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# Controlling group velocity in rectangular-lattice photonic crystal waveguides

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## ABSTRACT

A method for controlling the dispersion and thus group velocity of guided modes in photonic crystal (PC) waveguides using bi- and quasi-periodic lattices is presented. Rectangular lattice photonic crystals are proposed as possible candidates for implementing such control. However, these structures, and generally all bi-periodic lattices, develop undesirable characteristics as the perfect square lattice is perturbed. Thus, quasi-periodic photonic crystals, which have been shown to be promising in selective mode engineering, were examined next. A possible scheme for engineering of a single mode PC waveguide with guiding through the entire bandgap is presented.

## 1. GUIDING MECHANISMS IN PC WAVEGUIDES

Photonic crystals (PC's), which in general are simply periodic arrangements of dielectric materials (Fig. 1.a.), have engendered significant interest due to their light-controlling behavior [1, 2]. In Fig. 1, a PC is created by etching a triangular lattice of air holes (relative permittivity = 1) in a slab of dielectric material, such as silicon. The band structure of a PC (Fig. 1.b.) is often plotted with respect to the irreducible Brillouin zone. Due to the periodic nature of these

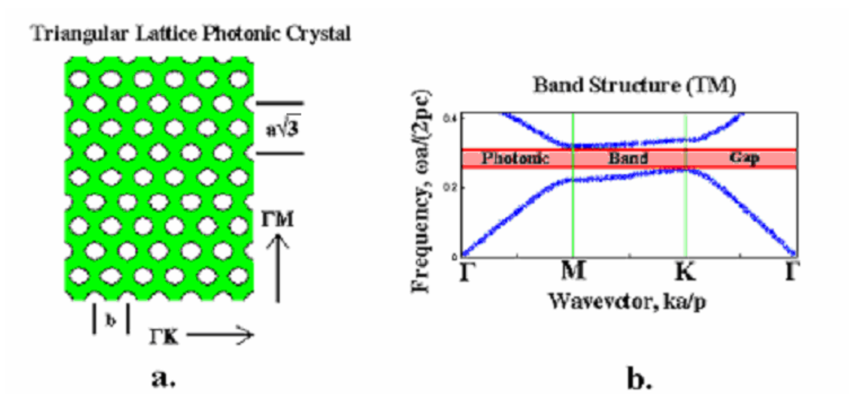


Fig. 1. (a.) Diagram of a sample photonic crystal, where the radius of the holes is equal to $r = 0.3a = 0.3b$. (b.) Band structure of the TM (magnetic field normal to the plane of periodicity) modes of the photonic crystal shown in Fig. 1.a.

crystals, they may be designed to exhibit a photonic bandgap (PBG), a range of frequencies that are not allowed to propagate in the crystal [3]. A defect PC waveguide may then be made by removing one entire row of holes in the perfect PC (Fig. 2.a.), thus creating defect modes in the bandgap that allow light to propagate [4]. The resulting dispersion diagram showing the properties of the guided modes is plotted in Fig. 2.b. The primary issue surrounding PC waveguides is that the waveguide made by simply removing one row of air holes often does not possess the ideal characteristics sought for in most applications. Referring back to Fig. 2.b., there are often at least two guided modes present, namely the first even and first odd mode. However, single mode operation is usually preferred in communications and computing applications. Also, as highlighted in Fig. 3, a given guided mode may include a region that flattens out, indicating near zero group velocity. Such mode flattening significantly degrades transmission through



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the waveguide. Furthermore, only a fraction of the bandgap may actually be used in waveguiding applications (where the fundamental even mode exists), effectively reducing the operational bandwidth of the structure. These issues may be

