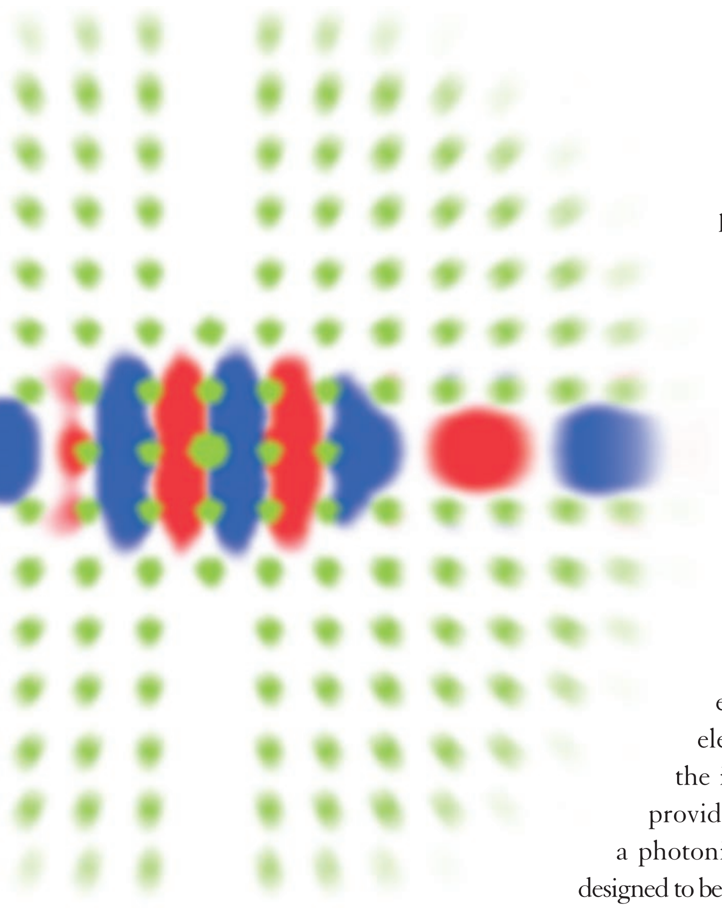
A class of materials has recently emerged that provides new capabilities for the control and manipulation of light. These materials, known as "photonic crystals," affect the properties of a photon in much the same way that a semiconductor affects the properties of an electron. This ability to mold and guide light leads naturally to many novel applications of these materials in a variety of fields including optoelectronics and telecommunications. The author presents an introductory survey of the basic concepts and ideas, including results for photon phenomena that have never been possible before.

John D. Joannopoulos

Molding the Flow of Light

For the past 50 years, semiconductor physics has played a vital role in almost every aspect of modern technology. Advances in this field have allowed scientists to tailor the conducting properties of certain materials and have initiated the transistor revolution in electronics. New research suggests that we may now be able to tailor the properties of light. The key in achieving this goal lies in the use of a new class of materials called photonic crystals,[1] whose underlying concept stems from the pioneering work of Yablonovitch[2] and John.[3] The basic idea is to design materials that can affect the properties of photons in much the same way that ordinary semiconductor crystals affect the properties of electrons. This is achieved by constructing a crystal consisting of a periodic array of macroscopic uniform dielectric (or possibly metallic) "atoms." In this crystal, photons can be described in terms of a band structure, as in the case of electrons. Of particular interest is a photonic crystal whose band structure



possesses a complete photonic band gap (PBG), namely, a range of frequencies for which light is forbidden to propagate inside the crystal. Forbidden, that is, unless there is a defect in the otherwise perfect crystal. A defect can lead to localized photonic states in the gap, whose shapes and properties would be dictated by the nature of the defect. Moreover, a very significant and attractive difference between photonic crystals and electronic semiconductor crystals is the inherent ability of the former to provide complete tunability. A defect in a photonic crystal could, in principle, be designed to be of any size, shape or form and could be chosen to have any of a wide variety of dielectric constants. Thus, defect states in the gap could be tuned to any frequency and spatial extent of design interest. In addition to tuning the frequency, one also has control over the symmetry of the localized photonic state. All of these capabilities provide a new "dimension" in our ability to "mold," or control, the properties of light. In this sense defects are good things in photonic crystals, and therein lies the exciting potential of these novel materials. Photonic crystals should allow us to manipulate light in ways that have not been possible before. The purpose of this article is to highlight some of these novel possibilities.

Here, computation plays a particularly important role. Indeed, unlike electronic structure in semiconductors, photonic crystals are unique in that phenomena described by Maxwell's equations can be calculated on a computer to any desired degree of accuracy. Thus computer calculations and design play a particularly important complementary role to experimental investigations in the study of photonic crystals.

