

Y junctions in photonic crystal channel waveguides: high transmission and impedance matching

S. Boscolo and M. Midrio

Dipartimento di Ingegneria Elettrica Gestionale e Meccanica, Istituto Nazionale per la Fisica della Materia, Università degli Studi di Udine, Viale delle Scienze 208, 33100, Udine, Italy

T. F. Krauss

School of Physics and Astronomy, University of St. Andrews, St. Andrews, Fife KY16 9SS, Scotland

Received February 25, 2002

We investigate the efficiency of transmission through photonic crystal Y junctions and show the importance of matching mode symmetries. Furthermore, we show that by adding tuning holes to the input waveguide it is possible to achieve almost perfect impedance matching, leading ideally to unitary transmission through the junction. The model system is based on a triangular photonic lattice of holes in dielectrics to reflect experimental reality. © 2002 Optical Society of America

OCIS codes: 130.3120, 250.5300.

The development of integrated optics components based on planar photonic crystals (PhC) is an active and rapidly developing field. Following the formulation of numerical proposals for efficient waveguiding, sharp bends, and junctions in photonic lattices,¹ the race is on to demonstrate these concepts in real optical systems. Straight waveguides with respectable losses have now been demonstrated by a number of groups of researchers.^{2–6} S bends⁷ and the first systems that consist of guides connected to cavities⁸ are also beginning to appear. All these experimental demonstrations have raised an important point: Unlike the model system of dielectric pillars in air,¹ real optical systems that consist of air holes in dielectrics tend to be multimoded. Multimodes lead to mode-mixing problems at intersections and to difficulties in matching input and output fields at discontinuities, thus resulting in reflections, an important problem that has received surprisingly little attention in the PhC community. Here we propose a solution based on impedance matching, in which the PhC waveguide is treated as an equivalent transmission line, and show numerically that low reflections as well as high transmission at a Y junction can indeed be obtained in a system that can be achieved experimentally. The specific structure that we investigated is a Y junction formed by the intersection of three PhC channel waveguides at 120° (Fig. 1) in an otherwise uniform photonic lattice. We assume a triangular lattice of air holes etched in a dielectric substrate with refractive index $n = 3.4$. The structure is assumed to be bidimensional; i.e., the air holes are infinitely long and the ratio between their radius and the pitch is $r/a = 0.3$. The lattice has a bandgap in the region $0.211 < a/\lambda < 0.280$. When a channel defect is introduced along the ΓK direction, two localized modes are allowed to propagate. The first is a mode whose one-component (H_z) magnetic field has even symmetry with respect to the waveguide axis, and it propagates for wavelengths in the range $0.218 < a/\lambda < 0.280$. The second mode has odd symmetry, and it propagates in the range $0.238 < a/\lambda < 0.251$.

The existence of guided modes with different parities is an important factor that deeply influences the transmission through the Y junction. To illustrate the point, we show a contour plot of the modulus of the magnetic-field amplitude for $a/\lambda = 0.26$ [Figs. 1(a) and 1(b)] and $a/\lambda = 0.24$ [Figs. 1(c) and 1(d)]. For $a/\lambda = 0.26$, we observe that the cavity is filled with a mode that has odd symmetry with respect to the axes of the output arms [Figs. 1(a) and 1(b)]. At this frequency the PhC waveguide supports only the even mode (Fig. 2, solid curve). As a result, no field is transmitted from the input to the output arms of the Y junction. A different behavior is observed for $a/\lambda = 0.24$. The cavity now produces a skewed field that can be understood as a superposition of modes with odd and even parities [Figs. 1(c) and 1(d)]. Inasmuch as both the even and the odd modes

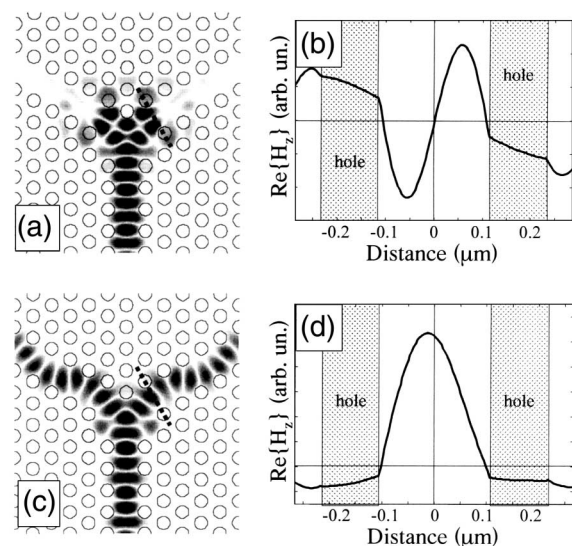


Fig. 1. (a) Contour plot of the modulus of the magnetic-field amplitude for wavelength $a/\lambda = 0.26$. (b) Real part of the magnetic field along the dashed line in (a). (c) Same as in (a), with $a/\lambda = 0.24$. (d) Same as in (b), with $a/\lambda = 0.26$.

