DESIGNING PHOTONIC CRYSTAL DEVICES FOR ACCELERATORS*

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Abstract

Photonic crystals (periodic dielectric structures with a lattice constant on the order of the wavelength of light) can have a wide range of properties. For instance, photonic crystals can be designed to be completely reflective within a certain bandwidth, thereby becoming a replacement for metal in accelerator structures such as waveguides and cavities. To see whether photonic crystals might find application in accelerators, and to design potential accelerator structures, we will need reliable computer simulations to predict fields and frequencies and other properties of photonic crystal structures. We propose to build photonic crystal structures in the microwave regime and test the validity of computer simulation against experiment. We can then explore more complex issues such as coupling to photonic crystal structures, higher-order mode rejection, and tunable photonic crystals.

INTRODUCTION

Introduction to Photonic Crystals

A one-dimensional photonic crystal (a 1D PC), more commonly known as a dielectric mirror, is a stack of alternating slabs of dielectric. If, for a given frequency of incident light, each slab contrives to be one-quarter wavelength thick, then light incident at that frequency will interfere destructively with its reflection from the interfaces between adjacent slabs, preventing propagation of that frequency. Such a dielectric sandwich, if infinitely long and made of completely lossless dielectric materials, would be a perfect reflector of light (within certain frequency ranges, depending on the angle of incidence). However, a 1D PC cannot reflect light incident from all angles. (A periodically-loaded waveguide is another familiar sort of 1D photonic crystal.)

Although much more difficult to understand, 3D photonic crystals have been designed to reflect all incident light, regardless of polarization and incidence angle, but again within a narrow frequency range. Photonic crystals are to photons what ionic crystals are to electrons; the periodic dielectric or potential imposes a band structure on the allowed energy levels. Like semiconductors, which have band gaps (ranges of energy) in which no electron can propagate, some PCs also have band gaps—ranges of frequency in which no photon can propagate. Electromagnetic waves of frequencies within a complete band gap of a photonic crystal cannot propagate in any direction (any fields with those frequencies are evanescent, decaying exponentially as they penetrate the crystal). To make an electromagnetic resonant cavity with a photonic crystal, one must hollow out a cavity within a PC (*e.g.*, by removing one of the dielectric atoms), so that the cavity has a resonant frequency within the band gap; light with the resonant frequency will then be trapped within the cavity (figure 1).

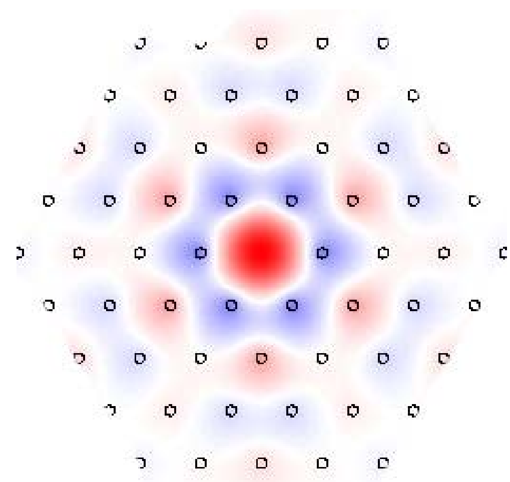

Figure 1: The electric field trapped at a defect in a triangular lattice of sapphire rods.

A Few References to Relevant Previous Work

[4] is a good basic introduction to photonic crystals.

Most experiments with photonic crystals have been at optical frequencies, usually propagating light within a 2D lattice of holes in a thin slab of silicon (often with a line defect) [7, 14, 15], or at microwave frequencies, simply measuring the transmission through 2D and 3D photonic crystals [11, 12, 3]. Actual 2D PC cavity structures using metal atoms instead of dielectric (with accelerator applications in mind) have also been tested [8, 17, 16]. Experiments on dielectric PC structures (cavities, waveguides) at microwave frequencies seem to be rare.

Some Advantages of PCs

Future accelerators might exploit photonic crystals for the following reasons (among others):

- PCs reflect light only within a certain frequency range, unlike metals which reflect all light. Therefore a PC cavity might have only one mode (or a few modes), rather than the infinity of modes of a metal cavity that

* This work is supported by the U.S. Department of Energy grant DE-FG02-04ER41317.
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endanger beam stability when excited by the beam [10]. It may even be possible to operate PC waveguides and cavities in a chosen high-order mode, without the dense spectrum of mostly undesirable high-order modes that exists in a metal waveguide or cavity.

- For some applications (especially at high frequencies) dielectrics are less lossy than metals; a PC cavity might have a higher Q factor than a copper cavity.
- At near-optical frequencies (and maybe well below), dielectrics can withstand higher electric fields than metals [18].
- The electromagnetic properties of PC structures are more "configurable" than those of metal structures.

EXAMPLE: A DIELECTRIC 2D PC CAVITY

Unfortunately the construction of three-dimensional photonic crystals poses something of a challenge. For initial investigation we decided to see what could be done with much more easily-fabricated two dimensional photonic crystals. In this section we present some details of a cavity made of a 2D PC with metal end-plates to trap the fields in the third dimension.

To explore different configurations we used the MIT Photonic Bands code [5], a frequency-domain periodic-boundary-conditions electromagnetic field solver.

The $\mathrm{TM}_{\mathrm{mn0}}$ band-structure (including only modes with TM fields and wavenumber $k_z = 0$ in the "third dimension") for:

- an infinite triangular lattice with lattice constant a
- of rods with radius $r = 0.087a$ and dielectric constant $\epsilon/\epsilon_0 = 10$ (like sapphire)

has a band gap from $f = 0.47c/a$ to $0.57c/a$, where c is the speed of light. In other words, no $\mathrm{TM}_{\mathrm{mn0}}$ mode has a frequency between $0.47c/a$ and $0.57c/a$. If we remove a single rod, a single mode appears within that band gap, the fields of which are trapped within a small area around the removed rod (the defect) because fields at that frequency decay as they penetrate the crystal. That mode resembles the TM_{010} mode of a cylindrical cavity (which is often, but not always the case when removing a single rod from a lattice with a band gap).

