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Negative Refraction and Focusing of Photonic Crystals with Graded Negative Index in Visible Regime

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Abstract In this paper, we designed a hexagonal lattice photonic crystal (PC) which presents negative refraction behavior in the broadband visible region. By varying the PC parameters, a graded index PC was obtained for the purpose of focusing a plane wave with large transmission. Finite-difference and time-domain algorithm-based numerical calculation was adopted to demonstrate the negative refraction and analyze the focusing effect. Calculation results demonstrate that the designed PCs have good focusing property together with large transmission. The proposed structures provide an approach for designing the negative refraction-based imaging systems.

Keywords Photonic crystals · Negative refraction · Focusing · FDTD

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Introduction

Recently, negative index materials (NIMs) attracted great interest and became the topic of extensive worldwide research because it can enable many unusual optical phenomena [1–3]. The concept of NIMs was firstly proposed by Veselago in 1968. He predicted many unusual properties of a "hypothetical" isotropic medium with simultaneously negative electrical permittivity (ε) and magnetic permeability (μ) [4]. His idea remained completely hypothetical until Smith et al. presented an evidence for a composite medium displaying negative values of ε and μ in 2000 [1, 5]. One of the most exciting applications of the negative index materials is the possibility of imaging with sub-wavelength resolution, which is often called superlensing [2, 3].

Negative refraction and negative index imaging are also possible in the photonic crystals whose optical index is periodic on the scale of the incident wavelength. A PC can behave like a material with a negative refractive index within some spectral regions due to its photonic band structure. This feature was exploited for designing and fabricating PC-based superlenses. Both negative refraction and superlensing were demonstrated in PCs [6–8]. A graded index PC can be used to focus a plane wave. Graded index PCs can be obtained by gradually modifying the PC parameters. Recently, flat lenses were designed by use of graded index PCs, and their focusing properties have been studied. The flat lenses gave rise to new prospects for developing negative refraction-based imaging systems [9–12].

It is well-known that negative refraction in the microwave region was reported firstly. However, considering the fabrication and observation challenges, some of the corresponding results have not been realized in the optical regime. Berrier et al. [13] and Zhaolin Lu [14] experimentally demonstrated negative refraction in the near-infrared frequency region. To our knowledge, no PC structure-based negative refraction in the visible region of the EM spectra has been reported at present. In this paper, we designed a hexagonal lattice PC which presents negative refraction behavior in the visible region. Computational numerical simulation was carried out for the purpose of demonstrating this phenomenon. Furthermore, by varying the PC's parameters, a PC with graded index was obtained and used to focus the plane wave. The designed PC has good focusing property and high transmission. The negative index graded PC provides an approach to design a negative index imaging system and may find potential applications in future optoelectronic systems.

PC Structure Description and Calculation Setup

In order to realize negative refraction in the visible region, we constructed a 2D hexagonal lattice PC which is constituted by a dielectric medium with circular air holes. The refractive index of the dielectric medium was set to be 4, which approximately corresponds to the refractive index of silicon in the visible region. The lattice constant (a) and the air-hole radius (r) were empirically set to be 150 and 50 nm, respectively. There are 19 and eight layers of the air holes distributed along the transverse direction (y) and the axis (x) of the PC, respectively. The PC schematic diagram is shown on the right side of Fig. 1. The designed dimension is 1.17×3 μm. A commercial professional software (FDTD Solution from Lumerical Inc., Canada; http://www.lumerical.com) was employed to study the transmission and focusing properties of the designed PC. The designed PC is surrounded by air, and a transverse magnetic (TM) polarized electric dipole (acts as a point source here) is placed at 500 nm in front of the PC on its axis. The perfectly matched layer boundary condition is used, and the broadband wavelength (λ) of the electric dipole varies from 400 to 900 nm.

