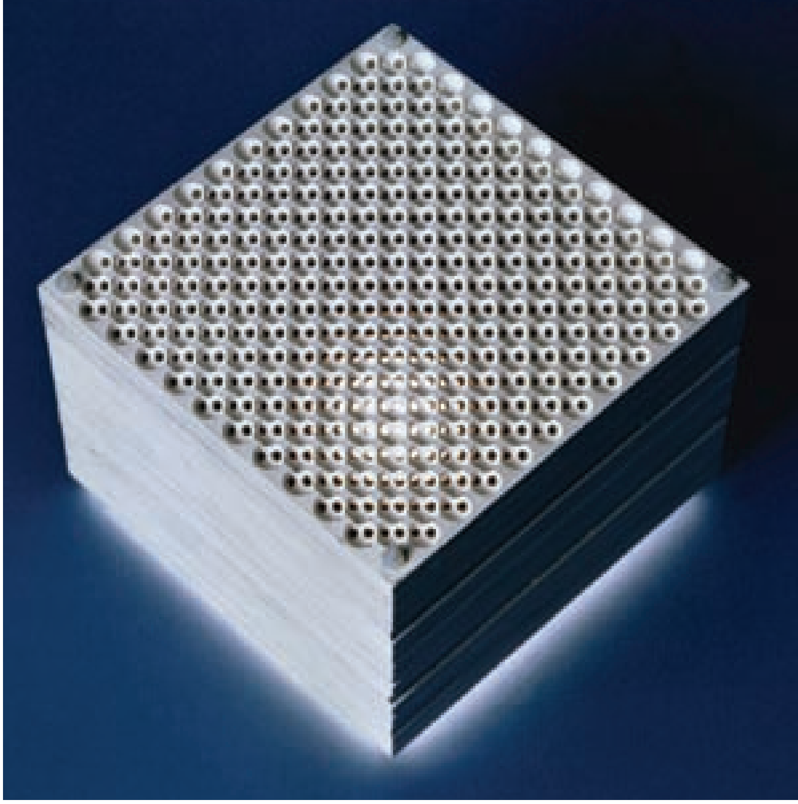

Photonic Crystals: What's in a Name?

Eli Yablonovitch

The progenitor of the term "photonic crystals" discusses its history and reflects on its use—and occasional misuse—within the optical community.

Each year, thousands of papers are published with the phrase "photonic crystal" in the title or as a keyword. Some have questioned whether "photonic crystal" is merely a clever new name for a long-standing field of research that goes back 120 years. After all, wave scattering from periodic structures has been known for a long time. Or does the name represent a distinct physical regime that was only recognized when the name emerged about two decades ago?

Origins of the stop-band

I am the guilty party who introduced the name "photonic crystal." It happened in the text of an article in a 1989 issue of *Physical Review Letters* (**63**, 1950). In that same article, I also announced (somewhat prematurely) the successful creation of a "photonic bandgap."

The idea of a one-dimensional stop-band is itself rather old, having been derived by Lord Rayleigh in an 1887 issue of *Philosopical Magazine*. In his paper, partially titled, "The Propagation of Waves through a Medium Endowed with a Periodic Structure," Rayleigh included a modern-looking formula (equation 74 in the original) for the edges of the forbidden gap in terms of the modulation period l, and of the relative strength of the periodic density modulation ρ_1/ρ_o:

$$\lambda^2/4l^2 - 1 = \pm\, \rho_1/2\rho_o\,.$$

In a footnote, Rayleigh wrote about applying these ideas to light incident on a layered silver structure produced by interference exposure of a photographic medium. In a follow-up paper in 1888, Rayleigh stated:

> "I have discussed in a recent paper the propagation of waves in an infinite laminated medium (where, however, the properties are supposed to vary continuously according to a harmonic law), and have shown that, however slight the variation, reflexion is ultimately total, provided the agreement be sufficiently close between the wavelength of the structure and the half-wavelength of the vibration."

Thus, by 1887 Lord Rayleigh had already known the actual magnitude of the forbidden stop band. He also understood well that even an infinitesimal periodic variation in the structure would produce a bandgap, and that it would make a "total reflexion mirror." That a band-gap could arise, even from infinitesimal modulation, is peculiar to the one-dimensional case. It is clear that Rayleigh had in mind "laminated" 1D structures.

