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The focusing effect of graded index photonic crystals

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We describe an approach to implement graded index (GRIN) structures using two-dimensional photonic crystals (PCs). The lattice spacing along the transverse direction to propagation is altered and we show, both theoretically and experimentally, that such a spatial perturbation is an effective way to obtain GRIN PC. The response of the structure to spatially wide incident beams is investigated and strong focusing behavior is observed. The large spot size conversion ratio can be attainable and is mainly limited by the finite size of the structure. The designed GRIN PC shows promise for use in optical systems that require compact and powerful focusing elements compared to the traditional bulky lenses. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3009965]

The photonic crystals (PCs) are multidimensional periodic dielectric structures with their spatial periodicity at the same length scale as the subwavelength of light. If the operating frequency of the incident light is within the prohibited frequency region, called the photonic band gap, then PC may act as a mirror reflecting the entire incoming wave.[1] The periodic nature of the crystal along with the high-index contrast dielectric materials governs some of the remarkable properties of PCs, such as self-collimation and superprism.[2–6] The pure periodicity of PCs can be broken by introducing spatial perturbations in terms of point- or line-type defects. As a result, artificially created modes can be localized in a small area or guided through waveguides with sharp bends.[7–12]

In addition to guiding and confining the light, focusing it to a small spot size is an imperative procedure in photonics. The bulky lenses with curved surfaces have to be replaced with more compact ones. PCs also possess potential for this kind of application. Plano-concave lenses that are obtained with PCs that have a negative effective index and left-handed electromagnetic properties have been proposed to focus the light.[13–18] There have been various other studies addressing the different applications of PCs that certain types of structural modifications are introduced. The self-collimation, focusing, mirage, and superbending effects were explored previously with the graded PCs.[19–22] The beaming effect from a corrugated concave surface of PCs was studied in Ref. 23, in which the pattern of the emitted beam demonstrated the focusing effect. In the present study, we consider index based confinement using a graded index (GRIN) PC by modulating the lattice spacing of the crystal. The average index amount (the dielectric filling factor) is larger at the center of the PC than that at the sides, in which the incident wave with a planar wave front converges toward the central region. The surfaces of the GRIN PC are flat and the complete structure is very compact. We theoretically show, and experimentally prove, that only a few columns of PCs are capable of strongly focusing spatially wide beams to a narrow area. The appeal of GRIN PC encourages us by using it as an interface device that can act as a coupler by enhancing the coupling efficiency of wide input beams to narrow PC waveguides. However, this aspect of the GRIN PC will be pursued in another study.

There can be other ways of achieving GRIN variation rather than modulating the lattice spacing. The radii of the rods or the refractive index of the dielectric rod are the parameters to be engineered in order to have an index gradient along certain directions. The changes in the rod radii require precise and small increments. Furthermore, it limits the range of the index gradient that can be achieved. Similarly, the index changes of the rods require different materials to be used. As a result, when a comparison is made among the choices, we can state that the selected method that uses the lattice spacing seems to be more practical than the others. Therefore, in the present study we modulate the lattice spacing in order to implement GRIN PC.

The advances in fabrication technology allow for the fabrication of them in the optical frequency regime. At the same time, the scalability of Maxwell's equations makes it possible to scale the wavelength to any spectral region. Since targeting the microwave frequencies lifts some of the technological and practical burdens, the experimental work is performed at the microwave regime.

