lower for more closed/loaded structures. The Q-factor reduction observed in a test at MIT [11] qualitatively confirms our simulation results, which show an ~1.5 order of magnitude reduction (see Table 2 for the 3rd order lattice). Table 2 is also in good correlation with the results of a 7 × 7 rectangular-lattice PBG structure [3], its Q-factor being reduced with peripheral absorber by 2 orders for the next (after the fundamental one) monopole TM_{02}-like mode.

Table 2: Radial line outcoupling characterization.

Mode	f, GHz	Q_{ext}	β_c
TM_{02}	23.04	(272) 632	(~21) 8.92
TM_{31}	17.85	2086 (>10^5)	3.6 (<0.08)
TM_{21}	17.59	3973	1.8
TM_{21}	17.58	(171) 3346 (89000)	(40) 2.11 (13)
TM_{11}	17.094	2228	2.84
TM_{11}	17.095	(~70) 2181 (8900)	(90) 2.9 (0.71)
TM_{01}	16.85	(~69) 1959 (77000)	(82) 2.9 (0.07)

FLAT-FIELD, ROD-LOADED CAVITY

A rectangular cavity loaded by finite rows of rods (and defects) can have a very high vacuum conductance. Since the fields diminish rapidly away from the rods, the cavity can take on a large volume, which can easily facilitate insertion of non-evaporative getter (NEG) modules with high pumping speed, diagnostic ports or laser beams (to illuminate, *e.g.*, a photocathode at optimal angles). The field flatness in a structure with a row of defects between several rows of rods can be adjusted with just a slight shift of one or few side rods. Such a flat-field PBG cavity is depicted in Figure 4. The performance of the fundamental mode is nearly identical to the barbell cavity [12] (see Figure 5). The effective aspect-ratio [13] of both cavities is high and lies in the range of 11-12 to fit the typical needs of, for example, a sheet-beam klystron.

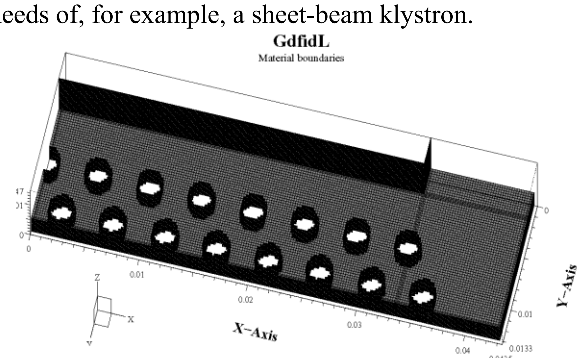

Figure 4: One eighth of an X-band, planar PBG structure with 2 rows of rods on each side of a sheet beam.

Figure 6 shows the modal spectrum and HOM losses for the vertical TE mode. In spite of very different modal spectra for the barbell and the rod-loaded cavities, the losses are essentially the same with the exception of extremely short and long bunches.

For the coupler design of a flat-field cavity, the major difficulty is that significant coupling dramatically affects the flatness. Several coupling schemes were examined for an X-band, flat-field PBG cavity. We found that a cavity with only 1 + 1 rows of rods worked quite well with inductive slots (parallel to the beam) made in both side walls as depicted in Figure 7. The coupling for the fundamental mode is characterized in Table 3 in which dimensions of the slot gap are varied with respect to the WR90 pipe vertical height; <Δf/f> is the averaged relative frequency deviation from an analytical fit [8,9].

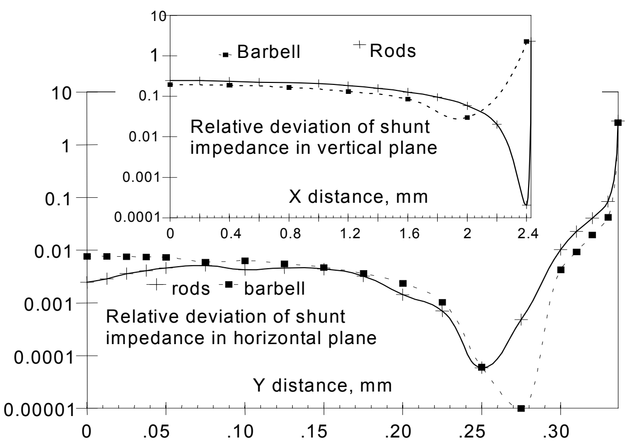

Figure 5: Relative non-flatness of shunt impedance of two planar cavities for the fundamental TM_{11} mode: barbell (dashed), and one loaded by 2+2 rows of rods (solid line).

