Realization and Sensitivity Analysis of Low Loss Hybrid Photonic Crystal Waveguides Using Low Index Dielectric Materials

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ABSTRACT

Complex photonic bands and strong anisotropic dispersion characteristics of artificially engineered periodic dielectric structures have been widely investigated. In this paper we explore the self-guiding effect possessed by photonic crystals and the possible applications for integrated photonics. Since this approach does not require a full photonic bandgap, low refractive index materials (i.e. glass or organic polymers) are considered as an alternative with advantages over conventional semiconductor materials. Sensitivity analysis reveals how structural variations influence the performance of this type of photonic crystal based system.

Keywords: Photonic crystal, photonic bandgap, dispersion engineering, waveguide, simulation, structural deviation, feasibility, statistical analyses

1. INTRODUCTION

The area of photonic crystals (PhC) and photonic bandgap (PBG) structures has been the subject of numerous research studies over the past several years. These structures could enable the engineering development of a whole new class of materials, which exhibit unique transmission properties created through an ordered arrangement of the dielectric properties[2,3,4]. Most of the effort has been in the area of photonic bandgap (PBG) devices—a special class of PhC devices—that prohibit photon propagation within certain frequency bands. By introducing a linear defect or a series of resonate structures into PhC lattice, one can design a waveguide with good lateral confinement and low loss transmission even through sharp bends and turns[5,6]. They show promise as a platform technology for applications such as ultra-compact integrated photonic circuits. In particular, two dimensional membrane-like photonic bandgap waveguides[2,7,8] have demonstrated fully confined wave-guiding characteristics that can lead to the realization of ultra-compact and highly efficient photonic waveguide circuits. However, it is not always possible to obtain such a full bandgap in a PhC. For example, materials with permittivity below 7.2 are generally believed to not exhibit a full photonic bandgap[9] for two-dimensional PhCs.

Recently, exciting developments in complex photonic bands and strong anisotropic dispersion characteristics of artificially engineered periodic dielectric structures have been widely investigated[10,11,12]. A new class of PhC waveguide relying on the self-guiding effect has been proposed and demonstrated through this dispersion engineering[10,11,12]. Instead of guiding the light by defect modes, the highly anisotropic dispersion characteristics of the PhC is utilized for the self-guidance. For example, a two-dimensional (2D) cubic dielectric lattice is shown to possess a square-like iso-frequency dispersion characteristic for a range of electromagnetic frequencies. As a result, the group velocity of such an electromagnetic wave can only take place within two preferred directions thus providing a self-guiding effect. This interesting behavior can also be applied to design compact micro-lenses and prisms[10-13]. Particularly targeted applications can be achieved through some specific yet relatively direct approaches and designs.

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In this paper we propose a different approach: a hybrid structure consists of PhC and PBG configurations as linear waveguides based on the self-guiding effect. The fact that these devices rely on the shape of dispersion relationship rather than on the existence of the complete bandgap implies that it is not necessary to exclusively use high-index contrast material systems. Materials with lower refractive index (such as silica and optical polymers with refractive index n in the range of 1.5 to 1.7) can be applied as well. This could leverage a new development of integrated photonic devices into more diversified materials systems. Potentially, as an example, conventional gain-mediums such as Erbium-doped glass can even be utilized to fabrication such ultra-compact integrated photonic circuits and also to compensate for the high losses that have been commonly observed in such devices. Two types of 2D PhC systems—one with high and the other with low index contrast— are investigated in this work in terms of guiding and insertion losses. Sensitivity analysis including detailed descriptions of a developed software package reveals how structural variations influence the performance of this type of system as compared to the conventional photonic bandgap based systems.

2. SIMULATION OF HIBRID PHOTONIC CRYSTAL WAVEGUIDES

In this section, we first introduce the full photonic band diagram for square-lattice two-dimensional PhC and analyze its iso-frequency dispersion diagrams. Then, we illustrate different propagation patterns using the example of a point source radiating in the PhC. Finally, we demonstrate the concept of a new hybrid PhC structure that can guide the light without lateral spreading which is suitable for both low- and high-index contrast material systems.