The structure under study is composed of aluminum dielectric rods in an air background. The refractive index is taken to be $n=3.13$ and the radius of the rod is $r=0.22a$, where a is the lattice constant. The unmodified PC structure has a square-lattice crystal but the lattice spacing along the y-direction is altered. The GRIN PC geometry under study is shown in Fig. 1(a). It is a two-dimensional PC, in which the polarization is taken to be TM (electric field is along the rod axis). The TE polarization is not considered in the study. The lattice spacing along the y-direction is changed, in turn keeping the spacing in the x-direction constant at a. Half of the GRIN PC that is surrounded by the dashed lines in Fig. 1(a) is enlarged and is shown in Fig. 1(b). The other half of the GRIN PC is the exact replica of this enlarged portion. The spatial increment $(\Delta y_{i+1}-\Delta y_i)$ occurs at every row of the dielectric rods, where the subscript i takes the values from 0 to 6. The distances between each set of rows are labeled as $2\Delta y_i$. The rows closest to the central part have $2\Delta y_0$

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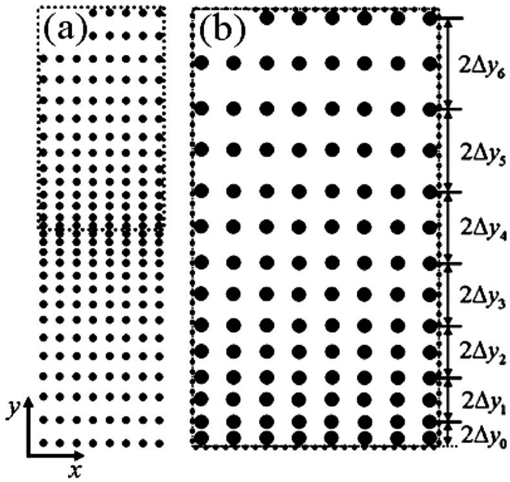

FIG. 1. (a) The schematic representation of the GRIN PCs. The lattice spacing is increased along the y-direction and is kept constant at a along the x-direction. The distances between each set of rows are labeled as $2\Delta y_i$, where the subscript i takes the values from 0 to 6. (b) Half of the structure surrounded by the rectangular area with the dashed line is enlarged at the right-hand side in the figure.

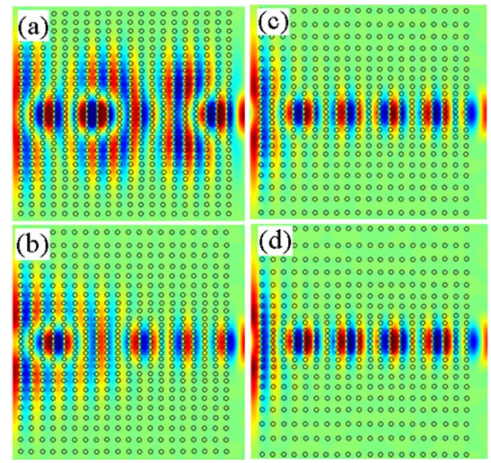

FIG. 2. (Color online) The electric field pattern of the incident Gaussian beam at the center frequency of $a/\lambda=0.38$ for four cases of increments. $\Delta y_{i+1}-\Delta y_i=0.05a$ for (a) and it is $0.10a$, $0.15a$, and $0.20a$ for (b), (c), and (d), respectively.

$=0.75a$ and the incremental step is taken to be $0.15a$. This means that $2\Delta y_1=1.3a$, $2\Delta y_2=1.6a$, etc. The reason behind this selection will be explained later. The width of the GRIN PC is $26.54a$ and the length of it is varied in order to study the focusing mechanism with respect to the column numbers. In the figure, there are $N=8$ columns that make the length become $(N-1)a$.

The finite-difference time-domain (FDTD) method is carried out to observe the field propagation throughout the computational domain, which is terminated by the perfectly matched layer absorbing boundary condition.[24] The input source is a spatially broad modulated Gaussian pulse with a center frequency at $a/\lambda=0.38$. This center frequency is within the waveguide modes of a regular PC waveguide (PCW) that is obtained by removing one row of rods. In the present study, only a GRIN PC structure is investigated, but the integration of GRIN PC with PCWs will be studied in another work.