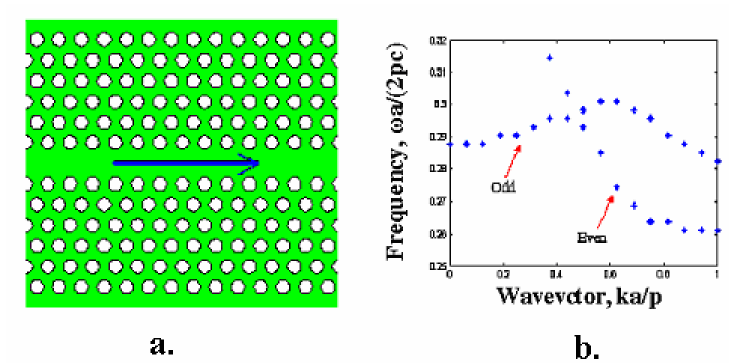



Fig. 2. (a.) Diagram of a PC waveguide made by removing one row of air holes from a triangular lattice PC. (b.) Dispersion diagram for the guided TM modes of the waveguide shown in Fig. 2.a. for $r = 0.3a = 0.3b$. The dielectric material is assumed to be Si [7], and the frequency range in this plot corresponds to the PGB of the structure.

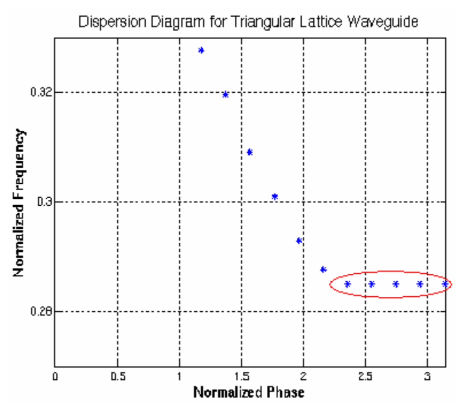



Fig. 3. Dispersion diagram of the fundamental even TM mode of the waveguide in Fig. 2 showing zero group velocity region. The mode flattening at $\omega \approx 0.284$ is highlighted here.

resolved by first examining the mechanisms that allow PC waveguides to guide light [5].

Guiding is permissible as a result of two principal effects, namely total internal reflection and distributed Bragg reflection (DBR). The first effect, total internal reflection, is the same property that allows a simple dielectric slab to guide light. Distributed Bragg diffraction effects arise from the periodic nature of the photonic crystal along the guiding direction [5]. This effect is similar to the DBR in a corrugated waveguide. DBR is the primary reason for mode flattening.

From the mode profiles of the guided modes, we know that most of the energy in those modes is confined to the middle of the guiding slab region and the first row of air holes directly adjacent to it [6, 7]. Therefore, it can be deduced that by changing the periodicity and the size of the air holes next to the guiding region in the direction parallel to the waveguide, the dispersion characteristics may be modified in a controlled matter as the effective permittivity and DBR effects change.

## 2. DESIGNING SINGLE MODE WAVEGUIDES

The triangle lattice structure is one of the most popular PC geometries, due to the fact that is has a relatively large bandgap for transverse-magnetic (TM) polarization [5], where the magnetic field is normal to the plane of periodicity. However, as mentioned before, there are two guided modes present is the PC waveguide formed by eliminating one row of air holes. It has been shown [7] that by increasing the radius of the air holes adjacent to the slab waveguide region, designated as *r'* (Fig. 4), the guided modes may be shifted higher in frequency with respect to the bandgap of the bulk

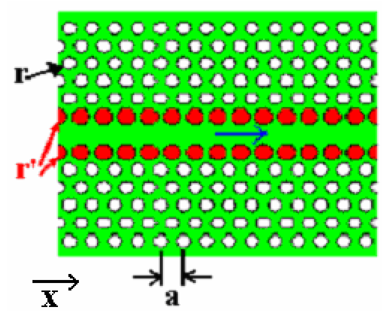



Fig. 4. Triangular lattice waveguide with enlarged air holes adjacent to the slab region.