Results and Discussions

The calculated transmission versus wavelength was plotted in Fig. 1. It can be seen that the transmission generally increases with larger wavelength. The largest transmission is 0.35 at λ=798.7 nm. There are eight major peaks from which their transmission are larger than 0.1, as illustrated in Fig. 1, and the corresponding wavelength is noted in this figure. The wavelength of the electric dipole was set to be the wavelength of the eight transmission peaks shown in Fig. 1 separately. Thus, the corresponding eight focusing images were obtained after calculation, as shown in Fig. 2. Light originated from a point source is diverging in free space. But in our simulation, when light originated from an electric dipole passes the PC, a single spot appears behind the PC for the cases of λ=571.5, 602.7, 639.6, and 680.8 nm. This phenomenon is caused by negative refraction of the designed PCs and not observed in a flat positive index material. For other wavelengths, two or more spots appear behind the PCs. A finite-difference and time-domain (FDTD) algorithm was employed here to calculate the band structure of the designed hexagonal lattice PC working in the TM mode. The first three bands are shown in Fig. 3 (solid red line). Eight horizontal dot-dash lines in Fig. 3 correspond to the wavelengths of the eight transmission peaks, respectively.

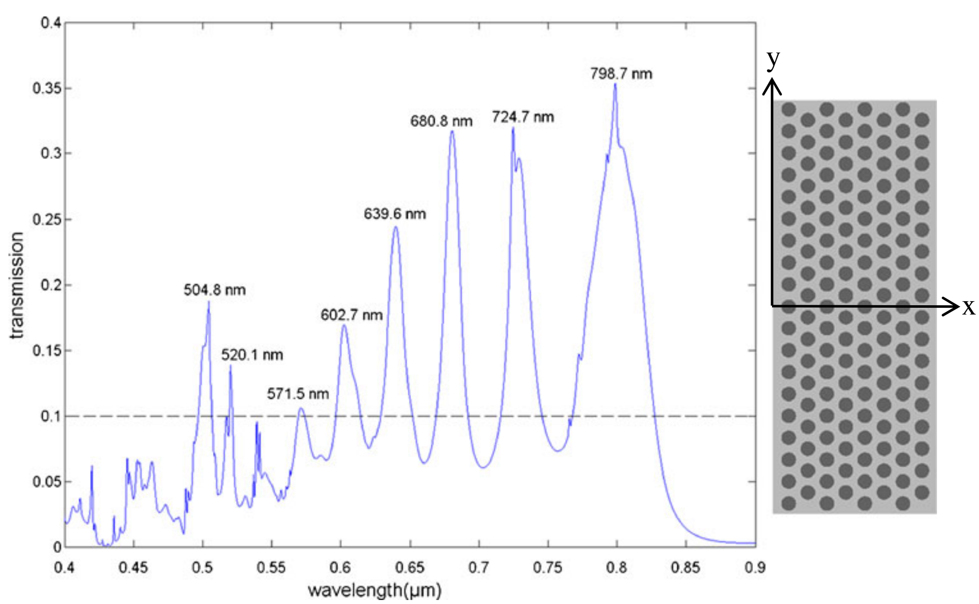

Fig. 1 Point source transmission spectrum for the designed PC; the PC schematic diagram is shown on the *right side*

