Photonic-crystal Lens Coupler Using Negative Refraction

Pi-Gang Luan and Kao-Der Chang
Wave Engineering Laboratory, Department of Optics and Photonics
National Central University, Chungli 320, Taiwan

Abstract—A novel photonic crystal lens working in the negative refraction frequency region that can focus a beam of light into a wavelength-sized spot is proposed. The device is formed by drilling air holes of triangular lattice in a portion of a dielectric slab, and the whole structure is designed appropriately such that it can be easily fabricated using today’s technology. The finite-difference time-domain simulations confirm that the focusing effect is mainly due to the negative refraction in the photonic crystal region, and the focused light can be efficiently coupled into a dielectric waveguide.

DOI: 10.2529/PIERS060905234755

1. INTRODUCTION
Photonic crystals (PC) are artificial periodic dielectric structures made for controlling light [1, 2]. The propagating mode of the electromagnetic (EM) wave in a photonic crystal is the Bloch wave [3], and its dispersion relation is the photonic band structure, containing passbands and bandgaps—the frequency ranges forbidding the propagation of light. Up to now, most applications of the PCs rely on the presence of the bandgaps, and various devices have been designed for reflecting, trapping, and guiding light [4, 5]. Beyond the bandgaps, the photonic passbands are also useful [6]. When operating in the linear region well below the first gap, a PC plays the role of an effective homogeneous medium, and lens-like devices can be constructed from it [7]. However, since such devices must be working at the long-wavelength limit (there the lattice constant is much smaller than the wavelength), it is difficult to fabricate them for applications in optical or telecommunication regime.

Recently, the interesting phenomenon of negative refraction (NR) has received much attention [8–21]. A block of negative refraction medium (NRM) has many fascinating properties. For example, a slab of NRM is a “superlens”, which can focus the light emitted from a point source into a subwavelength spot, overcoming the diffraction limit [9, 12, 14–18]. Also, a concave lens made of NRM can focus a beam of light into a sharp image spot [19, 20]. In fact, an NRM can be realized by PC under certain conditions. When an EM wave is injected into a PC from a homogeneous medium, the energy flow and phase propagation directions of the transmitted EM wave are determined by the phase matching condition on the interface together with the equifrequency surfaces (EFS) of the two media [11, 12]. According to this theory, a photon in PC sometimes acquires a negative effective mass, and then the PC becomes an effective NRM [11–13]. More importantly, it has been found that the NR of PC can appear in high frequency bands [11, 13, 16–18]. This fact implies that it is more practical to design devices operating in the NR regime than operating in the long-wavelength regime [21].

In practice, an useful integrated-optical system must have large enough coupling efficiency between different parts of the system. One important step towards this goal is to reduce the insertion loss for the light launched from air and injected into a conventional (dielectric) waveguide (CW) or a photonic crystal waveguide (PCW). Usually the width of the waveguide can be made as small as one wavelength, whereas the incident light has a much larger beam waist. Therefore, a device to focus the incident light before sending it into the waveguides is needed. Since it is difficult to reduce the spot size of the focused light dramatically using conventional methods, we try to use the NR effect of the PC to overcome this problem.

In this letter, we demonstrate numerically that by using a PC lens device working in the NR regime, focusing a beam of light into a wavelength-sized spot is possible. We also show that the focused light can be efficiently coupled into a CW if its width is about the same size as the spot. The shape and the inner structure of the device is appropriately designed so that it can be easily fabricated using today’s technology even for using in the optical regime. Besides, to evaluate the size of the focus spot, we propose a method based on the calculation of root-mean-square (RMS) of the field distribution, which gives us more definite results than using other methods.
2. STRUCTURE DESCRIPTION AND SIMULATION RESULTS

The two-dimensional (2D) PC being considered here is a triangular lattice of air holes in a dielectric slab with dielectric constant \( \varepsilon = 12.96 \) (e.g., GaAs). The hole radius is \( r = 0.4a \), here \( a \) is the lattice constant. The photonic band structure is calculated using the plane wave expansion method [2] for the transverse magnetic (TM) modes (the electric fields are parallel to the axis of the holes). In the calculation, 961 plane waves were used, and the result is shown in Fig. 1. It is observed that, in the second band, the \( \Gamma \) point is a local maximum of the band structure curve. According to Notomi’s theory [11], around that point in the \( k \)-space there is a frequency range the PC has NR property. In the following simulations, the frequency of the incident light will be taken as \( f = 0.3c/a \), here \( c \) is the speed of light in vacuum.