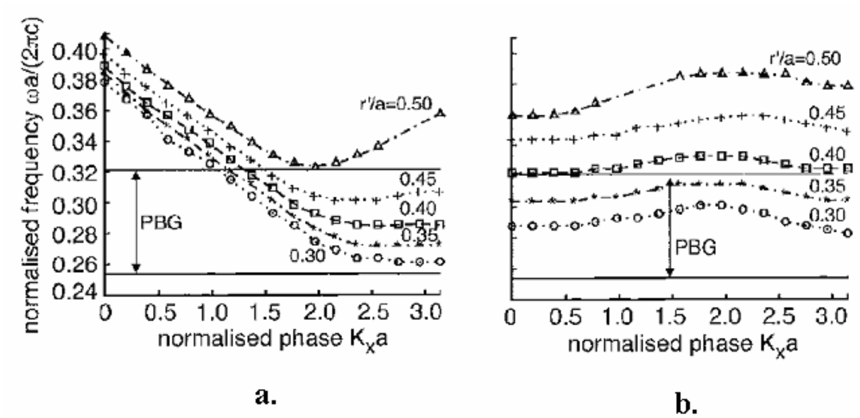



Fig. 5. Effects of increasing *r'/a* on dispersion diagram of the (a.) even and (b.) odd TM modes of the PC waveguide in Fig. 4 with r = 0.3.

crystal (Fig. 5). In fact, for a normalized radius (*r'/a*, where *a* is the lattice constant) value of 0.4, the odd mode may be shifted completely out of the bandgap while the even mode still covers a portion of it, making the waveguide single-mode. This asymmetric shifting of the odd and even mode may be attributed to the fact that the odd mode has its energy in the air hole region surrounding the slab waveguide, whereas the energy of the even mode is primarily confined to the slab itself. Thus the odd mode is effected more by changes in the hole radius. Unfortunately, though, the zero group velocity region of the even mode is still present in the bandgap and the mode itself has shifted higher, leaving most of the bandgap unused. Obviously, this waste of the bandgap for guiding is highly undesirable, creating the need for a method of extending the even mode through the entire bandgap with approximately constant group velocity.

## 3. RECTANGULAR LATTICE PHOTONIC CRYSTALS

In order to extend the bandwidth of the even mode in the triangle lattice PC waveguide, the mechanism causing the zero group velocity flattening is first examined. The high-reflection mode dispersion flattened region is a result of DBR from the periodic corrugation in the guiding direction, and thus occurs in the vicinity of the frequency peak of DBR for that periodicity. Hence, if the frequency of the DBR peak could be changed while leaving the PBG intact, it may be possible to shift the flat dispersion regime completely out of the bandgap. This can be accomplished by changing the periodicity of the air holes adjacent to the guiding region.

The first method presented for changing the hole periodicity in the guiding direction is to change the periodicity for the entire crystal in that direction, leading to a bi-periodic structure. The most straightforward case is created by applying this method to the square lattice photonic crystal, effectively stretching or compressing the lattice in the horizontal direction to produce a rectangular lattice geometry (Fig. 6). The normalized parameter *b*/*a* is used to measure the

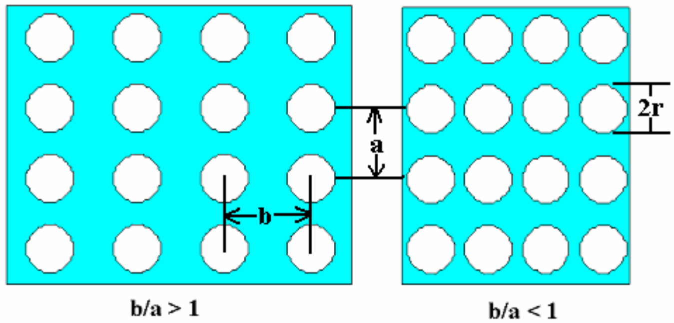



Fig. 6. Bi-periodic rectangular lattice photonic crystal.