In order to decide the value of the incremental step value, four cases ($0.05a$, $0.10a$, $0.15a$, and $0.20a$) are selected and a comparison is made among them. Figure 2 shows the steady-state electric field map of these cases when a spatially broad Gaussian pulse is sent to different GRIN PC. As we can see in Figs. 2(a) and 2(b), small increments of $0.05a$ and $0.10a$ have less focusing power. As a result, the beam is partly focused. When we increase the increment step from $0.10a$ to $0.150a$, the field becomes strongly focused at the focal point and the beam pattern shows small and periodic oscillations. There is not much change in the field's focusing behavior if the increment step is increased from $0.15a$ to $0.20a$. As a result, $2(\Delta y_{i+1}-\Delta y_i)=2(0.15)a$ is selected by considering the need to have a compact structure.

The focusing behavior of the designed GRIN PC with respect to the number of columns N is studied next. In this part, the number of the columns is increased and the nature of the spatially broad incident beam is analyzed. The full width at half maximum (FWHM) value of the beam at the focal point of the GRIN PC is recorded. The incident beam has a FWHM value of $10.8a$. We can clearly see in Fig. 3(a) that one layer hardly shows the respective focusing behavior. As the layer number increases to 2, the focusing effect of GRIN PC becomes more apparent. The FWHM values show little change after the layer number exceeds 3. The decrement in the FWHM value means that the maximum peak of the field at the focal point increases and is also a measure of the focusing power. From the figure, we can claim that one may not need a very large PC structure in order to focus a wide beam to a small area. The power of the focusing behavior can be quantified by looking at the spot size conversion ratio, which is around 8.4. By sending even spatially broader pulses to GRIN PC in turn produces tightly focused beams. As a result, the spot size conversion ratio increases. We should note here that the finite size of the GRIN PC along the y-direction restricts the sending of spatially very wide pulses. The photonic devices that produce a small spot size ratio play a crucial role, especially for interconnect devices. Figure 3(b) shows the amplitude profile of the beam for three cases. The broadest profile with the blue line represents the input pulse without GRIN PC. The green and red lines indicate the beam profiles at the exit side of the GRIN PC with $N=4$ and $N=6$, respectively. The strong focusing effect and small changes in the FWHM values of the beams after focusing occurs can be observed from the figure.

The magnitude of the steady-state electric field of the GRIN PC structure with four columns is monitored with the FDTD method. The result is shown in Fig. 4(a). The spatially wide input beam can be seen at the input side of the GRIN PC. The input beam reduces its spatial width considerably after traveling through a few columns of the dielectric rods and focuses to the central part of the structure. It remains confined within this central area. The experimental characterization of the designed GRIN PC, which is composed of aluminum rods with $a=7$ mm, is performed at 18 GHz by using a network analyzer as well as horn and monopole antennas. The horn antenna illuminates the structure at a distance of 70 mm and one monopole antenna at the output of the GRIN PC is used to capture the field scanning area. Figure 4(b) shows the measured intensity distribution at the exit side of the GRIN PC. The intensity is confined spatially to a narrow region. The measurement is in good agreement with the FDTD calculation. The cross sectional profiles of the

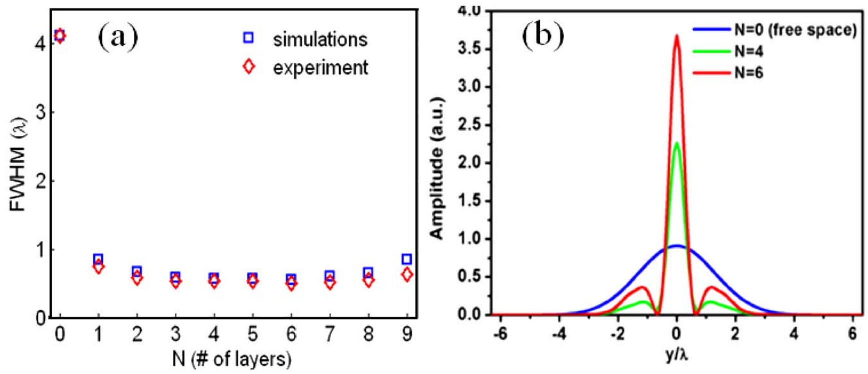

FIG. 3. (Color online) (a) The FWHM values for different numbers of GRIN layers. Simulation and experimental results are shown by square and diamond shapes, respectively. (b) Field profiles at the output side of the GRIN structure for $N=4$ layers (green line) and $N=6$ layers (red line). The free space profile (blue line) has also been added for comparison.