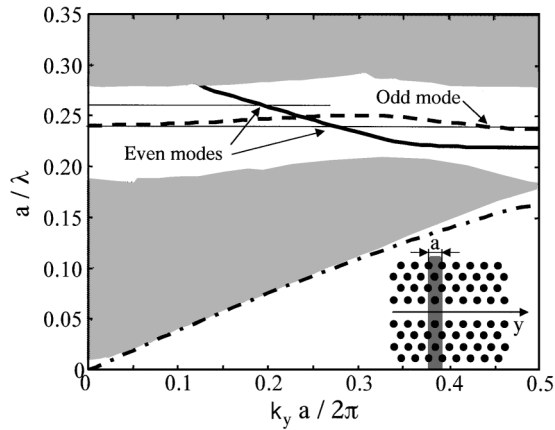


Fig. 2. Dispersion relations of modes guided by a PhC waveguide with air holes etched in a substrate with refractive index $n = 3.4$. The hole radius-to-pitch ratio is $r/a = 0.3$. Solid curve, dispersion relation for a mode whose one component magnetic field has even symmetry with respect to the guide axis. Dashed curve, dispersion relation for a mode with odd symmetry. Dashed-dotted curve, dispersion relation of a mode guided through total internal reflection.

can propagate in the output arms at this frequency (Fig. 2), we now observe good transmission through the junction. The field in the output arms is clearly a superposition of two modes with different parities and different propagation constants, as is evidenced by the beating that can be observed in the contour plot of Fig. 1(c). Please note that the effect is the same for a junction that consists simply of three intersecting waveguides, i.e., without the additional holes removed; the only reason for removing the extra two holes was to demonstrate the effect more clearly. Our conclusion is therefore as follows: The transmission through a junction depends strongly on the relationship between the modes that may propagate in the PhC waveguides and the modes of the junction region. If the modes of the junction are not compatible with those of the waveguide, transmission will be poor.

To improve matters, the obvious choice is to modify the junction region. By adding a smaller hole at the center of the junction (Fig. 3), we reduce the optical size of the cavity, thus eliminating multimode effects. At $a/\lambda = 0.26$, for example, i.e., the frequency at which the junction was not working at all previously, we now observe good transmission. The new junction interfaces to the output arms with a mode that has a well-marked even parity, and a clean field thus propagates in the output arms (Fig. 3). The power transmission efficiency that we numerically measured in this case is 43% for each of the output arms and was optimum for the radius of the additional hole, $r/a = 0.2$. The marked improvement caused by the additional hole is underlined by the bandwidth plot [dashed versus dotted curve in Fig. 3(b)].

Although this transmission efficiency is quite close to the maximum that can be obtained in structures with simple threefold rotational symmetry, which is equal to $4/9 = 44.4\%$,⁹ it can be further increased. To this end we use the analogy between PhC waveguides

and transmission lines that was proved recently.¹⁰ Using this equivalence, one can easily understand why the transmission efficiency is limited to 43% and how this value can be improved. Indeed, what we are facing is a problem of impedance mismatch: The junction region, along with the output arms, is a load impedance, Z_L , that we are trying to feed through the input PhC waveguide. This waveguide has its own intrinsic impedance, i.e., Bloch impedance Z_B , and, as soon as $Z_B \neq Z_L$, a reflected wave appears in the input waveguide, and it reduces the power transmission efficiency. For instance, by using the procedure that was detailed in Ref. 10, we found that $Z_B = 102.5 \Omega$ and $Z_L = (77.4 + i67.3) \Omega$ for Fig. 4. The reflection coefficient thus is $|\rho|^2 = |(Z_L - Z_B)/(Z_L + Z_B)|^2 = 0.14$; i.e., the transmitted power is equal to 86% of the available power, and it splits into two equal amounts in the output arms of the Y junction.