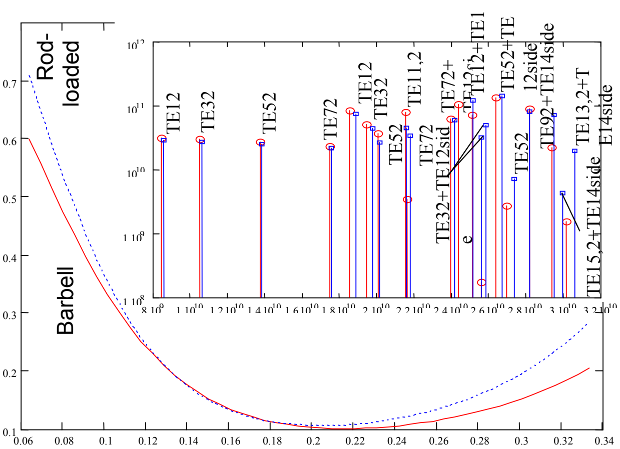

Figure 6: Relative contribution of vertical TE losses of displaced bunch Δy=0.43mm *vs* its relative length for barbell and rod-loaded structures. Inset: loss-factor modal spectrum (J-s/C^2) *vs* frequency (Hz) for vertical dipole symmetrical TE modes in barbell (circles) and rod-loaded (boxes) planar structures at σ=1.6mm.

Table 3. Coupling characterization for planar PBG cavity.

Slot WR90	*f*, GHz	Q_o	Q_{ext}	β_c	<Δf/f>
1/5	11.11	5643	7084	1.01	$2 \cdot 10^{-5}$
1/4	11.04	8026	2278-2018	3.07-3.48	$1.5 \cdot 10^{-4}$
1/3	11.5	7115	~330	~25	$1.5 \cdot 10^{-4}$

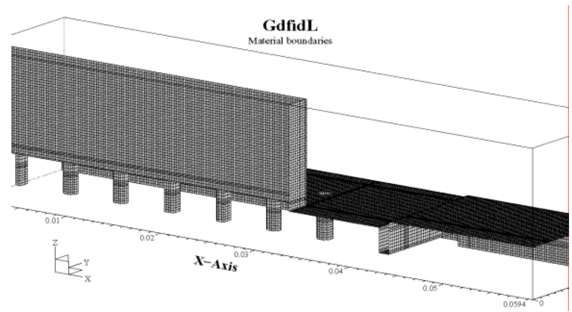

Figure 7: One eighth of a planar PBG structure with 1+1 rows of rods coupled with a WR90 waveguide.

APPLICATIONS

As noted, the relatively open nature of the planar PBG structure gives it several advantages. Planar PBG cavities can be used in a sheet beam klystron (SBK) or a planar lasertron (see Figure 5) to modulate a high current, moderate voltage, ribbon beam, and to generate high rf power from a bunched beam. A planar lasertron which requires only a simple output circuit would be more compact than an SBK, with an additional advantage of excellent pumping.

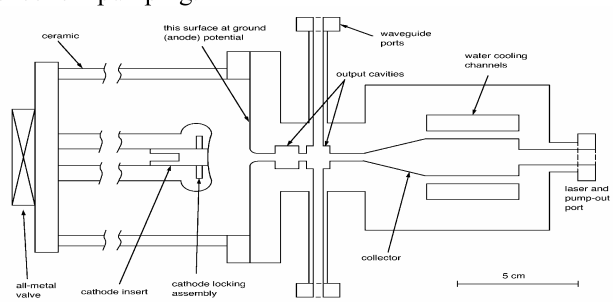

Figure 8: Schematic of a planar, X-band lasertron ("long" dimension into paper).

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