E-fields at the focal point, 0.6 mm away from the PC surface, is also presented on the right-hand sides in the figure.

A flat surface GRIN PC lens is obtained by modulating the lattice spacing of the PC. The curved surfaces of the conventional convex lenses behave in a similar way but their size is bulky and smooth curved surfaces are required, which places stringent requirements on the fabrication procedure. Our approach is free from curved surfaces, the structure is compact, and it can be integrated easily with other photonic devices. Due to the high-index contrast between the dielectric rods and the air background, the index gradient that is obtained by modulating the lattice spacing is also quite large compared to the traditional approaches. The presented results prove the importance of the engineering of the individual constituents of the PCs.

In conclusion, we performed the lattice space modulation of PCs in order to obtain GRIN structures. The focusing behavior of the designed device was analyzed, both theoretically and experimentally, and indicated that a small number of columns are sufficient to focus a spatially wide beam to a narrow region. The theoretical result obtained with the FDTD method agrees well with the result of the experiment that was performed at the microwave region. We have proven that structural modification in PCs yields important features to manipulate the spatial profile of spatially wide incident beams.

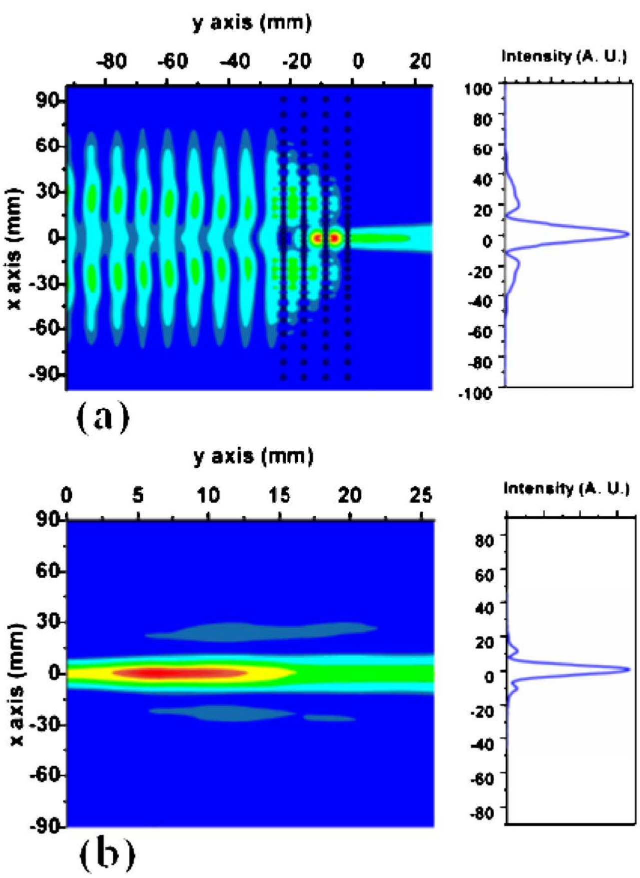

FIG. 4. (Color online) The focusing effect of the GRIN structure illuminated with a wide incident Gaussian beam at 18 GHz. (a) The electric field pattern obtained with FDTD for $N=4$ layers. The cross section profile of the *E*-field at the focal point, 0.6 mm away from the PC surface, is also presented on the right-hand side. (b) The electric field pattern obtained experimentally by scanning the output side of the PC utilizing a monopole antenna. The cross section at the focal point is again given for convenience.

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