To improve the transmission efficiency further we need to match load impedance Z_L to intrinsic impedance Z_B ; as was shown in Ref. 10, we may do this by designing an equivalent double-stub network, which we achieve by introducing suitable defects into the input arm of the junction [see Fig. 4(a)]. Double-stub tuners are frequently used in microwave circuits, and it therefore appeared worthwhile to extend this concept into the optical regime; single- and multiple-stub tuners are possible, and impedance matching (peak and bandwidth) improves with the number of stubs used. The underlying physics is the following: When we insert a defect into the guide and the guided mode impinges upon it, higher-order modes are excited in the vicinity of the defect itself. If these higher-order modes are below cutoff, they cannot propagate. In other words, they have an imaginary wave impedance, which gives rise to an imbalance between electric and the magnetic stored energies; i.e., they form an equivalent lumped reactive element (Fig. 4).

Notice that the values of C and L are not independent of each other, as they depend solely on the hole

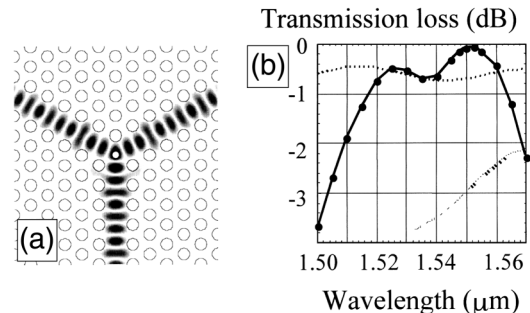


Fig. 3. (a) Contour plot of the modulus of the magnetic-field amplitude for wavelength $a/\lambda = 0.26$ through a suitably designed Y junction. The hole in the middle of the Y junction has radius $r_Y/a = 0.2$. (b) Spectral dependence of transmission on wavelength. Dotted curve, unmatched junction without the additional hole. Dashed curve, unmatched junction with the additional hole. Solid curve, matched junction with the additional hole. All curves were calculated numerically (multiple-scattering technique). Filled circles, theoretical results obtained with Eqs. (1)–(3).

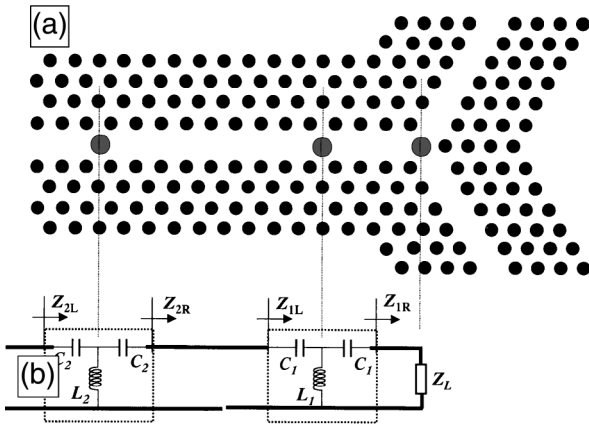


Fig. 4. (a) Dielectric arrangement that produces the matching network. (b) Equivalent circuit.

radius. For instance, by using the procedure described in Ref. 11 we estimated that $C = 8.1 \times 10^{-17} F$ and $L = 6.6 \times 10^{-14} H$ for a hole with radius $r_{\text{def}}/a = 0.2$ and for wavelength $\lambda = 1.55 \mu\text{m}$.

Extra holes (tuning holes) placed in the middle of the waveguide channel may be used to achieve an equivalent matching network. However, owing to the presence of series elements and to the fact that C and L depend on each other, there is no guarantee that perfect matching will always be achieved. All we can do is to evaluate the input impedance of the equivalent transmission line that encompasses an arbitrary number of these lumped reactive elements, and that is terminated to the load, and minimize the overall reflection coefficient by varying the number, position, and size of the tuning holes that are inserted into the waveguide channel. An example of a computation is as follows: Consider Fig. 4 and suppose that the first and the second defect holes are placed m_1 cells upstream from the load (i.e., the junction) and m_2 cells upstream from the first hole, respectively. Denote by Z_{1R} the load impedance that is found at the location site of the first tuning hole when this hole is absent. It is given by¹⁰

$$Z_{1R} = Z_B \frac{Z_L + iZ_B \tan(m_1 \chi_y a)}{Z_B + iZ_L \tan(m_1 \chi_y a)}, \quad (1)$$