amount of perturbation to the square lattice, where *b* is the lattice constant for the horizontal direction and *a* for the vertical directions. The value of *a* is held constant in all calculation, and all normalized values (such as phase, *k*) are calculated using *a* as the lattice constant. To make a waveguide, a dielectric slab is sandwiched between two such PC structures, where the slab is made thin enough so that the waveguide can only support one mode [8]. The fundamental guided mode of the resulting mode dispersion diagram is shown in Fig. 7 for various values of normalized horizontal lattice constant, *b*/*a*. The waveguide was excited with a (TE) polarized source (electric field normal to the plane of

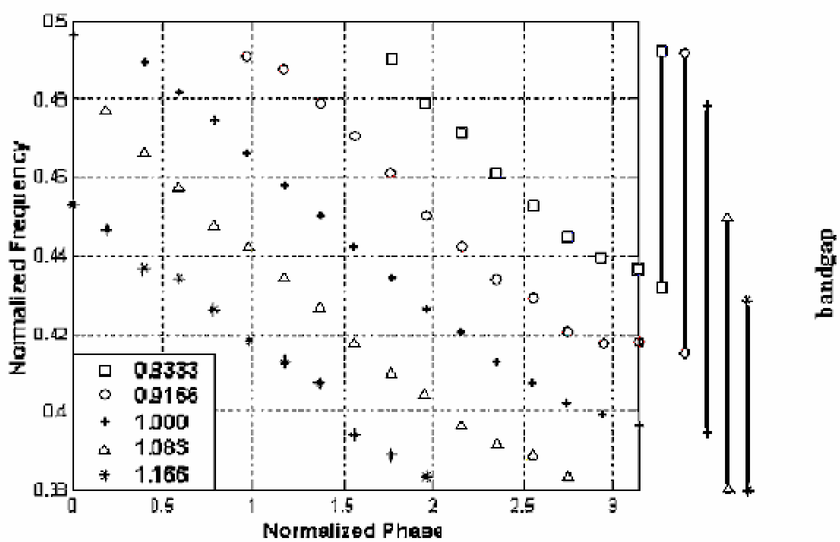
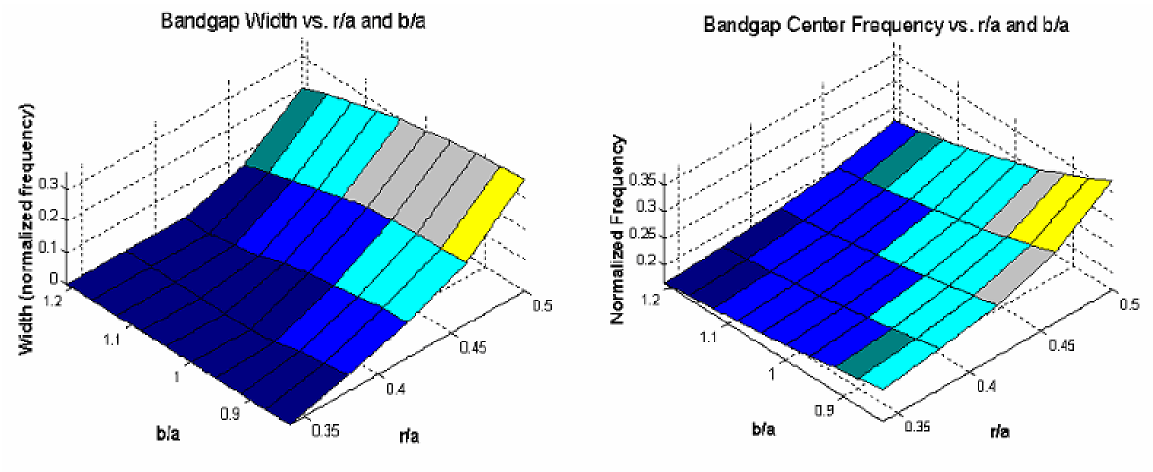



Fig. 7. Dispersion diagram of rectangular lattice PC waveguide for various values of *b*/*a*.

