THEORETICAL ANALYSIS OF OVERMODED DIELECTRIC PHOTONIC BAND GAP STRUCTURES FOR ACCELERATOR APPLICATIONS

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Abstract

An overmoded accelerator structure is proposed based on a dielectric photonic-band-gap (PBG) disk-loaded structure. The structure consists of dielectric rods and metal disks with irises. It is advantageous for application in high frequency (17 GHz and higher) linacs because of the large dimensions of the structure. The operating mode is a higher-order TM_{02} mode. One unique feature is that the fundamental TM_{01} mode is not supported by the structure. Along with that, the dipole mode TM_{11} is strongly suppressed. The dielectric PBG structure can also be attractive for application in a dielectric wakefield accelerator.

INTRODUCTION

In recent years major progress in novel accelerating structures using dielectrics has been reported. These experiments include the two-beam dielectric accelerator [1] and the millimeter-wave accelerator on a dielectric substrate [2]. It has been demonstrated that breakdown and charging can be avoided in the dielectric accelerating structures. We have been focused on the electromagnetic properties of dielectric structures for accelerator applications. Using low loss dielectrics, high Q-factor microwave cavities can be built, and, therefore, high shunt impedances can be achieved. The dielectric structures can be designed to be mode selective, providing a high Q-factor of the operating mode along with low Q-factor, high losses for all unwanted modes. These electromagnetic properties of the dielectric structures make them very attractive for accelerator applications because wakefields can be suppressed through the selective excitation of the operating mode.

One possible way to build a mode selective cavity is to utilize a photonic band gap (PBG) structure in the cavity. An example of a PBG structure is a 2D lattice of dielectric or metal rods with a defect (missing one or several rods) in the center [3,4]. The metallic PBG cavity was proposed as an accelerator cell [5]. We have previously reported on the cold test of metallic PBG cavities at X- and Ka-bands [6-8]. Dielectric PBG cavities have been cold tested at a variety of bands including X-band [9]. The dielectric PBG fibers have been proposed for laser accelerators [10].

We propose the dielectric PBG cavity for application as a cell of an accelerating structure. The PBG cell includes the dielectric PBG structure placed between two metal disks. A stack of the PBG cells coupled through the beam holes forms an accelerating structure. We have designed a dielectric PBG cavity operating at 17 GHz (Ka-band) and at a higher-order mode TM_{02}. The unique feature of this dielectric structure is that the fundamental TM_{01} mode is not confined. This effect could not be observed in a metal PBG cavity where the fundamental mode TM_{01} always exists. The higher-order accelerating mode TM_{02} allows us to enlarge the transverse dimensions of the accelerator, which is advantageous at high frequency operation. Also, the dipole modes are suppressed.

FREQUENCY SELECTIVE CAVITIES UTILIZING DIELECTRIC PBG STRUCTURES

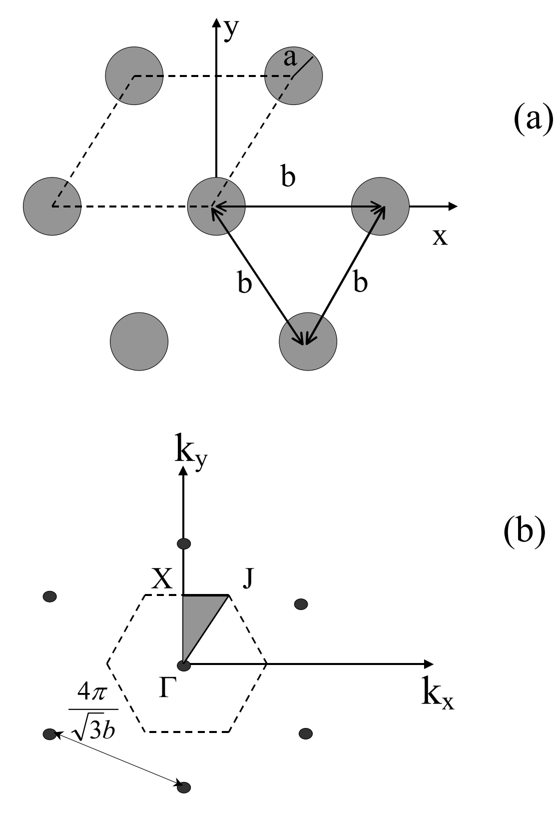

Figure 1: 2D triangular crystal lattice (a) and reciprocal lattice (b).