Finally, Maxwell's equations do not possess a fundamental length scale and this

"Photonic crystals should allow us to manipulate light in ways that have not been possible before."

has important implications to both theory and experiment. For theory, this means that calculations can be done at a generic lengthscale, and the final results can be simply scaled up or down to the required wavelength of interest. For experiment, this means that measurements could be performed with photonic crystals designed at millimeter or centimeter lengthscales, where fabrication and characterization is simple, and that these results would have immediate relevance to photonic crystals designed at the ~1.5 micron lengthscale (the canonical wavelength in optoelectronics and telecommunications), but for which fabrication and testing are much more demanding.

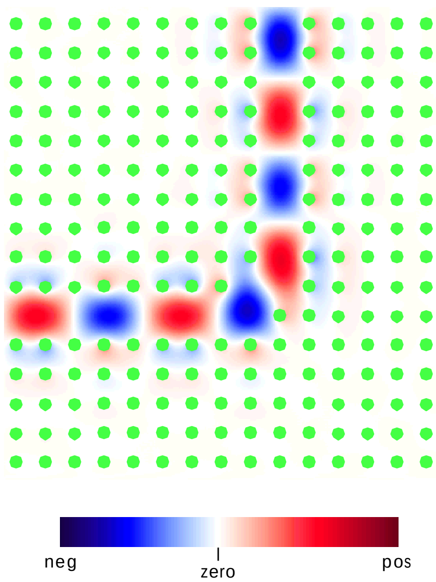


FIGURE 1

Electric field pattern in the vicinity of the sharp 90-degree bend. The electric field is polarized along the axis of the dielectric rods. The green circles indicate the position of the rods. Note that unlike the mechanism of total internal reflection, a photonic crystal may allow light to be guided in air.

Computational Methods

Maxwell's equations for the propagation of light in mixed, loss-less dielectric media can be cast in a form reminiscent of Schrödinger's equation. Consequently, techniques that are used to study electrons in solids may also be used to study photon modes in photonic crystals.[4,5] The main difference is that electrons are described by a complex *scalar* field and strongly interact with each other, whereas the photons are described by a real *vector* field and do not interact with each other. For all practical purposes, then, solution of the photon-equations leads to an "exact" description of their properties. This represents one of the few cases in science where computer experiments can be as accurate as laboratory experiments!

There are two types of computational methods that we employ to study photonic crystals numerically: *time domain*, a "numerical experiment" in which the time-evolution of Maxwell's equations is simulated directly; and *frequency domain*, in which one solves for the time-harmonic eigenmodes — band structures or dispersion relations — of light in the structure. To solve Maxwell's equations in 3D for periodic dielectric media in the *time* domain, we employ Yee-lattice Finite Difference Time Domain (FDTD) methods, which can include periodic as well as absorbing boundary conditions.[6] To solve Maxwell's equations in 3D for periodic dielectric media in the *frequency* domain, we begin by expanding the fields in plane waves. As in the case of electrons, the use of a planewave basis set has a number of desirable consequences.[5] First, the set is complete and orthonormal. Second, finite sets can be systematically improved in a straightforward manner. Third, *a priori* knowledge of the field distribution is not required for the generation of the set. Fourth, the constraint of divergenceless fields is easily maintained. Finally, there are extremely reliable and efficient methods for calculating the eigenfields, such as preconditioned conjugate gradients. The chief difficulty, however, in using plane waves would appear to be that huge numbers of plane waves are required in order to describe the very rapid changes in dielectric constant of photonic crystals. Actually, this is not the case and the potential problem can easily be overcome by a better treatment of the boundaries between dielectric media. In particular, it has been discovered[4] that construction of a dielectric tensor to interpolate in the boundary regimes leads to a rapid convergence of all eigenmodes, improving by over an order of magnitude on previous techniques! Thus, combination of this interpolation scheme together with a conjugate gradient approach leads to a very efficient method for frequency-domain calculations.

Concepts and Properties Using a Simple Model System

In this article we shall introduce concepts and properties that are generally valid in three-dimensional photonic crystals, but for the sake of simplicity and ease of visualization, our examples will involve two-dimensional photonic crystals. We begin by considering a perfect array of infinitely long dielectric rods located on a square lattice of lattice constant *a* and investigate the propagation of light in the plane normal to the rods. The rods have a radius of 0.20*a* and a refractive index of 3.4 (which corresponds to GaAs at a wavelength of 1.5 microns). Such a structure possesses a complete gap between the first and the second transverse magnetic (TM) modes. (For TM modes, the electric field is parallel to the rods.) Once we have a band gap, we can introduce a defect inside the crystal to trap or localize light. In particular, we shall investigate defects and defect-complexes that will correspond to specific components and devices leading to novel waveguides, waveguide bends, microcavities, waveguide crossings, waveguide splitters, and channel-drop filters.