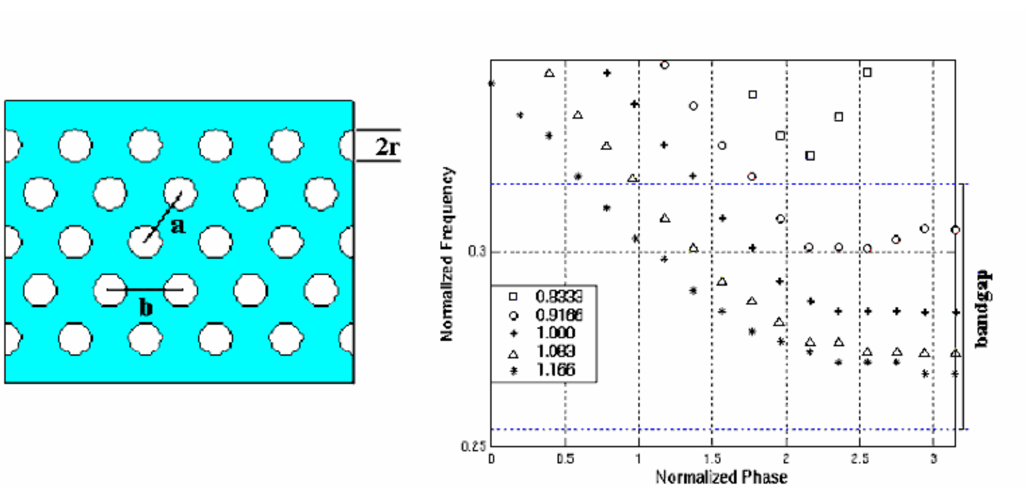
periodicity), which offers the largest bandgap in a square lattice photonic crystal. Clearly, there is a trend of downward shift in frequency as *b*/*a* is increased, which is expected since frequency is inversely related to the periodicity. It appears that the flattening trend to the right of the plot for smaller values of *b*/*a* tends to shift downward as well while the rest of the guided mode covers the POG bandgap. However, one should note that the bandgap of the photonic crystal itself is also modified, as shown in the gap map calculated for the rectangular lattice (Fig. 8). Besides a shift in center frequency, the width of the bandgap is altered significantly for relatively small changes in both *b*/*a* and the normalized radius, *r*/*a*. In particular we see that the bandgap width decreases dramatically as *r*/*a* is decreased as expected, but that the width also decreases as *b*/*a* is increased or decreased from unity. Thus it appears that as the symmetry of the perfect square lattice is broken, the bandgap of the rectangular lattice shrinks.




**a.** **b.**

Fig.8. Bandgap map for rectangular lattice photonic crystal (TE polarization) for variation of the (a.) width of the PBG and (b.) center frequency with $b/a$ and $r/a$ (defined in Fig. 6).

This rectangular lattice concept is next applied to the triangular lattice (Fig. 9.a.), which can be thought of in terms of a square lattice with an added hole in the center. For this lattice, the constant $a$ is the distance between two hole centers in adjacent vertical layers, and $b$ is again the periodicity in the direction parallel to the waveguide. A single-mode waveguide is formed in this case by removing air holes in one horizontal row of the lattice, and then increasing the radii of the holes adjacent to the guiding region to $r'/a = 0.4$ [7]. The dispersion diagram for this structure showing the fundamental guided mode for various values of $b/a$ is displayed in Fig. 9.b. The waveguide was excited with a TM-polarized source since it provides the largest bandgap for the perfect triangular lattice (60º orientation, or $b = a$), and the bandgap is highlighted in the plot for only this case. Again, the guided modes are shifted downward in frequency, as expected, although the mode shape changes considerably as well. In addition, for each value there is a zero group velocity region, and it is never shifted out of the bandgap. Since we know from the original rectangular lattice case that the bandgap is altered using this method, and given that it does not eliminate the mode-flattening problem, this method does not appear to be effective for extending the guiding bandwidth of PC waveguides.