![Figure 1: Band structure of the TM (E-polarization) modes of the PC. The radius of the air holes is \( r = 0.4a \) and the dielectric constant of the background material is \( \varepsilon = 12.96 \).](image1)

![Figure 2: The shape and structure of the PC lens. The two periods of the terraced structure are \( L_1 = 3a \) and \( L_2 = 4a \), respectively. The size of the lens is \( 38a \times \sqrt{3}a \).](image2)

The structure of the device is shown in Fig. 2. The transverse and longitudinal dimensions of the PC slab are \( 38a \) and \( 5\sqrt{3}a \), respectively. The “hole region” and the remaining homogeneous dielectric region are separated by a terraced V-shaped interface, with periods \( L_1 = 3a \) and \( L_2 = 4a \) along two symmetry directions of the lattice periodicity. The reason for choosing such an interface is because it is easier to align the holes along the symmetry directions of the lattice than to arrange them along an smooth curve [19]. Besides, for the utility in the integrated-optical system, the “hole in dielectric” system is more practical than the “dielectric rods in air” system. If this lens is used for focusing the light of wavelength 1550 nm, the corresponding lattice constant \( a \) would be 465 nm, and the diameter of the air holes is \( 2r = 372 \) nm, quite easy to fabricate using today’s technology.

The optical behavior of the device can be simulated using the 2D finite-difference time-domain (FDTD) method [22]. The absorbing boundary conditions are the perfectly matched layers [23]. The lattice plane of the PC is taken to be the XZ plane, and the \( Z \)-axis is the propagation direction of the incident light beam. The source \( \mathbf{E} \) field is assumed to be a \( y \)-polarized EM wave \( (\mathbf{E} = E\hat{y}) \) with a Gaussian type modulus along the transverse direction, given by

\[
E(\omega, r) = E_0 \exp \left[ -\frac{(r - r_0)^2}{W^2} \right] \exp(-j\omega t),
\]

where \( r \) is the transverse position, \( r_0 \) is the reference center for the source field, and \( W \) is the waist of the beam. Throughout the paper, we assume that \( W \) is always greater than \( 3\lambda \), here \( \lambda \) is the wavelength.

In the following simulations, the light beam is incident onto the PC lens from below. After passing through it the light propagates in the air and then converges at the focal point. To evaluate the spot size of the image and locate the position of the focal point, we define the RMS width of the field distribution (at \( z \)) as

\[
\Delta_{\text{RMS}}(z) = \sqrt{\frac{\sum_r |E(r, z)|^2 r^2}{\sum_r |E(r, z)|^2}}
\]

Here, \( r \) is the transverse position, \( r_0 \) is the reference center for the source field, and \( W \) is the waist of the beam. Throughout the paper, we assume that \( W \) is always greater than \( 3\lambda \), here \( \lambda \) is the wavelength.

In the following simulations, the light beam is incident onto the PC lens from below. After passing through it the light propagates in the air and then converges at the focal point. To evaluate the spot size of the image and locate the position of the focal point, we define the RMS width of the field distribution (at \( z \)) as

\[
\Delta_{\text{RMS}}(z) = \sqrt{\frac{\sum_r |E(r, z)|^2 r^2}{\sum_r |E(r, z)|^2}}
\]
where $r$ is the transverse spatial distance from the distribution center, and $E(r, z)$ is the amplitude of the E field evaluated at $(r, z)$. The $\Delta_{\text{RMS}}(z)$ for incident beams of different waists ($W = 3\lambda, 6\lambda, 9\lambda, 15\lambda$) are shown in Fig. 3. For each case, the location of the focal point is indicated by the $z$ value that corresponds to the smallest $\Delta_{\text{RMS}}$, say, $z_0$, and the spot size is given by $2\Delta_{\text{RMS}}(z_0)$. From these results we find that the spot size is about one wavelength, and the focal point is located at about $z_0 = 7.56\lambda$.

Figure 3: The “root-mean-square” (RMS) widths of the transverse distribution of the E field, evaluated for incident beams of different waists, $W$ is the waist width. The spot sizes are around one wavelength, and the focal lengths are almost the same in all the cases. The dash line indicates the position of the output interface, whereas the dotted dash line shows the location of the focal plane.