Photonic-Crystal Waveguides

By making a line defect, we can create an extended mode that can be used to guide light. Using photonic crystals to guide light constitutes a novel mechanism. Traditionally, waveguiding is achieved in dielectric structures, such as optical fibers, by total internal reflection. With this mechanism, the light is forced to propagate in the high-index portion of the waveguide. When a fiber is bent very tightly, however, the angle of incidence becomes too large for total internal reflection to occur, and light escapes at the bend. Photonic crystals can be designed to continue to confine light even around tight corners because they do not rely on index guiding or the angle of incidence for confinement.

To illustrate this point, we remove a row of dielectric rods from the photonic crystal described above. This has the effect of introducing a single guided-mode band inside the gap. The field associated with the guided mode is strongly confined in the vicinity of the defect and decays exponentially into the crystal. A truly unique aspect of photonic crystal waveguides is their ability to guide optical light, tractably and efficiently, through narrow channels of *air*, using only dielectric material. This has never been possible before, and has important practical consequences because of lower absorption losses, much weaker nonlinear effects, and the potential for very high-power transmission.

Once light is introduced inside the waveguide, it really has nowhere else to go. The only source of loss is reflection from the waveguide input. This suggests that we may use photonic crystals to guide light around tight corners as illustrated in *Figure 1*. To determine the performance of this waveguide-bend configuration, we study

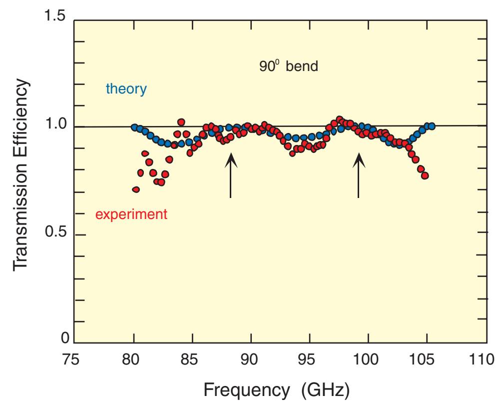


FIGURE 2

Transmission efficiency around a sharp 90-degree bend for a waveguide "carved out" of a square lattice of alumina rods in air. The red circles are experimental measurements and the blue circles are the theoretical prediction.

the effects of sending a broad-spectrum Gaussian pulse at one end of the bend. The fractional intensity is then evaluated as a function of frequency at points before and after the bend, yielding the transmitted and reflected power, respectively. Although the radius of curvature of the bend is less than the wavelength of the light, nearly all of the light is transmitted through the bend over a wide range of frequencies through the gap. The small fraction of light that is not transmitted is reflected. For specific frequencies, 100% transmission can be achieved![7] Clearly, a very basic principle must be at work and it is the following: Because of the presence of the gap, and the linear topology of the defect, light can only scatter forwards or backwards once it is in the defect. For all practical purposes, therefore, the light "thinks" it is in one dimension (1D). And we can now map this problem onto the elementary quantum mechanics problem of an electron resonant scattering over a barrier in 1D. If the barrier is symmetric, with width equal to integer multiples of half a wavelength, one obtains complete transmission. Note that a critical and necessary condition for 100% transmission efficiency is that the photonic crystal waveguide be single-mode in the frequency range of interest.

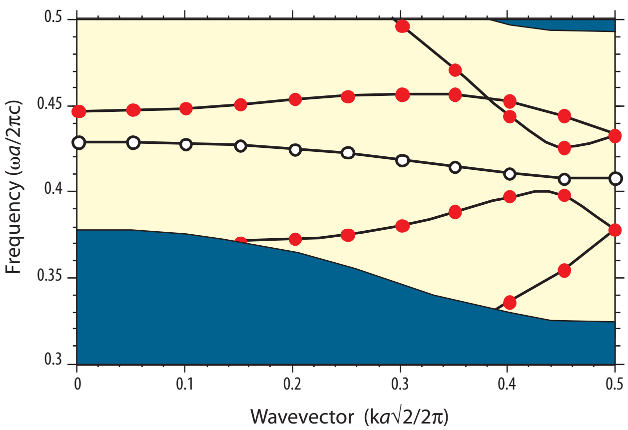


FIGURE 3

Superimposed dispersion relations for the two guides along the (1,1) direction. Open circles are for the narrow waveguide and filled circles are for the wide waveguide, as discussed in the text.