Many techniques have been developed for the modeling and simulation of PhC and PBG structures[14-20]. For example, the electromagnetic propagation in perfect 3D photonic crystals has been solved with the use of the plane-wave expansion methods[14,15]. Methods such as the super cell technique[22-24], transfer matrix method[20], and generalized Rayleigh method[21] have been developed and employed for simulating disordered photonic crystals. A commercial package containing FullWAVE® based on the finite difference time domain (FDTD) technique and BandSOLVE® based on the plane-wave expansion technique from RSoft Design Group, Inc. is used for the simulations presented in this work. This technique is based on direct numerical integration in time of Maxwell's equations using the Yee mesh[21]. Perfectly matched layer (PML) boundary conditions are utilized for absorbing electromagnetic waves incident on the edges of the computation domain in space[23].

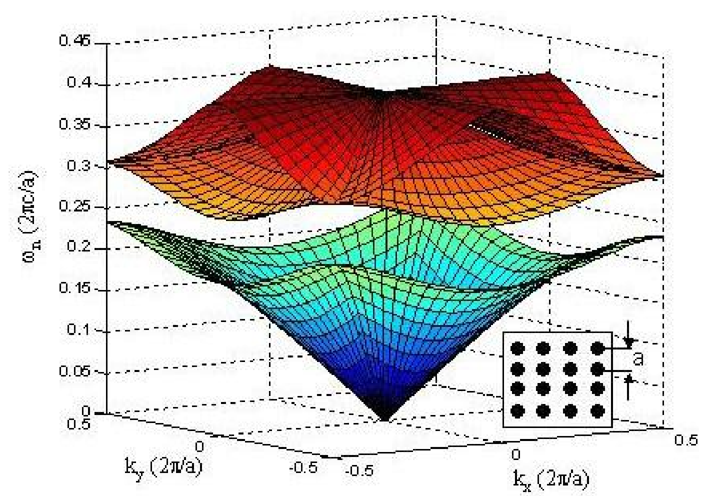


Figure 1. Three-dimensional dispersion diagram for a two-dimensional square lattice photonic crystal of air holes (n=1.0/3.4) within the first Brillouin zone; r = 0.45a.

When analyzing PhC and PBG devices, it is sufficient to plot band diagram along the high symmetry points of the crystal. However, in order to fully understand the wave propagation in PhC, one needs a full band diagram for all the k vectors within the first Brillouin zone. Figure 1 shows the three-dimensional photonic band diagram for the first three bands of a square lattice, two-dimensional PhC. It contains air holes within a slab material with an index of refraction of n=3.4 and infinite thickness, while the hole radius r = 0.45a and "a" is the lattice constant. After extracting several iso-frequency plots of the dispersion diagram at various frequencies from the second band, we are able to observe the square-like dispersion characteristics that mimic the shape of the first Brillouin zone. As shown in Figure 2, four particular iso-frequency dispersion curves within the second band at several frequencies w_n exhibit such results. Note that these dispersion relationships exhibit square-like shape often with sides that are either convex or concave. Since the group velocity vg is defined as:

$$\vec{v}_g = \nabla_k \omega \qquad (1)$$

the direction of energy propagation is normal to the dispersion curves. In the ideal case, if the dispersion diagram was exactly square in shape, the crystal at that specific frequency would only permit energy to propagate along with wave vectors k_x=0 or k_y=0, as illustrated in Figure 2. For example, radiation from a point source (an omni-directional source) within such a PhC will propagate preferably in two mutually perpendicular directions as shown in Figure 3. However, since the dispersion characteristic is not perfectly squared the beam is not completely collimated. As a result, there is a small yet notable amount of lateral leakage of radiation as shown in Figure 3.

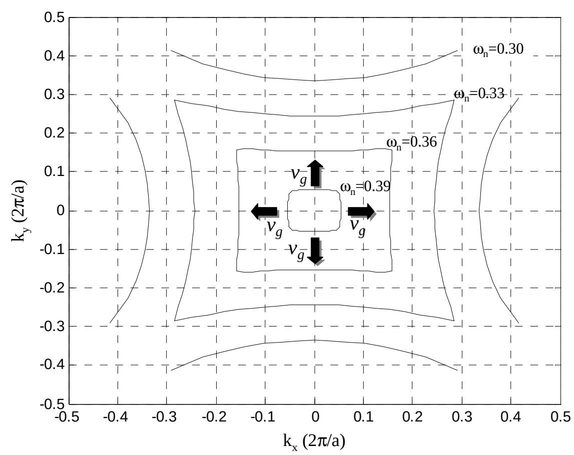


Figure. 2. Iso-frequency dispersion curves for the two-dimensional PhC from Figure 1 for different normalized angular frequencies: w_n = 0.30, 0.33, 0.36, 0.39

