Extraordinary transmission and left-handed propagation in miniaturized stacks of doubly periodic subwavelength hole arrays

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Abstract: Metallic plates embedded between dielectric slabs and perforated by rectangular arrays of subwavelength holes with a dense periodicity in one of the directions support extraordinary transmission (ET) phenomena, viz. strong peaks in the transmittance frequency dependence. Stacks of such perforated plates support ET phenomena with propagation along the stack axis that is characterized by the left handed behavior. The incorporation of the dielectric materials and dense periodicity allows significantly reducing the illuminated area of the perforated plate required experimentally to observe the ET phenomena as compared to the areas required in the case of free standing rectangular hole arrays. This facilitates the experimental investigation of ET under excitation in the Fresnel zone of Gaussian beams.

OCIS codes: (999.9999) Left-handed Metamaterials; (999.9999) Extraordinary Transmission; (999.9999) Photonic Crystals

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1. Introduction

Recently, there has been an increased interest among physical and engineering communities into the investigation of extraordinary wave phenomena supported by metamaterials and photonic crystal (PhC) structures. Veselago's seminal paper [1] predicted that electromagnetic waves propagating along media with simultaneously both dielectric permittivity and magnetic permeability have negative antiparallel phase and group velocities. Consequently, the electric, magnetic and wave vectors in these media form a left-handed triplet in contrast with the right-handed triplet of standard media. This is accompanied by the fact that such media have a negative index of refraction. Therefore, the media are referred to as left handed or negative index metamaterials (NIM).

NIMs can act as perfect lenses focusing to subwavelength spatial spots [2] and can be constructed by using conventional materials and techniques [3-5,6]. It should be noted that NIMs are not the only means to achieve a left-handed propagation (LHP) behavior and subwavelength focusing. Notomi described negative refraction in Photonic Crystals [7], which are made fundamentally of dielectrics and do not suffer from the inherent losses associated with the use of metal resonators to construct NIMs [8-9]. These features connect PhCs to the phenomena of negative refraction and subwavelength focusing [7-9]. One difference compared to NIMs is that periodicities of PhC structures are of order of the wavelength of operation [3-5]..

Very recently, microwave LHP in a PhC that operated in far field (Fraunhofer zone) of radiating and receiving antennas was experimentally demonstrated. The PhC comprised a stack of metal plates perforated by arrays of subwavelength holes that operated in the regime of extraordinary transmission (ET) [10]. In this work, connections between ET [11], Photonic Bandgap (PBG) materials [12,13] and left-handed metamaterials [1] were demonstrated. The physics behind the operation of the structure can be interpreted by means of an electrical engineering based equivalent circuit approach as an inverse transmission line [10] or by means of equivalent artificial waveguide model [16]. It also was observed that by simply adjusting the longitudinal period, i.e. the distance between the hole perforated plates in the stack, a rich variety of propagation regimes can be obtained ranging from conventional right-handed propagation to LHP [10,16,17] opening also the possibility of a zero-group velocity band [16]. Other recent analytical papers confirming these results can also be found [18,19].

This paper extends and significantly improves the previously introduced ideas [10] for achieving left-handed propagation by considering a stack of metallic plates perforated by doubly periodic rectangular arrays of subwavelength holes that are sandwiched between dielectric slabs. It is experimentally shown that this structure shows a better performance with higher flexibility in tuning the structure's parameters than free standing square hole array structures [10]. It is shown that the introduced structure supports left- and right-handed propagation with nearly total transmission. The role and impact of the dielectric slabs and rectangular periodicity are analysed. Important insights are given based on simulations and theoretical comparisons.

2. Rectangular doubly-periodic and dielectric loaded subwavelength hole arrays

The analysis of ET phenomena is described in [20-24,30] from the point of view of surface and leaky wave concepts and diffraction methods. It is now well-established that ET phenomena are associated with the existence of surface waves supported by perforated metal plates and diffraction modes generated by periodic arrays of holes. In the optical regime, the surface waves are surface plasmon polaritons, viz. waves supported by plasma surfaces. In the microwave and terahertz regimes the surface waves are supported due to the hole interactions even when the metals behave as perfect conductors [23].