A recent experimental verification of 100% transmission efficiency at very sharp bends is illustrated in *Figure 2*. These are results from S.Y. Lin et al.[8] who performed experiments at millimeter lengthscales for a series of waveguide bends—similar to the configuration in *Figure 1*—using an appropriately scaled square lattice of alumina rods in air. The red circles are experimental measurements and the blue circles are the theoretical prediction. Good agreement is obtained over a wide range of frequencies.

Bound States at Waveguide Bends and Constrictions

Bound states in waveguide bulges, and especially in waveguide bends, have recently been the subject of widespread theoretical and experimental investigation. Goldstone and Jaffe[9] proved that bends, which behave like local bulges in the guide, always support bound states in constant cross-section quantum waveguides under the condition that the wavefunction vanishes on the boundary. Photonic crystals, however, provide a new mechanism for the appearance of bound states in waveguides.[10]

The key property of photonic crystal waveguides is that they can be designed to possess a mode gap in their spectrum. These mode gaps make it possible for bound states to exist in bends, bulges, and even constrictions, both above and below the cutoff frequency for guided modes. As an example, consider the guided-mode bands plotted along the diagonal (1,1) direction of the lattice as shown in *Figure 3*. These are a superposition of the bands for a (1,1) waveguide with one missing-row (open circles), and for a (1,1) waveguide with three missing-rows (filled circles). Note that the guided-mode band of the narrower waveguide falls completely within the mode gap of the wider waveguide. This suggests that a constriction in the wider waveguide could then lead to a bound state within the constriction. Moreover, this should not depend on the angle between the waveguides. This is exactly what happens, as shown in *Figure 4* for the case of a constriction at a 180° bend.

By choosing a configuration such that the constriction has length $3\sqrt{2}a$, we indeed find a bound state at $\omega = 0.41\,(2\pi c/a)$. The electric field of the mode is mostly confined to the inside of the narrow guide section at the 180° bend. Since the mode is close in frequency to the mode gap edge, the decay constant is small and the electric field decays slowly in the semi-infinite section. Nevertheless, it is a *bona fide* bound state whose counterpart would be impossible to obtain in conventional waveguides.

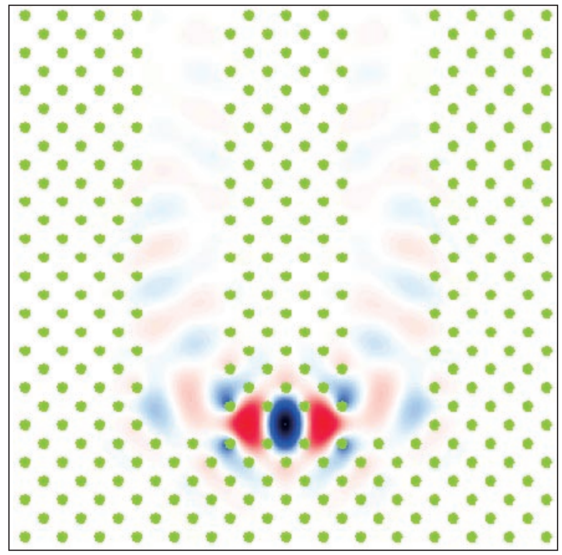


FIGURE 4

Electric field for the bound state at $\omega = 0.41\,(2\pi c/a)$ in a constriction of length 3a in a 180° waveguide bend.

Photonic Crystal Microcavities

In addition to making line defects, we can also create local imperfections that trap light at a point within the crystal. As a simple example, let us choose a single rod and form a defect by changing its radius. *Figure 5* shows the defect-state frequencies for several values of the defect radius. Let us begin with the perfect crystal—where every rod has a radius of $0.20a$—and gradually reduce the radius of a single rod. Initially, the perturbation is too small to localize a state inside the crystal. As the radius approaches $0.15a$, a singly-degenerate symmetric localized state appears in the vicinity of the defect. Since the defect involves removing dielectric material in the crystal, the state appears at a frequency close to the lower edge of the band gap. As the radius of the rod is further reduced, the frequency of the defect state sweeps upward across the gap.

Instead of reducing the size of a rod, we also could have made it larger. Starting again with a perfect crystal, we gradually increase the radius of a rod. As the radius reaches $0.25a$, a doubly-degenerate mode appears at the top of the gap. Since the defect involves adding material, the modes sweep downward across the gap as we increase the radius. They eventually disappear into the continuum (below the gap) when the radius becomes larger than $0.40a$. The electric fields of these modes have two nodes in the plane and are thus dipolar in symmetry. If we keep increasing the radius, a large number of localized modes can be created in the vicinity of the defect. Several modes appear at the top of the gap: first a quadrupole, then another (non-degenerate) quadrupole, followed by a second-order monopole and two doubly-degenerate hexapoles. We see that both the frequency and symmetry of the resonant mode can be tuned simply by adjusting the size of the rod. One important aspect of a finite-sized microcavity is its quality factor Q, roughly $\lambda/\Delta\lambda$ where $\Delta\lambda$ is the width of the cavity resonance, a dimensionless measure of the lifetime of the resonant state. Villeneuve et al.[11] have studied a finite-sized crystal made of dielectric rods where a single rod has been removed. They verified that the value of Q increases exponentially with the number of surrounding rods and found that it reaches a value close to 10^4 with as little as four rods on either side of the defect.