As the simulation of the point source in PhC highlights, a realistic dispersion relationship alone may not be capable of providing perfect lateral confinement needed for loss-less light guidance. In order to fully confine the propagating light, we propose the addition of laterally confining structures as illustrated in Figure 4 and 5. Those laterally confining structures have the same periodicity as the guiding section; however, they possess triangular symmetry that exhibits a partial (not full) photonic bandgap in the direction almost normal to the main guiding direction for both TE and TM modes. In details, the hybrid waveguide structure consists of six periods of PhC at the center section with square symmetry and additional three layers having triangular symmetry on each side for lateral radiation confinement.

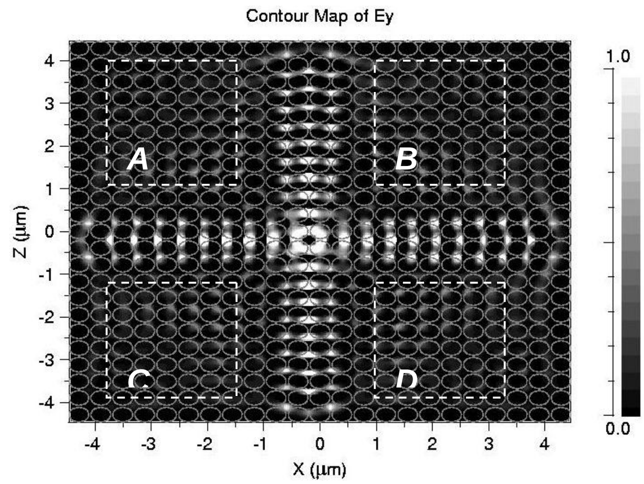


Figure 3. FDTD simulation of a point source radiating into a high-index contrast PhC, w_n = 0.39, and r = 0.45a. Small yet notable lateral leakage of radiation is seen in the region A, B, C, and D with six lattice-constants apart from each other.

A FDTD simulation result of TE modes for hybrid high-index contrast (n=1.0/3.4) PhC waveguide is given in Figure 4. In this particular structure, both guiding and confining PhC structures possess an identical r = 0.45a. The lattice constant “a” applied during this simulation is 0.38µm while the free space wavelength is normalized to 1µm. It is apparent that this structure exhibits excellent lateral radiation confinement and provides means for realizing linear waveguides without any defect mode and without a full bandgap.

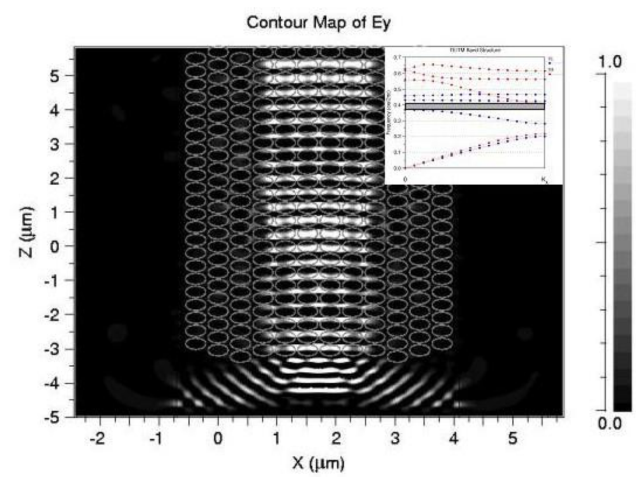


Figure 4. FDTD simulation of a high-index contrast (n=1.0/3.4) hybrid PhC waveguide is illuminated with a Gaussian beam launched from the bottom, w_n = 0.39; r = 0.45a. Insert figure shows the partial photonic bandgap along the $0 \pm k_x$ direction possessed by the additional laterally confining structure.