History of photonic crystals

The name "photonic crystals" is more frequently associated with two- or three-dimensionally periodic structures. These also have a venerable history. Actually, every ordinary 3D crystal of X-ray crystallography is a Bragg scatterer of X-ray waves. In 1914, C.G. Darwin (grandson of Charles) derived the "dynamical theory of X-ray diffraction"—in other words, the theory that includes the effect of X-ray standing waves, finite mini-gaps, etc. Darwin wrote:

> "The reflexion is found to be practically perfect for a certain range of angles. The transmitted beam is extinguished much more rapidly than corresponds to the true absorption of the crystal."

If ordinary crystals have bandgaps for X-ray waves, why isn't every ordinary crystal also a "photonic crystal"? I addressed this in a 1993 JOSA B review article (**10**, 283):

> "Nature gives us fcc crystals, and X-rays are bona fide electromagnetic waves. As early as 1914 narrow stop bands were known to open up. Therefore, what was missing? The refractive-index contrast for X-rays is tiny, generally 1 part in 10^4. The forbidden X-ray stop bands form extremely narrow rings on

> the facets of the Brillouin Zone. [If] the index contrast is increased, the narrow forbidden rings [would] open up, eventually covering an entire facet of a Brillouin Zone and ultimately all directions in reciprocal space. We shall see that this requires an index contrast $\gtrsim 2$. *The high index contrast is the main new feature of Photonic Band Structures beyond dynamical X-ray diffraction.*" [Italic emphasis added.]

The tiny index contrast of X-rays leads to dynamical diffraction that is essentially one-dimensional, even though the crystals themselves are three-dimensional. Thus, we talk about simple 1D Bragg planes and 1D layers of atoms, but within 3D crystals.

In contrast, a two- or three-dimensional bandgap requires substantial index contrast, unlike the 1D case explored by Lord Rayleigh. Furthermore, a 2D or 3D bandgap requires a non-obvious and complex crystallographic structure, unlike the 1D case in which arbitrarily small index contrast, in a simple layered structure, is adequate.

Defining photonic crystals

The new requirement for a complex 2D or 3D crystallographic structure led to the name "photonic crystal," but such a structure also demanded substantial index contrast. Therefore, the definition of a "photonic crystal" has two requirements: high index contrast and a 2D or 3D periodic structure.

In my observation of the literature, it appears that most authors understand these distinctions, and they use the name "photonic crystal" for two- and three-dimensional structures that have substantial index contrast. But a minority of authors who write about the properties of 1D laminated structures or structures with small index contrast call them "photonic crystals."

If scientists ignored the strong index contrast pre-requisite, they could rename the field of X-ray crystallography as "photonic crystal research." But it is not reasonable to rename fields that have been around for almost 100 years. Moreover, X-ray dynamical diffraction and photonic crystals occupy different physical domains: The former is in the domain of small index contrast, while the latter is in the realm of high index contrast.

One dimensional bandgaps had also existed for 100 years before the name "photonic crystals" came along. During that time, nobody saw a need to rename a 1D laminated structure as a "photonic crystal," probably because a 1D layered structure is too simple to be regarded as a crystal. It would be somewhat presumptuous, after 100 years, for authors to rename what Rayleigh accomplished.

Still, there have been many great achievements in extending the ideas of 1D laminated mirrors since Rayleigh's time. The field of layered optical interference filters emerged and became a thriving industry [J. Opt. Soc. Am. **59**, 508 (1969)]. Researchers found that facing two such mirrors together can create a distributed feedback laser cavity [Appl. Phys. Lett. **18**, 152 (1971) and Opt. Comm. **9**, 35 (1973)]. They also found that the reflection could become omni-directional by increasing the index [Science, **282**, 1679 (1998)], and that a Bragg wave-guide could be formed by allowing oblique reflection between the pair of Bragg mirrors [Opt. Comm. **19**, 427 (1976)]. All these 1D structures represent great achievements—but they are not photonic crystals. Respect for Lord Rayleigh, and other historical figures, requires us to use the photonic crystal name only for high-index-contrast 2D or 3D periodic structures. ◭

[Eli Yablonovitch (eliy@ee.ucla.edu) is with the electrical engineering department at the University of California, Los Angeles.]

[References and Resources]

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