Our earlier results on ET phenomena [25-27] showed that it was hard to experimentally observe ET phenomena under a Gaussian beam excitation in the Fresnel zone when the perforated plates comprised square free-standing arrays of subwavelength holes [28,29] . The reason is that these arrays support leaky waves with a large propagation length [23,30-32]. The ET phenomena are directly related to the coupling of the incident and transmitted fields to these leaky waves. The large propagation length of the leaky waves leads to a low radiation rate per unit length/area and, as a result, to a large illuminated area of the perforated plate (and a large number of holes) required for a significant increase of transmittance. However, the number of holes excited in the Fresnel zone is relatively small leading to only weakly transmittance enhancement [27].

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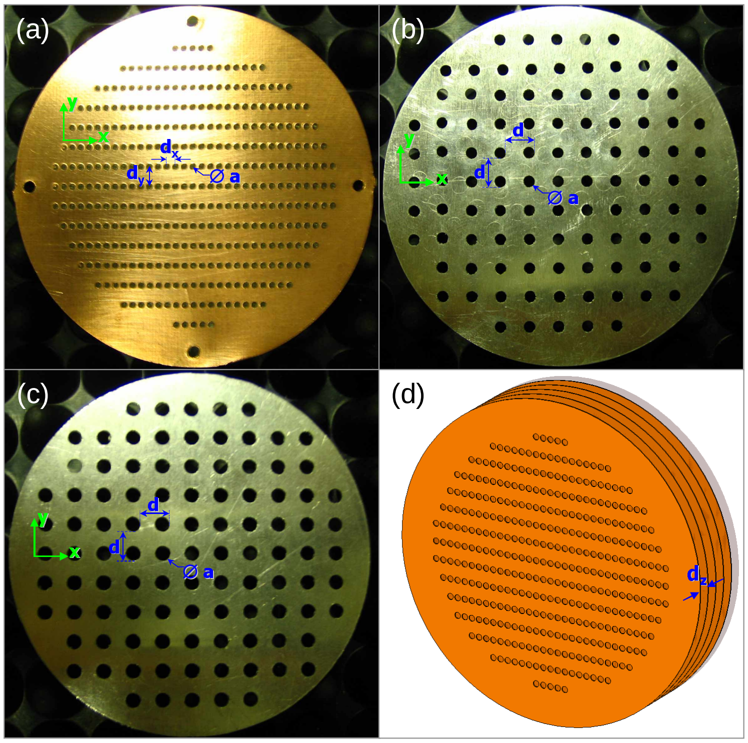

Fig. 1. Photographs of the prototypes. (a) Rectangular periodicity subwavelength hole array with parameters d_x = 1.5 mm, d_y = 4 mm, hole diameter a = 1.2 mm, metallization thickness (copper) t = 35 microns, dielectric thickness h = 0.49 mm and dielectric permittivity ε = 2.43. Squared periodicity subwavelength hole array with hole diameter a = 2 mm (b) and a = 2.5 mm (c), the rest of parameters being: d_x = d_y = 5 mm, metal thickness (aluminum) t = 0.5 mm. (d) Schematic of the stacked hole array with parameters d_y = 3.4 mm, d_z = 0.525 mm and the rest as in (a).

The illumination area and the number of required holes can be reduced significantly by introducing two modifications to the configurations presented in [25-27]. First, the perforated plates are embedded in a dielectric material. Indeed, it can be shown that a perforated plate embedded between two dielectric slabs supports leaky waves that have propagation length much shorter than the one in the case of free standing perforated plates. The short propagation length means stronger coupling between the incident fields and the leaky waves and results in a much smaller area (and the number of holes) required to achieve prominent ET phenomena. In addition, the incorporation of dielectric slabs allows for more flexibility in tuning the structure's scattering properties. The second modification allowing reducing the area of illumination for experimentally observable ET phenomena, is to consider rectangular hole arrays where one of the periodicities is significantly smaller than the other (e.g. $d_x < d_y$ in Fig. 1(a)). This modification, by increasing the number of holes per unit area, further decreases the propagation length of the leaky wave and the area of illumination required for the transmittance enhancement. In addition, this modification allows for applications requiring transmittance polarization selectivity as only one (larger periodicity) components will lead to ET phenomena (assuming only lower frequency transmission bands).