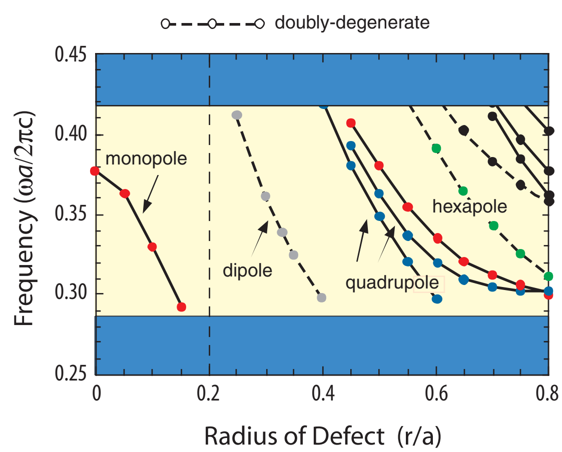


FIGURE 5

Defect states introduced into the gap by changing the radius of a single rod in an otherwise perfect square lattice of dielectric rods in air. When the radius is 0.2a there is no defect and when the radius is zero the rod has been completely removed. The shaded regions indicate the edges of the band gap.

Note also that these cavities possess small modal volumes, on the order of $(\lambda/2n)^3$. The combination of large quality factor with small modal volume offers a unique capability of maximally enhancing spontaneous emission.

Waveguide Crossings

The ability to intersect waveguides is crucial in constructing integrated optical circuits, due to the desire for complex systems involving multiple waveguides. Of particular importance is the possibility of achieving low crosstalk and high throughput in perpendicular intersections. Previous studies of traditional waveguide intersections[12,13] have lacked general principles that could be applied *a priori* to diverse systems. Moreover, they have typically been concerned with shallow-angle crossings for wavelengths many times smaller than the waveguide width. Although perpendicular crossings in such systems exhibit low crosstalk, the crosstalk is unacceptably high when the waveguide width is on the order of half a wavelength. In contrast, using photonic crystal waveguides, perpendicular crossings could be designed that effectively eliminate crosstalk—even when the waveguide width is small—permitting single-mode waveguides with optimal miniaturization.[14]

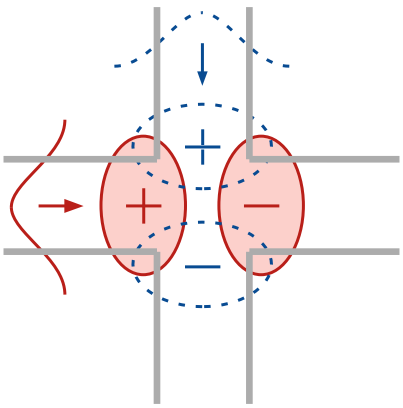


FIGURE 6.

Abstract diagram of symmetry requirements for waveguide crossing, showing waveguide mode profiles and resonant-cavity mode contours. By symmetry the solid-line modes cannot couple with the dashed-line modes and vice versa.

The fundamental idea is to consider coupling of the four branches, or ports, of the intersection in terms of a resonant cavity at the center. If the resonant modes excited from the input port can be prevented by symmetry from decaying into the transverse ports, then crosstalk is eliminated and the system reduces to the well-known phenomenon of resonant tunneling through a cavity. This situation can be achieved by means of the following conditions:

1. Each waveguide must have a mirror symmetry plane through its axis and perpendicular to the other waveguide, and have a sing1e guided mode in the frequency range of interest. This mode will be either even or odd with respect to the mirror plane.
2. The center of the intersection must be occupied by a resonant cavity that respects the mirror planes of both waveguides.
3. Two resonant modes must exist in the cavity, each of which is even with respect to one waveguide's mirror plane and odd with respect to the other. These should be the only resonant modes in the frequency range of interest.

If these requirements are satisfied, then each resonant state will couple to modes in just one waveguide and be orthogonal to modes in the other waveguide. An example of such a configuration is illustrated schematically in *Figure 6*. (For simplicity, we depict a lowest-order even waveguide mode.) Therefore, under the approximation that the ports only couple to one another through the resonant cavity, crosstalk will be prohibited. The transmission to the output port is described by resonant tunneling, and one can use coupled-mode theory[15] to show that the throughput spectrum will be a Lorentzian peaked at unity on resonance. The width of the Lorentzian is given by the inverse of the cavity's quality factor Q, which is proportional to the lifetime of the resonance mode.