where Z_B is the intrinsic waveguide impedance and χ_y is the Bloch wave number of the field that propagates in the infinitely long waveguide (in our case, $\chi_y = 2.94 \mu\text{m}^{-1}$ at 1550 nm). In the presence of the tuning hole the impedance at the left edge of the first hole itself is

$$Z_{1L} = \frac{1}{i\omega C_1} + \frac{i\omega L_1(1 + i\omega C_1 Z_{1R})}{1 - \omega^2 L_1 C_1 + i\omega C_1 Z_{1R}}, \quad (2)$$

where ω is the field frequency. In a similar fashion we can compute the impedance at the right-hand edge of the second hole, say, Z_{2R} , as in Eq. (1) by substituting Z_{2R} for Z_{1R} , with Z_{1L} for Z_L , and m_2 for m_1 . Moreover, we can compute the impedance at the left-hand edge of the second hole, say, Z_{2L} , as in Eq. (2) by substituting Z_{2L} for Z_{1L} , C_2 for C_1 , L_2 for L_1 , and Z_{2R} for Z_{1R} . The reflection coefficient to be minimized is finally

$$\rho = \frac{Z_{2L} - Z_B}{Z_{2L} + Z_B}. \quad (3)$$

We found a possible solution to minimizing ρ by inserting two tuning holes into the guide, both with a radius $r_{\text{def}}/a = 0.2$. The first was placed $m_1 = 4$ cells upstream from the junction; the second, $m_2 = 9$ cells upstream from the first. This matching network theoretically gives rise to a reflection coefficient as low as $|\rho|^2 = 0.014$, a value that was also verified by means of numerical simulations performed with a spectral code based on the multiple-scattering approach.¹¹ Hence the transmission from the input waveguide to each of the output arms of the Y junction now has improved to a peak level of 49.3%, i.e., the overall device loss has decreased to 0.06 dB. The bandwidth plot [Fig. 3(c)] shows that the double-stub tuner further improves the transmission compared with the single-hole case within a 20–30-nm window.

To conclude, we have explained the poor transmission at simple Y junctions in photonic crystal channel waveguides and shown the importance of matching mode symmetries to improve transmission, using a model system of holes in a dielectric that can easily be achieved experimentally. Furthermore, by adding tuning holes to the input waveguide one can achieve almost perfect impedance matching, surpassing the transmission of an ideal but unmatched Y junction of 44.4%.⁹ Some qualifications apply, however: The increased transmission achieved with the stub tuner occurs only over a limited bandwidth, and the presence of tuning holes in the center of the waveguide may increase out-of-plane radiation losses.

T. F. Krauss's e-mail address is tfk@st-andrews.ac.uk.

References

1. J. D. Joannopoulos, P. R. Villeneuve, and S. Fan, *Nature* **387**, 143 (1997).
2. C. J. M. Smith, H. Benisty, S. Olivier, M. Rattier, C. Weisbuch, T. F. Krauss, R. M. De La Rue, R. Houdré, and U. Oesterle, *Appl. Phys. Lett.* **77**, 2813 (2000).
3. A. Talneau, L. Le Gouezigou, and N. Bouadma, *Opt. Lett.* **26**, 1259 (2001).
4. M. Notomi, A. Shinya, K. Yamada, J. Takahashi, C. Takahashi, and I. Yokohama, *Electron. Lett.* **37**, 293 (2001).
5. M. Loncar, D. Nedejkovic, T. Doll, J. Vuckovic, A. Scherer, and T. P. Pearsall, *Appl. Phys. Lett.* **77**, 1937 (2000).
6. J. Arentoft, M. Kristensen, T. Sondergaard, and A. Boltasseva, *Electron. Lett.* **38**, 274 (2002).
7. E. Chow, S. Y. Lin, S. G. Johnson, and J. D. Joannopoulos, *Opt. Lett.* **26**, 286 (2001).
8. C. J. M. Smith, R. M. De La Rue, M. Rattier, S. Olivier, H. Benisty, C. Weisbuch, T. F. Krauss, R. Houdre, and U. Oesterle, *Appl. Phys. Lett.* **78**, 1487 (2001).
9. K. Kurokawa, *An Introduction to the Theory of Microwave Circuits* (Academic, New York, 1969).
10. S. Boscolo, C. Conti, M. Midrio, and C. G. Someda, *J. Lightwave Technol.* **20**, 304 (2002).
11. G. Tayeb and D. Maystre, *J. Opt. Soc. Am. A* **14**, 3323 (1997).