Band Gaps in a 2D Lattice of Dielectric Rods

Figure 1 (a) depicts a 2D triangular lattice of dielectric rods, and Figure 1 (b) depicts the reciprocal lattice in the wave-vector **k** plane. The hexagon in the k-plane is the first Brillouin zone of the lattice. The shaded triangle in Fig. 1(b) covers the meaningful values of k-vector at which waves propagating in the lattice should be calculated. The result of this calculation is presented in the Brillouin diagram (Fig. 2). The Brillouin diagram indicates the frequencies of the waves propagating in the lattice while the k-vector on the reciprocal lattice (Fig. 1(b)) varies from Γ-point to X-point, from X-point to J-point, and back to Γ-point. The Brillouin diagram plots the normalized frequency $\omega b/c$, where b is the spacing between the rods, and c is the speed of light. The diagram is calculated for the ratio of 0.39 of the rod radius a to the spacing b. The rods are made of alumina Al_2O_3, the dielectric constant ε=9.7.

The important characteristic of the lattice is the band gap. The band gap is marked in Fig. 2 indicating that there is no propagating wave in a certain frequency band. The existence and frequency bandwidth of the gap depends upon the dielectric constant and the ratio a/b. The band gaps in the triangular dielectric lattices are calculated in [11], and the results are plotted in Fig. 3. Two band gaps are contoured in Fig. 3; there is no propagating wave in the lattice if the frequency is inside the contours plotted.

PBG Cavity Design

A triangular lattice of rods with a defect forms a PBG cavity. We remove the central rod and three rows of rods around it (37 rods total) to form the defect. The spacing b is determined such that the operating frequency of 17 GHz falls into the band gap (Fig. 3). The ratio of a/b should be close to 0.4 because the band gap narrows down at this ratio. The cavity mode is a mode confined in the defect (defect mode). If the band gap is narrow, the number of defect modes can be reduced.

The HFSS code [12] has been employed to calculate the PBG cavity modes. Through optimization of the parameters a and b, a well-confined TM_{02}-like mode at the frequency of 17 GHz was found (Fig. 4). Using the calculated field distribution, the acceleration parameters of the PBG cavity are calculated and listed in Table 1. The Q-factor and shunt impedance are calculated for the dielectric loss tangent of $2\bullet10^{-4}$, which is the average measured loss tangent of alumina [13]. The cavity axial length of one third of the wavelength is selected.

Note that for the 17 GHz pillbox copper cavity with the fundamental mode $TM_{010,}$ the Q-factor is 6000, and the parameter r_s/Q is 540 Ω/cm. For the TM_{020} mode of the pillbox copper cavity, Q=8500 and r_s/Q =240 Ω/cm. Therefore, the designed dielectric PBG cavity operating at the TM_{020}-like mode has the Q-factor close to that of the TM_{010}-mode pillbox cavity and the r_s/Q close to that of the TM_{020}-mode. The Q-factor of the dielectric cavity combines the dielectric side-wall Q-factor calculated using HFSS and the end plates Q-factor calculated analytically assuming it is the TM_{020} mode; both Q-factors are about 12000.

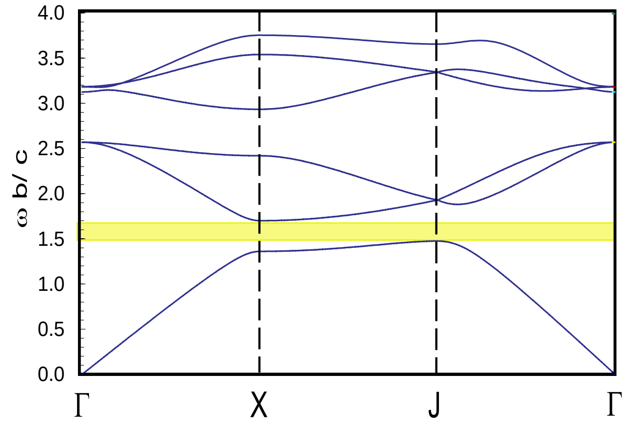

Figure 2: Brillouin diagram for the dielectric triangular lattice of rods. The normalized frequency vs. k-vector is plotted. The k-vector varies around the contour in the reciprocal lattice (Fig. 1(b)). The band gap is marked. The lattice parameters: ε=9.7 (alumina), a/b=0.39.