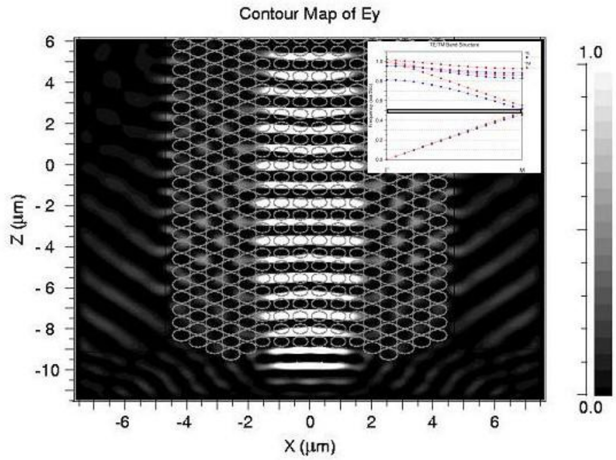


Figure 5. FDTD simulation of a low-index contrast (n=1.0/1.7) hybrid PhC waveguide is illuminated with a Gaussian beam launched from the bottom, w_n = 0.49. Insert figure shows the partial photonic bandgap along the 0±k_x direction possessed by the additional laterally confining structure.

Most importantly, the same approach can be applied to low permittivity (less than 3) materials. The FDTD simulation of TE modes for a low-index contrast (n=1.0/1.7) hybrid PhC waveguide is given in Figure 5. The radius of air holes within the guiding section is 0.4a; on the other hand, the air holes within confining sections possess a radius of 0.47a. The lattice constant "a" used during the simulation is 0.49 μm and the free space wavelength is 1mm. Even with the low-index contrast and incomplete photonic bandgap, this structure exhibits strong confinement of radiation.

Finally, a comparison of two hybrid waveguide structures for both high- (n=1.0/3.4) and low- (n=1.0/1.7) index contrast to the simple self-guiding PhC waveguides with respect to lateral power confinement is shown in Figure 6. The amount of power confined within a width of six lattice constants is measured along the wave propagation direction. While both high- and low-index self-guiding PhC waveguides show a fast energy spreading along the propagation direction, both high- and low-index hybrid PhC waveguides yield a stable energy confinement.

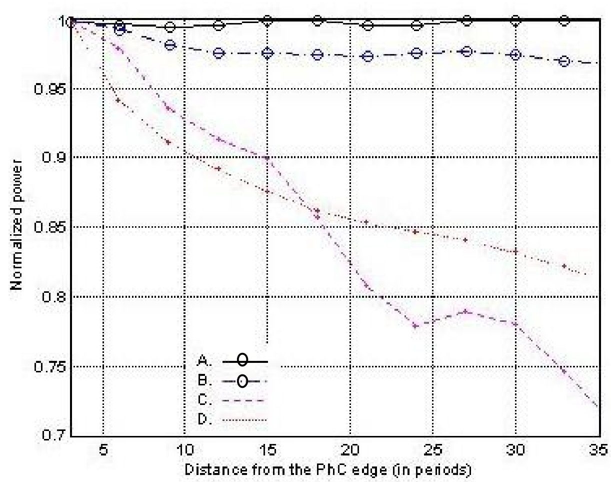


Figure 6. Total power confined within a width of six lattice constants along the propagation direction in:

A. Hybrid high-index contrast (n=1.0/3.4) PhC waveguide
B. Hybrid low-index contrast (n=1.0/1.7) PhC waveguide
C. Self-guiding PhC waveguide with high-index contrast (n=1.0/3.4)
D. Self-guiding PhC waveguide with low-index contrast (n=1.0/1.7)

3. WAVEGUIDE STRUCTURE IN THREE-DIMENTION

In the previous section, we explored the possibility of hybrid photonic crystal waveguide by using photonic band diagram and two-dimensional FDTD simulation. Even though the two-dimensional FDTD analysis is widely used for membrane-like photonic bandgap waveguides, a true three-dimensional analysis is usually necessary to ensure a well confinement of photons. For a membrane-like PhC or PBG waveguide, the in-plane confinement of photons is achieved by the dielectric structure while the out-of-plane confinement typically relies on the interface between membrane substrate and surrounding low-index cladding[2,7,8]. In other words, the in-plane k vector must lie outside of the cladding light cone to prevent vertical radiation. It leads to a condition of

$$k_n < \frac{w_n}{c} \qquad (2)$$

that has to be fully satisfied (c is the speed of light).