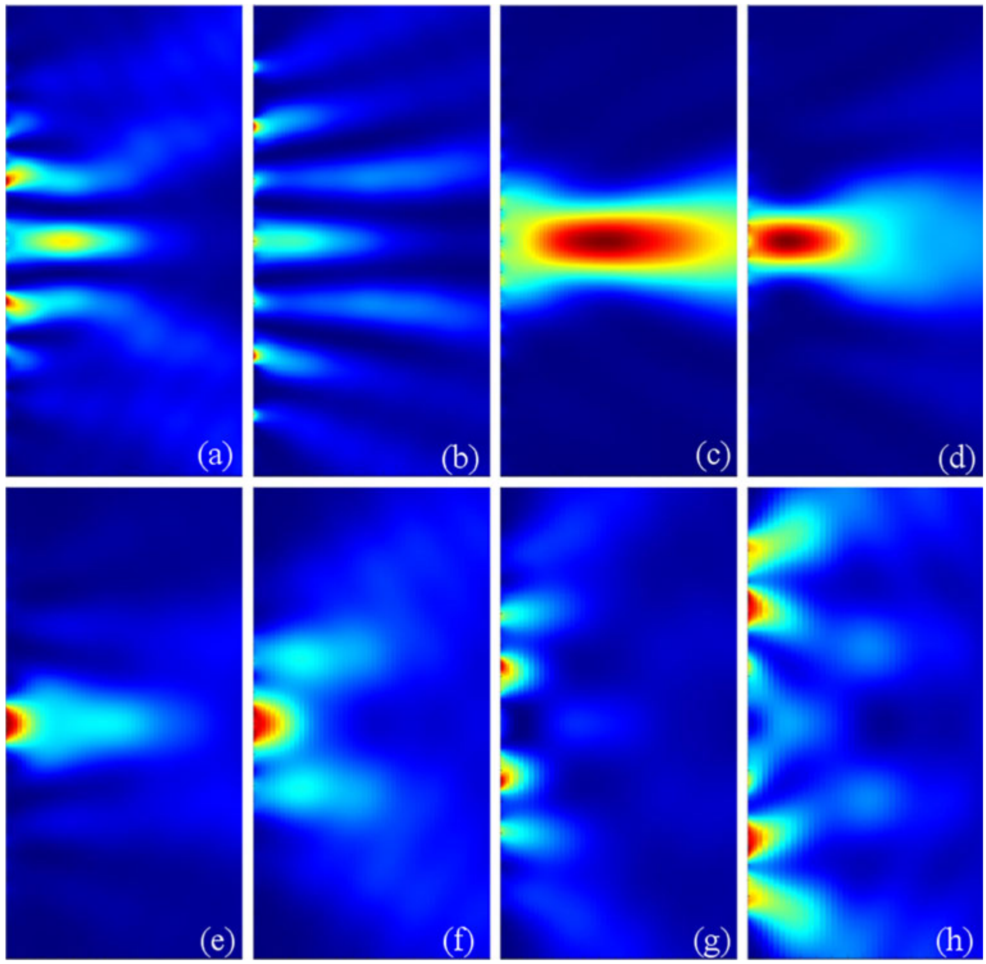

Fig. 2 Simulated electric intensity distribution behind the PC, the calculated size for each image is 1.5×3 μm. The corresponding wavelength are **a**504.8 nm, **b**520.1 nm, **c**571.5 nm, **d** 602.7 nm, **e** 639.6 nm, **f** 680.8 nm, **g** 724.7 nm, and **h** 798.7 nm

In the center area of the second band (λ=571.5, 602.7, 639.6, and 680.8 nm), a point source in front of the PC will produce a point image behind the PC (as shown in Fig. 2). This negative refraction behavior is caused by the negative slope of the second photonic band. The group velocity of the light propagation inside the PC is perpendicular to the

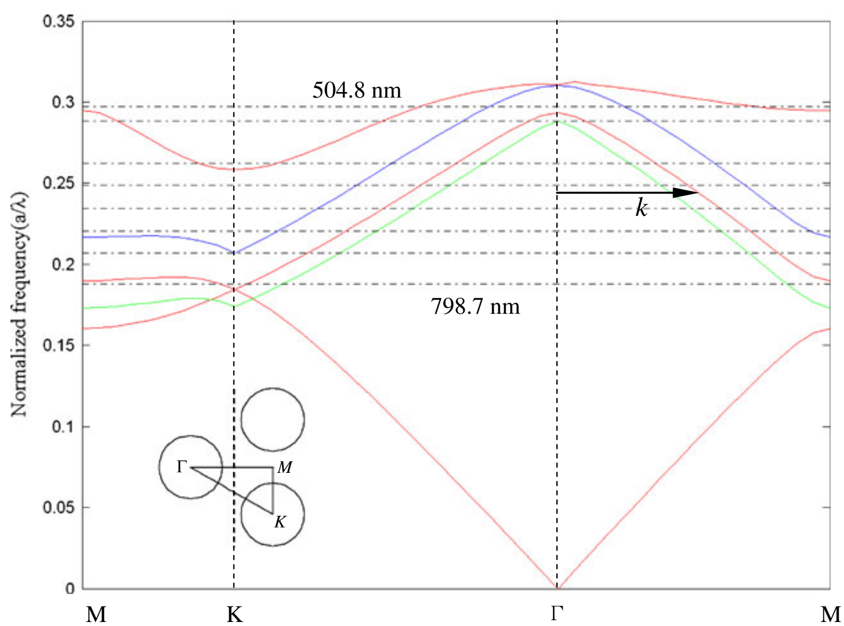

Fig. 3 Band structure of the designed hexagonal lattice PC (*red line*). The second band of the PC with hole radius of 40 nm (*green line*) and 60 nm (*blue line*) is also shown