The required parity of the cavity modes is easy to achieve using the results of *Figure 5*. The desired resonant cavity is created by introducing a single rod of radius $0.3a$ at the center of an otherwise perfect photonic crystal waveguide crossing, together with three rods of normal radius along the waveguides in the vicinity of the intersection, as shown in *Figure 7*. This leads to doubly-degenerate modes of the requisite symmetry with a frequency of 0.36 ($2\pi c/a$). To determine the performance of this waveguide-crossing configuration, we study the effects of sending a broad-spectrum propagation Gaussian pulse to the input port (*left*). The fractional power transmission is then evaluated as a function of frequency for the output port (*right*) and one of the transverse ports (*top*), yielding the throughput and crosstalk, respectively. We find that both the throughput and the crosstalk for an empty intersection lie in the 20–40% range. This is because the empty intersection does not support resonant states of the correct symmetry. In contrast, the intersection shown in *Figure 7* reaches nearly 100% throughput with an unprecedented crosstalk of only 5×10^{-9}!

Waveguide Splitters

Waveguide branches also play an important role in integrated photonic circuits. Ideally, such a device splits the input power into the two output waveguides without significant reflection or radiation losses. Motivated by the goal of miniaturizing photonic components and circuits, there have been many efforts to construct wide-angle branches.[16] Despite such efforts, the splitting angles are still limited to a few degrees for conventional structures, due to the inherent radiation loss at the branching region. Moreover, while such loss can be substantially reduced by increasing the index contrast between the guide and the surrounding media, it cannot be completely suppressed. Photonic crystals offer a way to completely eliminate radiation losses, and thereby open the possibility of designing wide-angle branches with high performance. Very recently, estimates of the transmission characteristics of a 120° Y-branch in a photonic crystal with hexagonal symmetry have been presented by Yonekura et al.[17] However, direct and accurate numerical characterizations of the transmission and reflection properties through a single waveguide branch have not been previously performed. Moreover, a general criterion for ideal performance of waveguide branches in a photonic crystal has only recently been presented.[18]

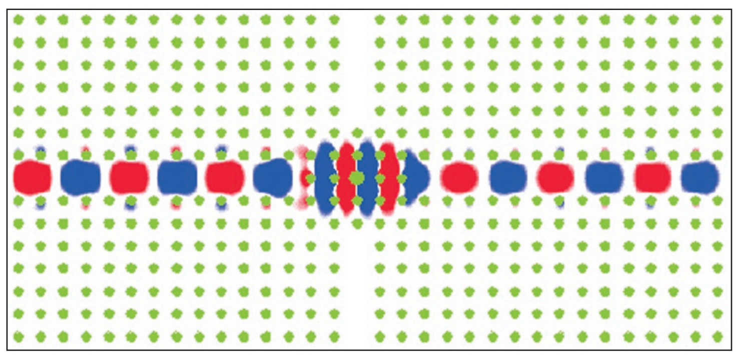


FIGURE 7

Steady-state electric field distribution for the case of the photonic crystal waveguide intersection discussed in the text. Essentially, all the power is transported through the junction with negligible crosstalk in the transverse waveguides.

In order to obtain a qualitative understanding of waveguide branches in a photonic crystal, we consider the theoretical model shown in *Figure 8*. The branching region is treated as a cavity that supports a single symmetric resonant mode that couples to the input and output waveguides. The resonance in the cavity then determines the transport properties of the branch. The transmission and reflection properties of such a model can be calculated using coupled-mode theory[15], which relates the incoming and outgoing wave amplitudes at ports 1, 2, and 3 to the amplitude of the excited resonant mode itself. One can then show analytically[18] that a criterion for perfect transmission exists, and that it is given by the simple rate-matching condition:

$$(1) \quad \frac{1}{\tau_1} = \frac{1}{\tau_2} + \frac{1}{\tau_3}$$

where $1/\tau_j$ is the amplitude decay rate of the resonance into the j-th port. Equation (1) immediately predicts that a 120° Y-branch with C_{3v} symmetry (i.e., the symmetry group of an equilateral triangle) can never provide 100% transmission! This is because the decay rates into the three ports are then equal, i.e., $1/\tau_1 = 1/\tau_2 = 1/\tau_3$ and Eq. (1) cannot be satisfied. Thus the 120° splitters considered by Yonekura et al.,[17] do not completely eliminate reflection. Arbitrarily high transmission approaching 100%, however, can be achieved in a structure without three-fold rotational symmetry. For example, it is clear from Eq. (1) that 100% transmission could be achieved, if obstructions were introduced between the resonant cavity and the waveguides of ports 2 and 3, to *reduce* $1/\tau_2$ and $1/\tau_3$. This is a rather counter-intuitive result at first glance, but provides precisely the guidance needed to design large-angle splitters with high performance characteristics.