For instance, Fig. 2(a) represents the simulated response of two identical infinite rectangular subwavelength hole arrays (see the caption to Fig. 1(a)): cyan curve, sandwiched between two dielectric slabs of thickness h = 0.49 mm and relative dielectric permittivity ε_r = 2.43, and blue curve, the same metallic hole array in air. Clearly, when the hole array is inserted between a dielectric sandwich, the ET peak is shifted to lower frequencies, in the

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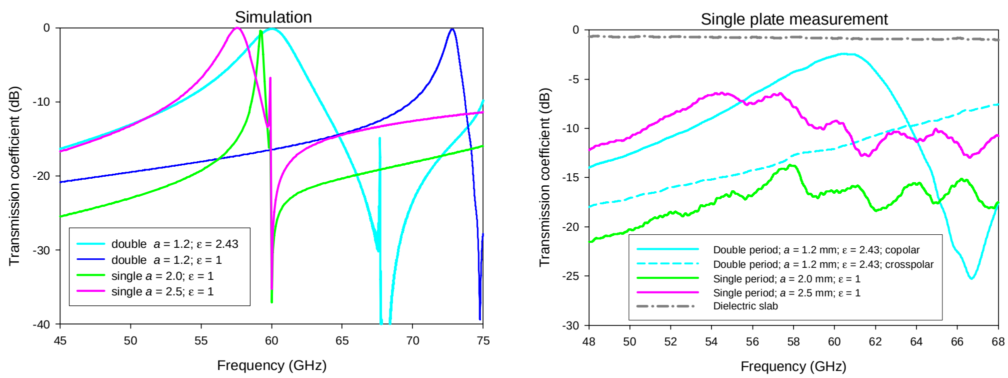
present case from 73 GHz to 60 GHz. The peaks also broaden. For completeness, Fig. 2(a) also shows the simulated transmittance of infinite square hole arrays embedded in air with the dimensions of Fig. 1(b) (green curve) and Fig. 1(c) (magenta curve). Notice that the simulation results are for infinite hole arrays under plane wave excitation and therefore, total transmission is achieved for the infinite structure. This is fundamentally different from the real finite structure experiment, where the transmittance has reduced values.



(a) (b)

Fig. 2. (a) Simulated transmission coefficient magnitude comparing two rectangular periodicity infinite hole arrays with parameters as in Fig. 1(a), one immersed in air (blue curve) and the other one sandwiched between two dielectric slabs of thickness h = 0.49 mm and relative dielectric permittivity ε_r = 2.43 (cyan curve). Green and magenta curves correspond to square periodicity infinite hole arrays embedded in air shown in Fig. 1(b) and (c) respectively. (b) Measured transmission coefficient magnitude for single plate subwavelength hole arrays prototypes. Solid cyan curve corresponds to the parallel polarization excitation (copolar) of the rectangular periodicity hole array shown in Fig. 1(a) and sandwiched between two identical dielectric slabs of thickness h = 0.49 mm and dielectric permittivity ε_r = 2.43. Dashed cyan curve is for the orthogonal polarization (crosspolar). Green and magenta curves correspond to square periodicity hole arrays embedded in air shown in Fig. 1(b) and (c) respectively.

A rectangular double periodic hole array was drilled by a numerical milling machine on a metallic layer of a commercial microwave substrate with the following parameters: dielectric thickness h = 0.49 mm and dielectric permittivity ε_r = 2.43. The remaining parameters were (see also Fig. 1(a)): periodicities d_x = 1.5 mm, d_y = 4 mm, hole diameter a = 1.2 mm, metallization thickness (copper) t = 35 μm and circular wafer diameter ∅ = 62.4 mm. The fractional area of the hole, defined as the ratio of hole to unit cell area, was approximately F = 0.2. For comparison purposes, two square hole arrays made in aluminum prototypes also were built with hole diameter a = 2 mm and 2.5 mm, periodicity d_x = d_y = 5 mm, and metal thickness t = 0.5 mm (see Fig. 1(b) and (c)). The corresponding fractional hole areas were F = 0.12 and 0.2 for a = 2 mm and 2.5 mm, respectively.