equifrequency surfaces (EFSs) and points toward the center of the EFSs due to the negative slope of the second photonic band. The negative slope leads to negative refraction at the interface between a positive index medium and the PC [15]. Therefore, for the designed PC, negative refraction mainly occurs in the center area of the second band. In our case, the center area varies from 570 to 680 nm, and latter discussion will focus on this region. For λ=504.8 or 520.1 nm (in the third band) and λ=724.7 or 798.7 nm (near the first band), two or more spots appear behind the PC (illustrated in Fig. 2).

We also used the designed PC to calculate the focusing of a plane wave. The same code and parameter as mentioned before were used except for replacing the electric dipole with TM polarized plane wave as the light source. The wavelengths in the calculation are 571.5, 602.7, 639.6, and 680.8 nm, as shown in Fig. 4. It can be seen that all these wavelengths have focusing effect for the plane wave. The corresponding transmission is 0.66, 0.68, 0.68, and 0.74, respectively. They are much larger than the transmission of the point source. The results demonstrate that the transmission of the designed PC in *x*-direction is much larger than that of the other directions.

The focusing property shown in Fig. 4 is not ideal. For a thin slab of graded negative index material acting as a convex lens and focus plane wave, its refractive index profile in the transverse direction has to vary in such a way that the modulus of the index is the smallest at the center and increases toward the edges [16]. It is opposite to a regular graded positive index lens which maximum index profile is located at the center of the optical axis. According to the band structure shown in Fig. 3, the PC with large air hole has a large wave vector magnitude and thus a large effective refractive index as well. Considering this, we constructed a 2D graded negative index PC lens by means of varying the PC air hole radius in such a way that the smallest radius is in the center and the hole radius increases along the transverse direction. For a graded index lens, the desired index profile should be able to modulate the incident plane wave and generate a wave front which is close to that of a cylindrical wave at the back surface of the lens. Thus, we varied the air hole radius from 40 to 60 nm following the function of $r=40+c\times y^n$, where r is the hole radius in unit of nanometers, c is a constant for each set value of n, and y is an integer approximately from 0 to 9 which refers to the hole number from center to outside. It is obvious that for different n values, different index gradients are decided, such as n=2 means a parabolic index gradient and n=1 is a linear index gradient. Thus, we designed four graded index PC with n=2, 1.5, 1, and 0.5. The transmission of these PCs is calculated during the center area of second photonic band (wavelength ranging from 570 to 680 nm). The maximum