**a.** **b.**

Fig. 9. (a.) Bi-periodic triangular lattice photonic crystal. (b.) Dispersion diagram for the fundamental TM mode of a bi-periodic triangular lattice waveguide with $r = 0.3a$ and for different values of $b/a$.

## 4. QUASI-PERIODIC PC WAVEGUIDES

Since modifying the horizontal periodicity of the PC lattice produces the desired shift in guided mode frequency but also affects the bandgap of the structure itself, a quasi-periodic approach is suggested as a solution that may circumvent the problems that plague the bi-periodic method. A PC waveguide is considered quasi-periodic when two (or more) periodicities are incorporated in one direction of the structure. An example is one periodicity for the holes in the bulk photonic crystal and a second for the two rows of air holes adjacent to the guiding slab (Fig. 10). The advantage of this

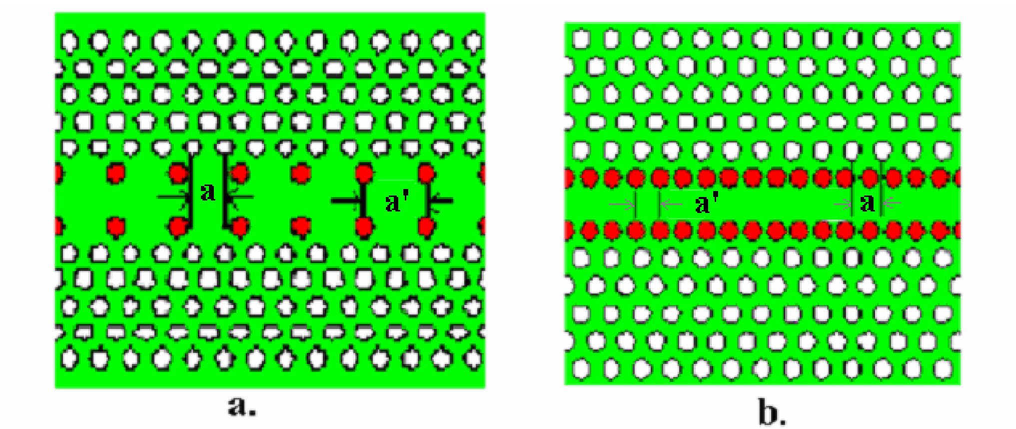



Fig. 10. Two examples of a quasi-periodic photonic crystal. In the left diagram, (a.) the periodicity of the air holes adjacent to the guiding region is larger than that of the bulk crystal, and (b.) smaller that the bulk crystal in the right diagram.

type of structure is that the bulk photonic crystal remains intact with its bandgap, while the DBR peak can be altered by changing the periodicity of the holes adjacent to the guiding region. In this structure, *a'* and *a* are the periods in the guiding direction for the adjacent air holes and the bulk crystal, respectively. Fig. 11 displays the simulation results obtained by increasing the adjacent hole periodicity in a quasi-periodic waveguide; the dispersion diagram is shown in Fig. 11.a. and the transmittance through a PC waveguide (length = 20*a*) in Fig. 11.b. The transmittance plot shows the output power measured at the exit of the waveguide versus the power at the input for various normalized frequencies.