We also compare the result to that obtained by the “maximum to the first minimum” (MTFM) method, as shown in Fig. 4. In the MTFM method, we define the focal point as the location of the peak of the EM field modulus, and the half width of the image as the distance from the peak to the first minimum along the transverse direction. In Fig. 4, the range of the beam waist $W$ is chosen between $3\lambda$ and $20\lambda$. In this range we find that: first, the RMS method always gives us a beam width larger than that obtained by using the MTFM method; and second, when $4\lambda < W < 9\lambda$, the focal distance obtained by the RMS method is a little smaller than that by the MTFM method. These results seem to imply that the meaning of “subwavelength imaging” or “subwavelength focusing” is a little ambiguous. To avoid the ambiguity, a clear definition about the image size like ours is needed.

Figure 4: The spot size and the focal distance obtained by using the RMS and MTFM methods. The dash line indicates the half wavelength.

Figure 5 illustrates the modulus of the resulting $E$ field for two different situations. In Fig. 5(a),
a typical simulation \(W_\text{in} = 6\lambda\) of the focusing phenomenon is shown. The light emerging from the output side of the PC lens travels in the air and converges into a focus point, forming an elliptical image. The focusing ability of the PC lens is obvious. However, in order to examine if this focusing effect is indeed caused by the NR effect in the PC area, we do the following test. We replace the “hole region” of the PC lens with a naively averaged medium and then re-simulate the focusing ability of this modified lens. The filling fraction of the PC in the hole region is 
\[f = \frac{2\pi r^2}{\sqrt{3}}a^2 = 0.5804,\]
so we have the averaged dielectric constant \(\bar{\epsilon} = f + 12.96(1 - f) = 6.0182\), or the averaged refraction index \(\bar{n} = \sqrt{\bar{\epsilon}} = 2.4532\). The result of the test is shown in Fig. 5(b). As one can see, the original image disappears, although a much weaker new image near the slab edge has been created. This result seems to imply that both the NR effect in the PC area and the discrete nature of the boundary of the hole region (there the holes are arranged to form a grating-like structure) are important for the formation of the wavelength-sized spot in the far-field region.

Figure 5: The intensity of the E-field in two different situations. The beam waist is 6\(\lambda\). (a) The incident beam is focused by the PC lens. A wavelength-sized spot can be easily observed. (b) When the “hole region” in the PC lens is replaced by a naively averaged medium, the spot disappears.

The PC lens can also be used as an optical coupler. To examine this statement, we add a CW into the original setup, and then recompute the E field. The result is shown in Fig. 6(a). The material of the CW has a dielectric constant \(\epsilon = 12.96\), which is the same as the slab. The width of the waveguide is 3\(a\), about one wavelength. We choose the input edge of the waveguide to be located at the same position of the focal point, \(i.e., \ 7.56\lambda\) from the output-side edge of the dielectric slab. For comparison, we also plot the field modulus in Fig. 6(b) for the situation that there is no
PC lens between the light source and the waveguide. The simulation result clearly indicates that the light power can be efficiently coupled into the waveguide.

3. CONCLUSION

In conclusion, we have proposed a novel optical component that can focus a beam of light into a small spot of wavelength-sized width. The device is a PC lens working in the NR frequency range, formed by drilling air holes of triangular lattice in a portion of a rectangular dielectric slab background. The “hole region” and the remaining homogeneous dielectric region are separated by a terraced V-curve shaped interface. This structure can be easily fabricated. Based on the band structure calculation of the PC and the FDTD simulations on the system, the optical behavior of the device can be predicted. The spot sizes for incident beams of different waists, evaluated by using the root-mean-square (RMS) method, are all about one wavelength. The image spot vanishes when the hole-region is replaced by an averaged homogeneous medium. This fact indicates that the focusing effect is mainly due to the NR in the PC area. Our simulations also confirm that the device can transmit the focused light efficiently into a dielectric waveguide, thus can be used as an optical coupler.

ACKNOWLEDGMENT

The authors are grateful to financial support from National Science Council (Grant No. NSC95-2221-E-008-114-MY3) and Ministry of Economic Affairs (Grant No. 95-EC-17-A-08-S1-0006) of Taiwan.

REFERENCES