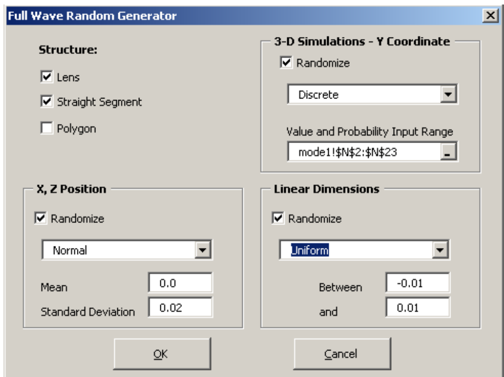
Since the hybrid PhC/PBG waveguide presented in this work in fact operates inside of the cladding light cone, an additional three-dimensional confinement of photonic is needed to realize the concept. A direct solution is to extend the same confining structures, as illustrated in Fig. 4 and 5, above and below the self-guiding waveguide core. Again, the additional confining structures can simply possess necessary partial (not full) photonic bandgaps. Other approaches including additional omni-reflectors or Bragg gratings can be considered.

4. SENSITIVITY ANALYSIS OF STRUCTURAL VARIATIONS

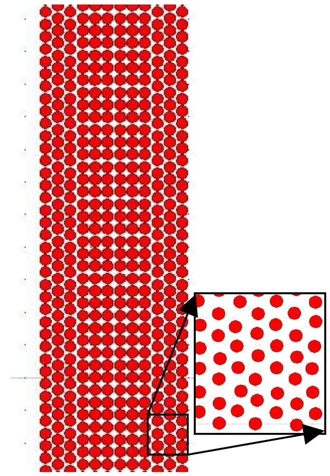
Many theoretical predictions indicate that PhC and PBG waveguides possess nearly perfect guiding efficiency; however, experimental measurements[8] show results of waveguide losses easily above several dB/mm. A possible explanation for the high losses could be the small structural deviations incorporated in the structure during the fabrication process [14-20]. Scattering loss in particular caused by such structural deviations is an important issue when considering that a propagating optical wave is in fact exercising multiple constructive and destructive interferences within the PhC/PBG structures. In this work, we attempt to analyze the effect of the structural deviations through a systematic simulation study that includes structural deviations using statistical methods. Structural waveguides fabricated using conventional lithographic systems such as a field-emission scanning electron microscope capable of an electron-beam direct write patterning typically with ~10 nm resolution are of particular interest.

In order to understand the effect of structural and positional deviations from the idealized PBG lattice described above, a special tool to extend the capabilities of the FDTD package based on the Visual Basic language and the Design for Six-Sigma (DFSS) tools by General Electric company was developed to generate the required statistical distributions. The various deviations that were studied are illustrated in Figure 7(a). Specific arrangements of the dielectric structures (i.e. PhC/PBG) with structural deviations in shape, location, and size are considered. These deviations reflect the expected tolerance of state-of-the-art sub-micron patterning systems that are commonly used to fabricate such structures. The developed tool is also capable of handling both two- and three-dimensional FDTD models. Figure 7(b) shows graphical distributions of the deviations that were incorporated into the actual CAD layout of simulation model. A normal distribution of dislocations and dis-sizing (as shown in Figure 8) is used in the simulation model as shown in Figure 4 and 5. This 10 nm mean for the distribution is chosen from the resolution of e-beam mask sets and/or direct write e-beam systems.

Figure 8 shows an example of the distributions of structural variation in both location and size embedded in the simulation models. The standard deviations of such distributions are both 10 nm. For any of the dimensional variations (i.e. a combination of dislocation and dis-sizing), five separate simulations are completed for comparison.



(a)



(b)

Figure 7. (a) A developed Visual Basic macro linking GE's DFSS tools for FDTD modeling. (b) An example of structural deviations with both dislocation and dis-sizing. Inserted picture shows a magnified portion of the models, and the structural variation has been exaggerated.