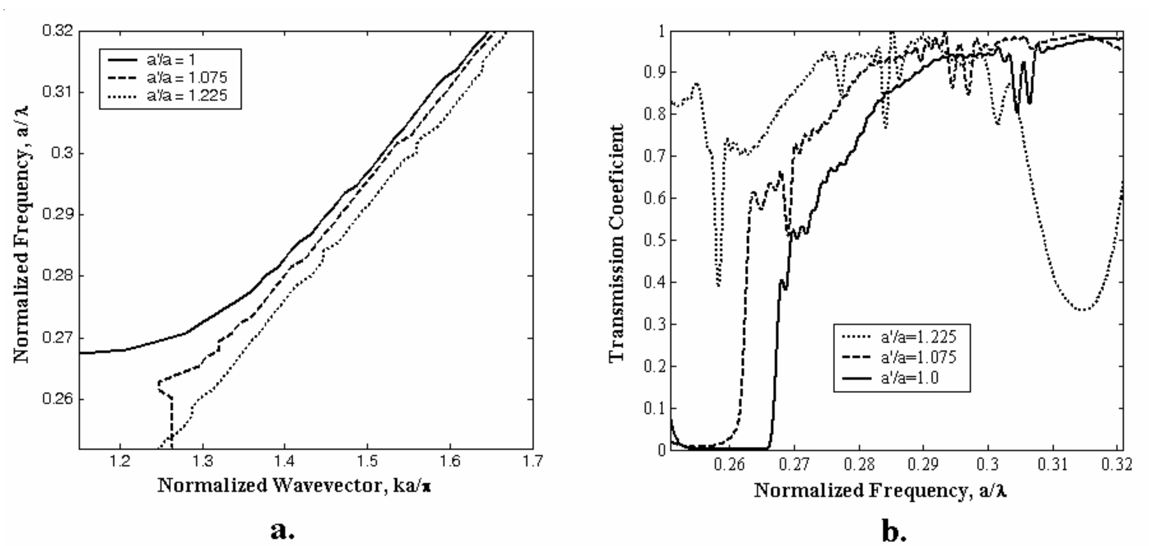



Fig. 11. (a.) Dispersion diagram and (b.) transmittance for the fundamental TM modes of a quasi-periodic triangle lattice waveguide for *a'* >= *a*, Fig. 10.a.

From the transmittance plot, which only shows values for frequencies in the PGB, the frequency range for strong DBR effects may be identified by the near-zero transmittance region at the lower frequencies. As expected, by increasing *a'* this region shifted towards lower frequencies, since the DBR frequency is inversely related to the period, and for *a'*/*a* = 1.225 it appears to be shifted entirely out of the bandgap. The same behavior is demonstrated in the dispersion diagram, which is now plotted using unfolded *k* values since the periodicity of the photonic crystal is being broken and there is no proper Brillouin zone to which *k* can be folded (this explains why the plot appears to be mirrored with respect to Fig. 3). In the dispersion diagram, the mode flattening starts out at just under $\omega$ = 0.27 in normalized frequency (*a'*/*a* = 1), and is shifted lower in frequency as the periodicity is increased. In fact, for *a'*/*a* = 1.225, the dispersion diagram is almost linear through the PBG.

In order to verify the validity of this method, the same goal is achieved by now decreasing the adjacent hole periodicity, as seen in Fig. 10.b. Again, in the transmittance plot (Fig. 12.b.) the DBR region may be seen at the lower end of the bandgap indicated on the plot for the unperturbed waveguide (*a'*/*a* = 1), and observed shifting higher in frequency as the periodicity is increased. Ultimately, for *a'*/*a* = 0.7 the DBR region is clearly completely outside the bandgap. The dispersion diagram in Fig. 12.a. corroborates this conclusion. The mode flattening region is seen shifting to higher frequencies, until it is shifted out of the bandgap (*a'*/*a* = 0.7) and guiding throughout the entire bandgap again observed.