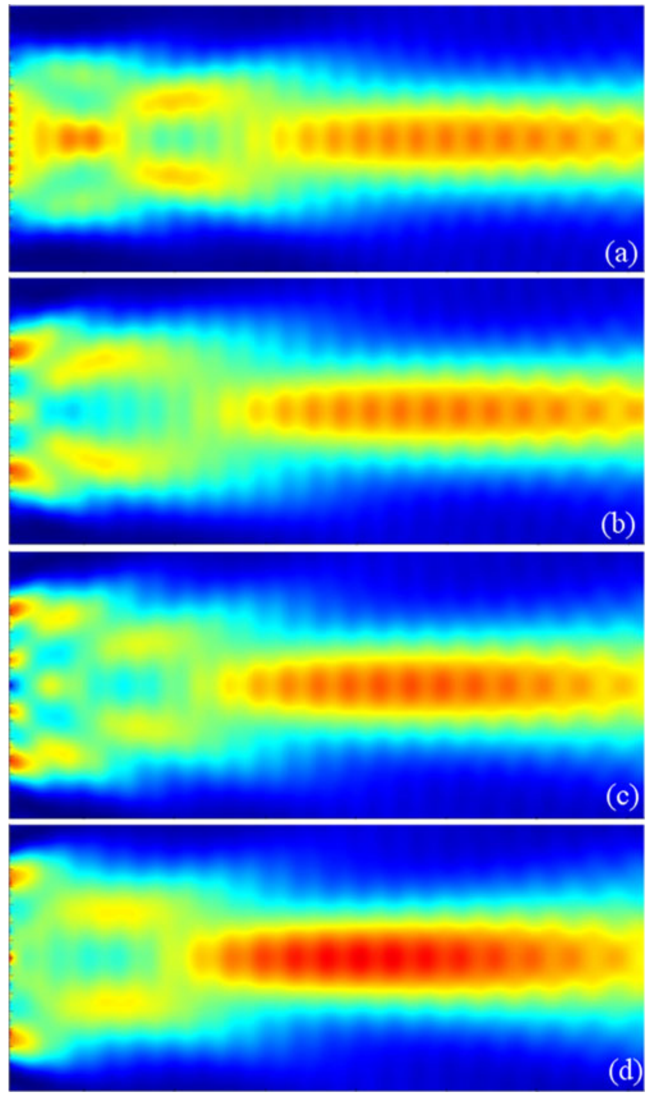

Fig. 4 FDTD simulation of the electric field intensity distribution behind the PC. The simulated area is 7×3 μm. The corresponding wavelengths are **a** 571.5 nm, **b** 602.7 nm, **c** 639.6 nm, and **d** 680.8 nm

transmissions for these PCs are 0.38 at 575.7 nm (n=0.5), 0.37 at 616.1 nm (n=1), 0.42 at 623.4 nm (n=1.5), and 0.42 at 627.2 nm (n=2). The transmission property is different from the different PCs. We used these wavelengths with maximum transmission to examine the focusing property of the corresponding PCs. The electric field intensity distributions of n=2, 1.5, 1, and 0.5 are shown in Fig. 5. Focusing effect is apparent in comparison to the results shown in Fig. 4 which refers to the PC with a constant hole radius.

All of the four designed graded index PCs have good focusing effect on plane wave in different wavelengths with large transmission. The back focal lengths were measured by finding the locations with maximum field intensity along the optical axis (propagation direction). Also the spot size was measured along the transverse direction with field intensity decreases from maximum to be half of maximum in