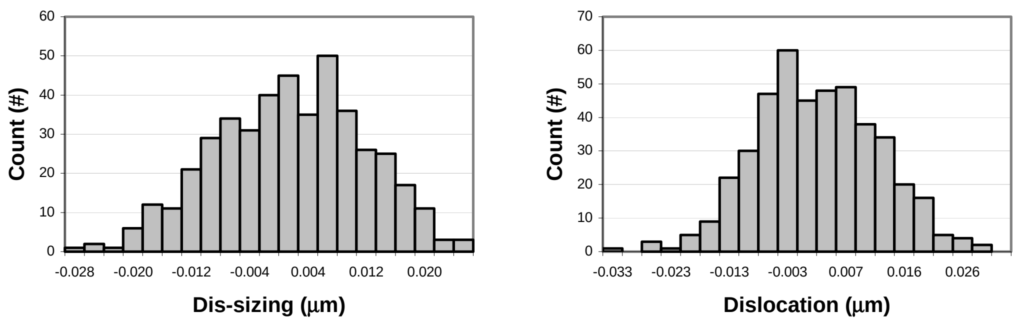


Figure 8. Examples of statistical summary of structural deviations, plots show the distributions of dislocation and dis-sizing implanted into the FDTD model. The standard deviations are both 10 nm.

After applying the structural deviations into the simulation model based on low permittivity materials, a small yet notable reduction, 2-6% in average from the efficiencies possessed the perfect hybrid PhC/PBG waveguides, of normalized transmission efficiency has been observed, as shown in Figure 9. This insensitivity of structural variation is due to the application of partial photonic bandgap and low index contrast. From a physical standpoint, structural deviations in a PBG device break any kind of discrete translational or rotational symmetry present in the area adjacent to the waveguide, resulting in a "spread out" of the values of the lattice constant throughout the sample. This translates into the slight shrinkage or deformation of any band gap present in the structure that would allow a loss less propagation of a mode through the waveguide. In other words, the effect of structural deviations on those laterally confining structures is limited. Similar condition can also be applied for the photonic crystals structure (i.e. the self-guiding core). In addition, according to our observation, the low index contact (n=1.0/1.7) throughout the structure in fact helps to regulate any additional losses from scattering and back reflection.

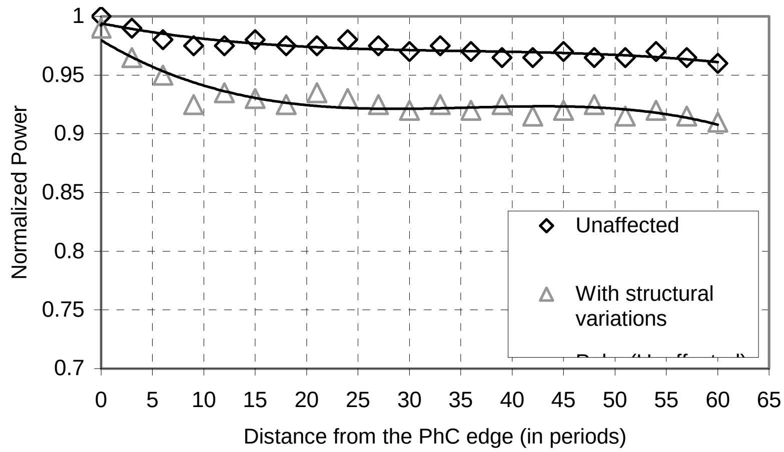


Figure 9. A comparison of hybrid PhC/PBG waveguide (a) without and (b) with structural variations, where the standard deviation of normal-distributed structural variations is 10 nm

5. CONCLUSION

In conclusion, we have shown that linear waveguides can be realized in PhC without a complete photonic bandgap or any defect or resonate mode. We explored and analyzed a self-guiding hybrid PhC/PBG structure and compared the losses in terms of lateral beam confinement. Furthermore, we have shown that the low-index contrast material can be used to design effective PhC waveguides. This opens up the opportunity for designing PhC waveguides using low-index materials (with permittivity below 3) and leverages the development of integrated photonic devices into more materials systems that have not been considered. However, in order to fully confine the propagation of photons, additional designs to completely eliminate radiation leakages will be necessary. Our simulation results also indicate that small structural deviations arising from real fabrication processes do not significantly impact the efficiency of PBG waveguides. The application of partial photonic bandgap and low index contrast maintains the robustness of the structure against structural variations potentially raised during manufacturing.

5. ACKNOLOGMENTS

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