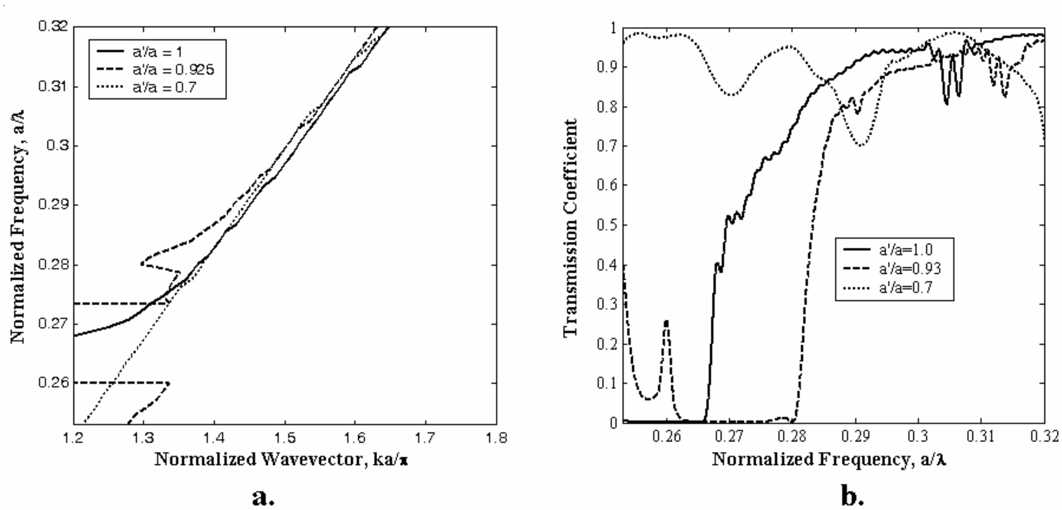



Fig. 12. (a.) Dispersion diagram and (b.) transmittance for the fundamental TM modes of a quasi-periodic triangle lattice waveguide for *a'* <= *a*, Fig. 10.a.

## 5. CONCLUSIONS

Two methods have been presented for controlling dispersion and thus group velocity in PC waveguides with the goal of near-linear mode dispersion with guiding through the entire bandgap. The first method uses a bi-periodic crystal lattice, which allows for shifting of the guided modes in frequency, but no direct modification of the mode dispersion. However, this method is not capable of shifting the zero dispersion region completely out of the bandgap, and it also directly modifies the bandgap of the bulk crystal in an undesirable manner. The second method involves a quasi-periodic structure, which leaves the bulk crystal (and its bandgap) intact, while effectively changing the periodicity of the holes primarily responsible for DBR effects. Using this method, two PC waveguide designs were demonstrated that achieve near-linear guiding throughout the bandgap of the device. A method was also presented for designing single mode PC waveguides by modifying the radii of the air holes next to the guiding region. By combining this method with the quasi-periodic design (in other words by modifying the radii and periodicity of the air holes adjacent to the guiding region), we can design a PC waveguide with single-mode propagation throughout the PBG.

## 6. ACKNOWLEDGMENTS

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## 7. REFERENCES

1. E. Yablonovitch, “Inhibited spontaneous emission in solid state physics and electronics,” Phys. Rev. Lett., vol. 58, pp. 2059–2062, 1987.
2. S. John, “Strong localization of photons in certain disordered dielectric superlattices,” Phys. Rev. Lett., vol. 58, pp. 2486–2489, 1987.
3. J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals: Molding the Flow of Light*. Princeton, NJ: Princeton Univ. Press, 1995.
4. P. Yeh and A. Yariv, “Bragg reflection waveguides,” Opt. Com., vol. 19, pp. 427–430, 1976.
5. M. Plihal, A. A.Maradudin, “Photonic band structure of two-dimensional systems: The triangular lattice,” Phys. Rev. B, vol. 44, pp. 8565–71, 1991.
6. A. Adibi, Y. Xu, R. K. Lee, A. Yariv, and A. Scherer, “Guiding mechanisms in dielectic-core crystal optical waveguides,” Phys. Rev. B, vol. 64, pp, 033308/1–4, 2001.
7. A. Adibi, R. K. Lee, Y. Xu, A. Yariv, A. Scherer, “Design of photonic crystal optical waveguides with singlemode propagation in the photonic bandgap,” IEEE Electr. Lett., vol. 36, pp. 1376–1378, 2000.
8. A. Adibi, Y. Xu, R. K. Lee, A. Yariv, A. Scherer, “Properties of the slab modes in photonic crystal optical waveguides,” J. of Light. Tech., vol. 18, pp. 1554–64, 2000.