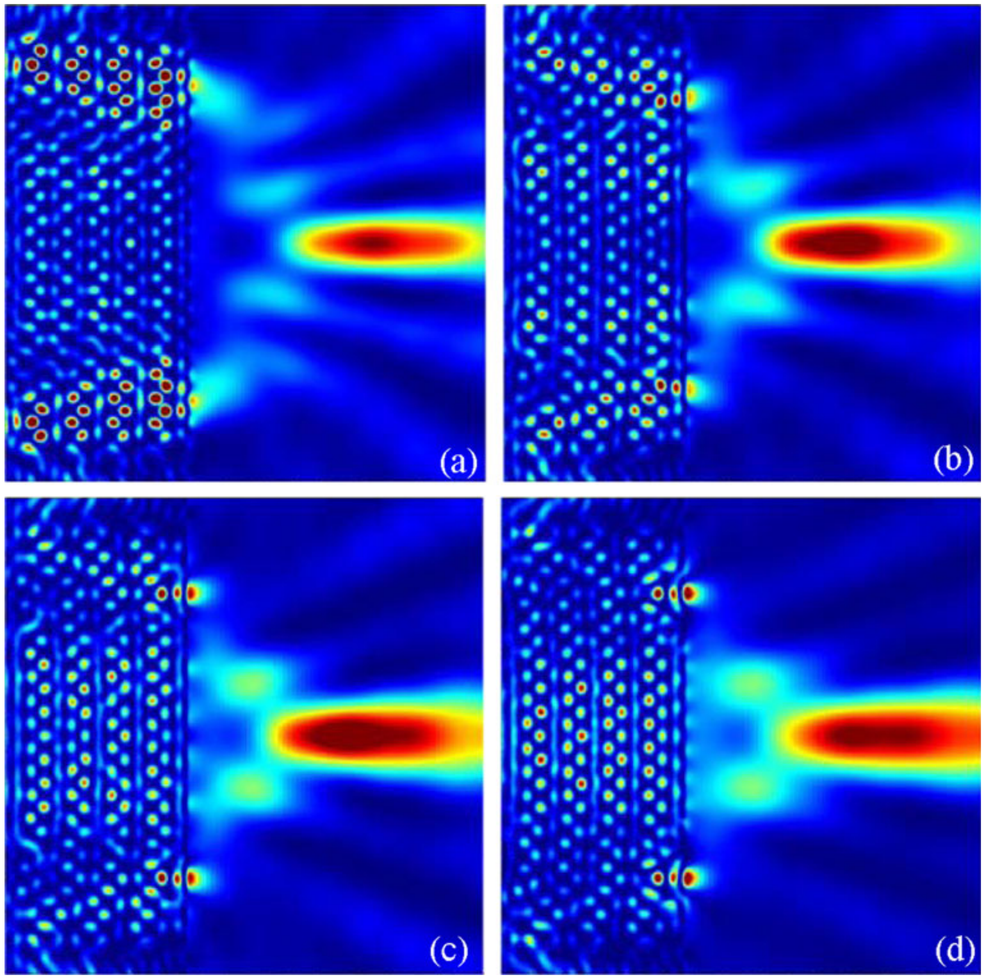

Fig. 5 Focusing effect for **a** n=0.5, **b** n=1, **c** n=1.5, and **d** n=2. The simulation area for each PC is 3×3 μm

both directions. Both the intensity profiles along the transverse direction in the focus and axis of the PCs with different n values were plotted in Figs. 6 and 7. As can be seen, with increasing n, spot size increases and focal length decreases slightly. The spot sizes are 288, 308, 340, and 384 nm for n=0.5, 1, 1.5, and 2 respectively, the corresponding focal lengths are 1.12, 1, 0.99, and 1.02 μm. Comparing to wavelength, the PC with n=0.5 index gradient possesses a largest focal length (~2λ) and the highest resolution

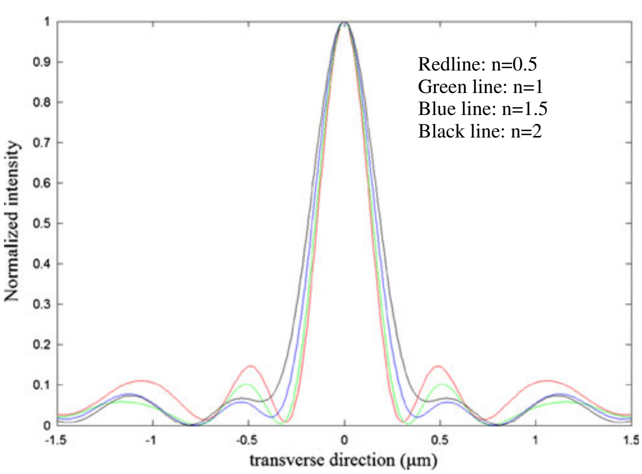

Fig. 6 Intensity distribution along transverse direction in the focus

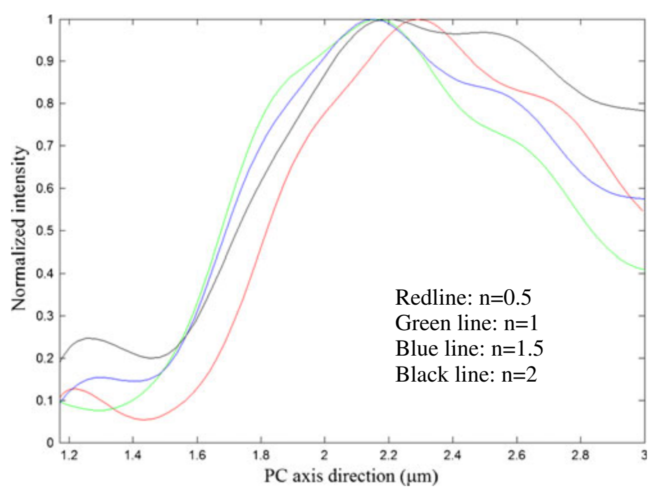

Fig. 7 Intensity distribution along PC axis (propagation direction) behind the PC

(full width at half maximum=0.5λ) between the four calculated PCs.

Summary

In summary, we designed a hexagonal lattice PC which presents a negative refraction behavior in the visible region. Numerical simulation was adopted to demonstrate this phenomenon. Furthermore, by varying the PC parameter, a graded index PC was obtained and used for the purpose of focusing the plane wave. Calculation results demonstrate that the designed PCs have good focusing property together with large transmission. The negative index graded PC provides an approach to design negative index imaging systems and may find applications in future optoelectronic systems.

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