Guest Editorial

A NEW paradigm has emerged, in which the band structure concepts of solid-state physics are applied to electromagnetics. This has led to a profusion of scientific creativity as new forms of electromagnetic crystal structures are invented for radio and microwaves, as well as for optical wavelengths. These new structures are inspired by the three-dimensional (3-D) geometry of both natural crystals and those artificial crystals that can arise only in the human imagination.

These artificial electromagnetic crystals (also known as photonic crystals) are impacting the diverse domains of electromagnetics, extending from radio waves to optical wavelengths. They are bringing together, under a common umbrella, scientists in the fields of classical electromagnetics, solid-state band theory, semiconductor device physics, quantum optics, nanostructures, and materials science. The number of papers in this field has been growing at roughly 70% per year since the early 1990's, and there are currently hundreds of papers per year being published on photonic crystals.

There have already been a number of books [1], special issue journals [2], [3], and conference proceedings [4], [5] on this topic, originating from the very first one [2], organized by Bowden *et al.* in Park City, UT (January 1992) extending to the "Workshop on Electromagnetic Crystal Structures," Laguna Beach, CA (January 4–6, 1999), which is the source of most of the papers in this TRANSACTIONS. This series will now likely extend through the next international conference on "Photonic and Electromagnetic Crystal Structures," which is scheduled to be held in Sendai, Japan (March 8–10, 2000).

Owing to the large number of papers that were submitted on the occasion of the January 1999 "Workshop on Electromagnetic Crystal Structures," the papers had to be divided among two publications, producing a pair of special issues. Most of the papers that relate to radio and microwaves are in this TRANSACTIONS, while the optically related papers are in the November 1999 issue of the JOURNAL OF LIGHTWAVE TECHNOLOGY.

Photonic bandgaps originated from a pair of papers that were published almost simultaneously in 1987. One by Yablonovitch [6] introduced the forbidden gap for controlling spontaneous and stimulated emission of light. The second by John [7] introduced gaps to induce Anderson localization of light waves. In exploring analogies with low-energy electron diffraction (LEED), in 1979, Ohtaka [8] actually first used the phrase "photon band structure," but he narrowly missed the problematic concept of a photonic bandgap. Indeed, there was no assurance in 1987 that any photonic bandgap could ever be produced experimentally with available refractive indexes. The search for a 3-D photonic bandgap entailed numerous blind alleys and false starts, culminating in 1990 with the remarkable discovery [9] that diamond crystal geometry was favored by nature. This led to the first experimental demonstration [10] of a 3-D photonic bandgap.

Today, many more types of electromagnetic crystal structures and designs are being investigated in various dimensions, and made of various materials, including metals. Even acoustic band structure is under study. Self-assembly and microfabrication have emerged as the main routes toward 3-D optical structures. In addition to the 3-D photonic crystals, an important role will be played by two-dimensional (2-D) thin-film photonic crystals. These are a good compromise between the total electromagnetic confinement of a 3-D structure versus the ease of fabrication of a 2-D patterned thin film. They appear to be capable of a Q-factor up to 10 000 in spite of being open structures, more than enough for lasing. In a milestone for the field, Painter *et al.* [11] report lasing in a nano-cavity, the smallest laser ever made. Thus, 2-D thin-film photonic crystals may form the underlying basis for a future technology of photonic integrated circuits.

While these dielectric structures have been very novel and exciting, a new element of richness has been introduced into electromagnetic/photonic crystal design recently with the incorporation of metallic components within the unit cells, i.e., metallo-dielectric photonic crystals. The physics of metallo-dielectric electromagnetic crystals is still being worked out, but it is clear that they follow their own set of rules, very different from the existing rules for dielectric structures. Thus, metallo-dielectric photonic crystals, both at radio frequencies, and optical frequencies behave quite distinctly from the dielectric crystal structures that were previously explored. At the same time, they present entirely new and very significant technological and scientific opportunities.

At radio and microwave frequencies, the constraint linking spatial period and electromagnetic frequency has been undone. By capacitive loading between the metallic elements, the electromagnetic "valence band" frequency can be pushed down; thereby electromagnetic crystal structures become valuable at radio frequencies. They become smaller and much more lightweight. Attention should be directed toward Sievenpiper *et al.* [12], in which a metal surface is converted to an insulator having a forbidden bandgap. It is expected that those types of high-impedance ground planes will be quite useful for antennas and for other applications in radio electromagnetics.

In the radio domain, photonic bandgap structures should not be confused with effective media or frequency selective surfaces. The key point is that the electromagnetic wave-vector component along the direction of periodicity is comparable to the reciprocal periodicity. In that case, the behavior of the wave-vector dispersion near a Brillouin zone boundary becomes important. Band structure becomes imperative, and

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an effective dielectric constant, or surface impedance, provides an incomplete description.

At optical frequencies, the metallo-dielectric structures become strongly influenced by plasmon resonance, arising from electron inertia in the metallic constituent. Plasma wave polaritons (plasmons) can have frequencies in the optical regime combined with wavelengths much shorter than the corresponding vacuum electromagnetic wavelength. The resulting very large wave vectors correspond to those of X-rays. This permits the design of very tiny electromagnetic cavities, much smaller than anything currently being considered. The concentration of zero-point electromagnetic energy in such tiny plasmon cavities can produce a giant Purcell effect, enhanced by many orders of magnitude, leading to spontaneous emission that is much stronger than even stimulated emission. There is a link between the Purcell effect for spontaneous emission, and the surface enhanced Raman effect for spontaneous Raman scattering, which is likewise enhanced by many orders of magnitude. There are but a few papers on this topic in the Special November Issue of the JOURNAL OF LIGHTWAVE TECHNOLOGY, but the plasmon band structure field is in its infancy, and we can expect to learn much more in the future.

The full practical impact of photonic bandgap structures is yet to be seen, but we may observe the first commercial and military applications in the realm of handheld wireless communications and global-positioning-system antennas using the high-impedance ground-plane structures. The optical applications are more long range, but we can expect an impact on white pigments that are ubiquitous in our surroundings, on optical signal processing, and on light emitting diodes for both commercial and military use.

Given the evident and tangible progress in the field, it is clear that this subject matter will soon outgrow special-issue topics. The spirit of comradeship and adventure among the researchers will remain, as we continue to explore the realm of photonic crystal structures. We do not know what extra surprises nature will have in store for us.

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