As previously mentioned, dielectric PC structures are more adjustable than metal structures. For instance, we chose $r = 0.087a$ to achieve a reasonably large band gap while minimizing the size of the cylinders (to minimize power dissipation by fields in the dielectric). We can also reduce power dissipation a little by moving the first ring of rods inwards so the rod centers are at a distance $0.80a$ from the defect, instead of a distance a. The resulting electric field (which is parallel to the rods) is shown in figure 2. With this geometry, the trapped-mode frequency is $f = (\omega/2\pi) = 0.52(c/a)$.

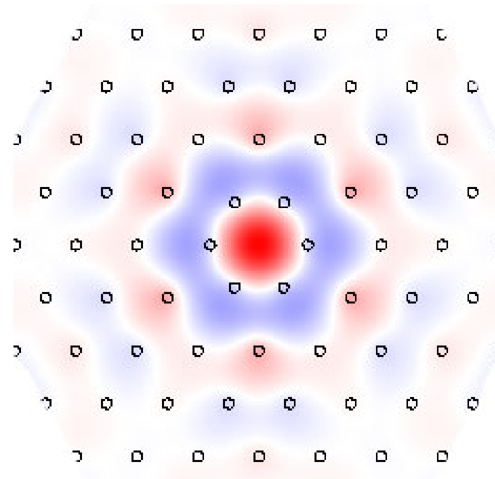

Figure 2: The axial electric field strength in the photonic crystal cavity. By moving the first ring of rods inwards towards the electric field minimum, dissipation within the rods is minimized.

Knowing the electric field, we can calculate the dissipation within the dielectric rods; the time-averaged power dissipated in volume V filled with dielectric $\epsilon(\mathbf{x})$ with loss tangent $\tan\delta(\mathbf{x})$ due to an electric field $\mathbf{E}(\mathbf{x})$ oscillating at angular frequency ω is [6]

$$P_{\mathrm{dis}} = \int_V d^3\mathbf{x}\, \frac{1}{2}\omega|\mathbf{E}(\mathbf{x})|^2\epsilon(\mathbf{x})\tan[\delta(\mathbf{x})]. \quad (1)$$

If the rods in our cavity have $\tan\delta = 1\times10^{-4}$, then its Q factor, ignoring the metal end-plates or considering the cavity to be infinitely long, would be 9.5×10^4 (independent of frequency to the extent that ϵ and $\tan\delta$ are independent of frequency). When calculating the Q factor above, we assumed the crystal to have infinite extent; in practice, one need only extend the crystal sufficiently far to ensure that the fields have decayed enough that power leakage will be negligible.

Since the fields in the PC cavity extend farther from the center than the fields in a metal cavity, we must also compare the strength of the field at the cavity centers relative to the stored energy in each cavity; an appropriate dimensionless descriptor for a 2D PC cavity is

$$\alpha := \frac{U/\ell}{\pi a^2\epsilon_0 E_0^2} = 0.41 \quad (2)$$

where U/ℓ is the stored energy per structure length.

For a metal pillbox cavity of radius r, operating in the TM_{010} mode (again, ignoring the ends or considering an infinitely long cavity), a corresponding dimensionless quantity is

$$\alpha := \frac{U/\ell}{\pi r^2\epsilon_0 E_0^2} = 0.27. \quad (3)$$

Its Q factor, given walls with surface resistance R_s, would be $Q = 907\Omega/R_s$.

Table 1: Comparison of Q factors at different frequencies and temperatures for cylindrical copper and PC cavities, neglecting end-cap losses, using the given surface resistance (for copper cavities) or loss tangent (for PC cavities).

material	f (GHz)	T (K)	R_s (mΩ)	$\tan\delta/10^{-5}$		R (mm)	a (mm)	Q
Cu	3	300	15		[19]	38		6.0×10^4
Cu	30	300	44		[2]	3.8		2.1×10^4
Cu	30	100	17		[2]	3.8		5.3×10^4
Sapphire PC	3	300		2	[13]		52	5×10^5
Alumina PC	3	300		4–13	[13]		52	7–20$\times 10^4$
Sapphire PC	22	300		0.7–2	[9]		7.1	5–15$\times 10^5$
Sapphire PC	22	100		0.02–0.05	[9]		7.1	2–5$\times 10^7$
Sapphire PC	72	300		3	[1]		2.2	3×10^5
Sapphire PC	72	100		0.1	[1]		2.2	1×10^7

Q and α together tell us what on-axis electric field E_0 could be reached with a given input power per structure length (which equals $P_{\rm dis}/\ell$, the dissipated power per structure length in the steady state):

$$\frac{\epsilon_0|E_0|^2}{P_{\rm dis}/\ell} = \frac{QA}{\omega\alpha} \tag{4}$$

where $A = \pi r^2$ for the metal cavity, and $A = \pi a^2$ for the PC cavity. If large E_0 is desired, smaller α is better, because it concentrates more of the field energy near the axis. If they had the same Q factor and the same power source, the PC cavity would reach a lower accelerating field than the metal cavity.

For comparison, table 1 shows Q factors for PC and metal cavities at different frequencies and temperatures. Although a metal's surface resistance generally increases as the square root of the frequency, a dielectric's loss tangent tends to be more stable with frequency; one must be careful, however, since dielectric losses, especially at low temperature, may be very sensitive to the details of composition and fabrication (see [1], for example).

CONCLUSION

See table 1.

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