Let us now demonstrate these ideas with a calculation of transmission through a T-shaped photonic crystal waveguide branch (i.e. with a 180° branching angle). The waveguide is introduced by removing one partial row and one full column of rods in our basic system of square lattice of dielectric rods in air. Moreover, to reduce the coupling between the resonance and the output waveguides, we place extra rods between the input and output waveguides, as illustrated in *Figure 9*. To characterize the transmission and reflection properties of this branch, we excite a Gaussian pulse in the input waveguide, and analyze the field amplitude at a point deep inside an output waveguide. For the case of a perfectly empty T-junction we find that the transmission coefficient remains around 80% for a wide range of frequencies. As the radius of the extra rods is increased from zero, the transmission is significantly improved and approaches the optimal value of 100% at a radius near $0.1a$. Further increasing the radius, however, results in a deviation from the rate-matching condition, and therefore leads to a decrease in transmission.

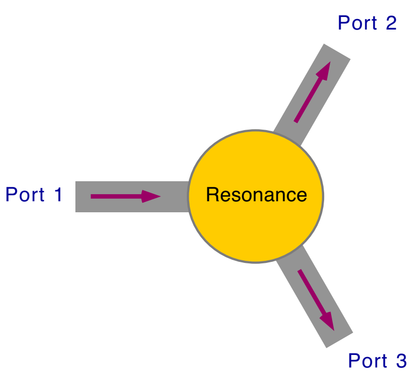


FIGURE 8

Schematic of a theoretical model for waveguide branches. The gray regions represent the waveguides and the circle represents a resonator cavity.

Channel-Drop Filters

One of the most prominent devices in the telecommunications industry is the channel-drop filter. This prominence is a consequence of both its importance and its size (~100cm^2)! Channel-dropping filters are devices that are necessary for the manipulation of *wavelength-division multiplexed* optical communications, whereby one channel is dropped at one carrier wavelength, leaving all other channels unaffected. Photonic crystals present a unique opportunity to investigate the possibilities of miniaturizing such a device to the scale of the wavelength of interest—1.5 microns. We now combine line defects and point defects to make a novel photonic-crystal channel-drop filter that gives access to one channel of a wavelength-division multiplexed signal while leaving other channels undisturbed. Two parallel waveguides—a main transmission line and a secondary waveguide—are created inside a photonic crystal by removing two rows of dielectric rods. A resonant cavity is introduced between the two waveguides by creating one or more local defects. Resonant cavities are attractive candidates for channel dropping since they can be used to select a single channel with a very narrow linewidth. The performance of the filter is determined by the transfer efficiency between the two waveguides. Perfect efficiency corresponds to complete transfer of the selected channel—into either the forward or backward direction in the secondary waveguide—with no forward transmission or backward reflection in the main transmission line. Moreover, all other channels should remain unaffected by the presence of the optical resonator. Fan et al.[19-20] have proved that there are three conditions that need to be satisfied by the coupling resonator in order to achieve optimal channel-dropping performance:

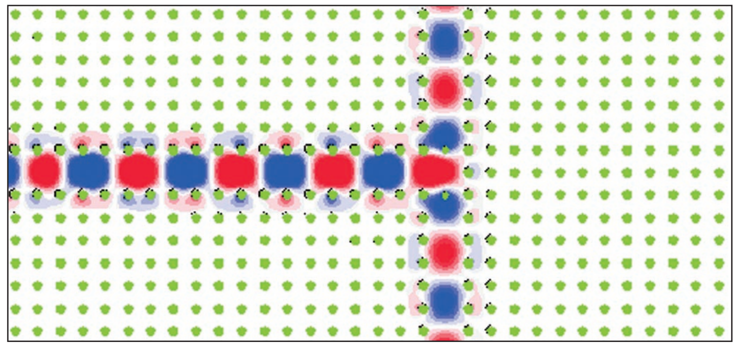


FIGURE 9

Steady state field distribution at $\omega_0 = 0.39$ ($2\pi c/a$) for a T-splitter with extra rods of radius 0.1a. The fields are completely confined within the waveguide regions and split equally into the output waveguides.

1. The resonator must possess at least two resonant modes, each of which must be even and odd, respectively, with regard to the mirror plane of symmetry perpendicular to the waveguides.

2. The modes must be degenerate (or nearly so). This condition is rather subtle because the intrinsic symmetry of the system does not support any degeneracies. Consequently one must force an *accidental* degeneracy!