Table 1: Acceleration parameters of a dielectric PBG cavity with the TM_{02} mode

Permittivity, ε	9.7 (Al_2O_3)
Loss tangent, tan δ	$2\cdot10^{-4}$
Lattice spacing b	0.44 cm
Rod radius a	0.17 cm
Ratio a/b	0.39
Minimal radius of defect	1.35 cm
Outer radius	3.5 cm
Number of rods	132
Number of missing rods in defect	37
Axial length	0.58 cm
Mode	TM_{02}
Frequency	17.14 GHz
Ohmic Q-factor	5900
Shunt impedance r_s	1.2 MΩ/cm
Parameter r_s/Q	212 Ω/cm

It is shown that the fundamental TM_{01} as well as dipole TM_{11} modes are not confined in the PBG cavity. This is consistent with the band gap map (Fig. 3): the frequencies of these modes are not in the band gap. A transverse wakefield mostly formed by the dipole mode is thus suppressed. As shown in Fig. 3, the modes TM_{21}, TM_{31}, and TM_{12} fall into the gap. Only a quadruple TM_{21} mode is well confined in the defect, however this mode is less dangerous than dipole modes.

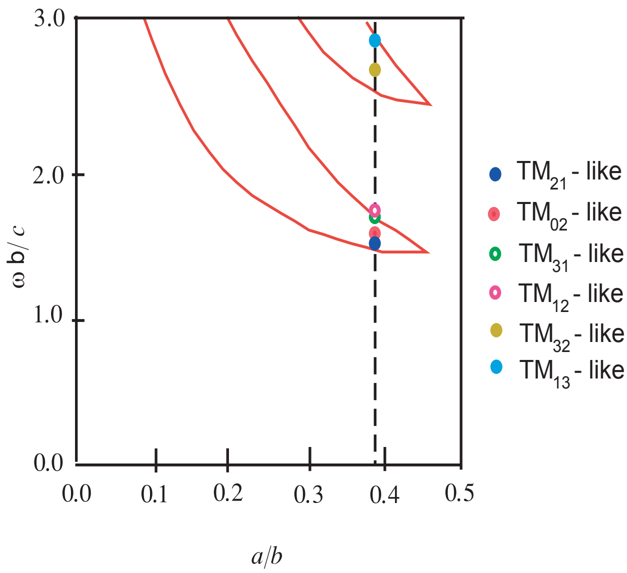

Figure 3: Areas of global band gaps are contoured on the plane of parameters: the normalized frequency and the ratio of the rod radius *a* to the spacing *b*. The simulations carried out for a triangular lattice, ε=9.7. For the design parameter *a/b*=0.39, the frequencies of the defect modes in the PBG cavity are shown.

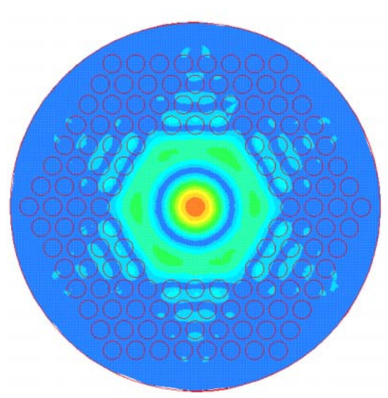

Figure 4: Field pattern of the TM_{02}-like mode in a dielectric PBG cavity formed by a 2D triangular lattice of dielectric rods with a defect.

CONSCLUSION

Dielectric PBG structures may allow extension of RF accelerator operation to higher frequencies using higher order modes, without facing the problem of wakefields. Use of dielectric PBG structures may allow construction of a PBG cavity, which selectively confines the TM_{02}-like mode. The design of the accelerator cell has been presented at the operating frequency of 17 GHz.

ACKNOWLEDGMENTS

The work was supported by DOE HEP.

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