3. The modes must have equal Q (or nearly so).

All three conditions are necessary in order to achieve complete transfer. The reflected amplitude in the transmission line originates solely from the decay of the localized states. The reflection therefore will not be cancelled if the optical resonator supports only a single mode. To ensure the cancellation of the reflected signal, the structure must possess a plane of mirror symmetry perpendicular to both waveguides and support two localized states with different symmetry with respect to the mirror plane, one even and one odd. Since the states have different symmetries, tunneling through each one constitutes an independent process. The even state decays with the same phase along both the forward and backward directions while the odd state decays with opposite phase. When the two tunneling processes are combined, because of the phase difference, the decaying amplitudes cancel along the backward direction of the transmission line. For cancellation to occur, the lineshapes of the two resonances must overlap. Since each resonance possesses a Lorentzian lineshape, both resonances must have substantially the same center frequency and the same width. When such degeneracy occurs, the incoming wave interferes destructively with the decaying amplitude along the forward direction in the transmission line, leaving all the power to be transferred into the secondary waveguide at the resonant frequency.

A photonic-crystal system provides precisely the control necessary to satisfy all three conditions. An example of a photonic-crystal channel-drop filter is shown in *Figure 10*. The cavity consists of a single point defect with a radius 0.60*a*. As we have already seen (*Figure 5*) this defect supports a doubly-degenerate hexapole state near $\omega_0 = 0.39\ (2\pi c/a)$ with the required symmetry. However, the presence of the waveguides next to the cavity breaks the degeneracy of the hexapoles. To restore the degeneracy, we change the dielectric constant (or equivalently, the size) of two rods adjacent to the defect. By properly changing the rods, we can affect the modes in different ways and force an accidental degeneracy in frequency. An approximate degeneracy in width exists between the states since the hexapoles possess large enough orbital angular momentum to ensure roughly equal decay of the even and odd modes into the waveguides. We simulate the filter response of the structure by sending a pulse through the upper waveguide. The transmission in the main line is close to 100% for every channel, except at the resonant frequency, where the transmission drops to 0% and the transfer efficiency approaches 100%. The quality factor is larger than 6,000. Since the even state—even with respect to the mirror plane perpendicular to the waveguides—is odd with respect to the mirror plane parallel to the waveguides, the transfer occurs along the backward direction in the secondary waveguide. Note that the size of this device is less than 100 square-microns instead of over 100 square-centimeters, as with present technology!

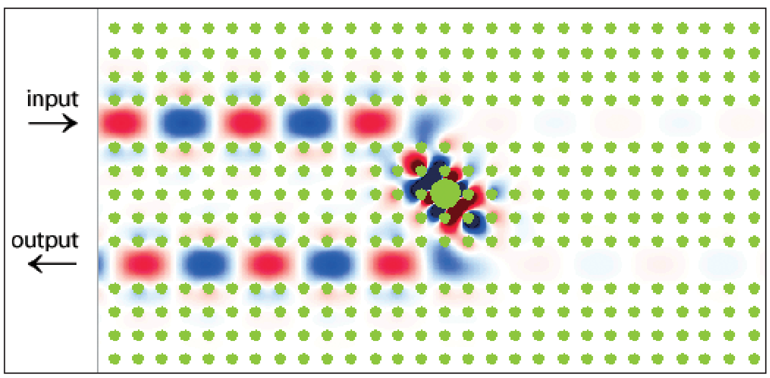


FIGURE 10

Steady-state field distribution of the photonic crystal channel drop filter at resonance. Note that the size of this device is on the order of the wavelength of the light in air.

Finally, although the lineshape of the current resonant modes is Lorentzian, it can be modified to be of the preferred "square-wave" shape by introducing complexes of coupled resonant modes as discussed in detail in *Ref. 21*.

Conclusions and Final Remarks

Presently in telecommunications and optoelectronics there is a great drive towards maximal miniaturization of optical devices, approaching the scale of the wavelength itself. The goal is eventually to integrate such devices on a single chip. To achieve such localization, however, it will be necessary to exploit mechanisms that go beyond index guidance (total internal reflection). Photonic crystals thus provide a new and promising foundation upon which to build future optical systems. In particular, the two most fundamental components of optical devices are waveguides and cavities, and in both cases photonic crystals promise important advantages in localization, tunability, and efficiency.

Minimizing radiation losses in optical structures is an important prerequisite for their use in efficient optical devices. In this regard, a new 3D photonic crystal structure has recently been introduced[22] that combines all the advantages of the networking simplicity of 2D photonic crystals with the control of an omnidirectional photonic band gap. This is a very important development that could help pave the way to future high-density integration of optical components and devices.

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