The transmission through the samples was measured by using the set-up shown in Fig. 3 and following the next procedure. A vertically polarized gaussian beam [28] was generated by a transmitting corrugated horn antenna (Tx). The beam propagated up to a focusing pair of elliptical mirrors (A-B) designed to obtain an undistorted beam having its beam waist in the half of the distance of the set-up, where the samples were located. Another identical pair of mirrors (C-D) focused the transmitted beam into a receiving corrugated horn antenna (Rx). The whole set-up can be considered as a beam waveguide [28] and, therefore, the transmitted power could be easily measured (see Fig. 2(b)).

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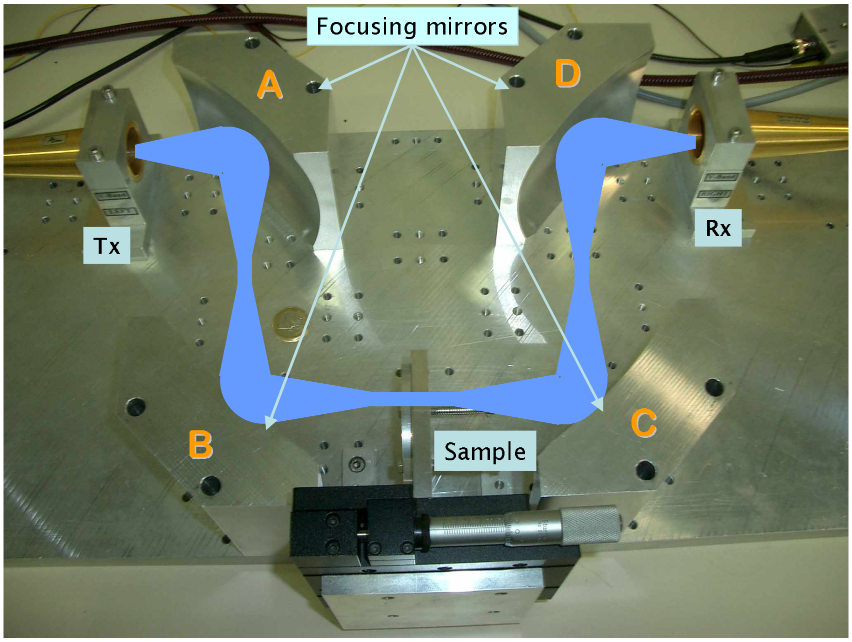

Fig. 3. Experimental quasi-optical bench set-up (QO bench). The transmitting and receiving corrugated horn antennas, the focusing mirrors and the sample positioning system are displayed. The propagating Gaussian beam contour is highlighted in blue.

The solid cyan curve in Fig. 2(b) shows the measurement of the rectangular hole array prototype, Fig. 1(a), sandwiched between identical dielectric slabs. A clear resonance ET peak with a level of –2.45 dB, arises at 60 GHz. In the orthogonal polarization (dashed cyan curve), no resonance is observed (as expected) and the level at 60 GHz is –11.6 dB. Note that the simulation results of Fig. 2(a) predict total transmission at the ET resonance. A possible cause of the lower level in the measurement is due to dielectric losses, which were not considered in the simulation. For a rough estimation, a single dielectric slab was also measured (dash-dot gray line in Fig. 2(b)). The measurement shows an attenuation of 0.9 dB in the passband. As the sandwich had two twin dielectric slabs, the total losses due to dielectrics are (roughly) 1.8 dB. Therefore, the attenuation due to the perforated plate can be estimated as 0.66 dB. Notice that the measurements are taken by using the Fresnel-zone illumination set-up and that, accordingly, the actual illuminated area had a diameter approximately equal to the gaussian beamwaist, i.e. 27.9 mm, and still the measured transmission is quite high. The effective number of illuminated holes is 19 × 8, which corresponds to an area (normalized to the ET wavelength) $S/\lambda^2 = 24.45$.

Transmission measurements for the two square hole array prototypes of Fig. 1(b) and 1(c) are also plotted in Fig. 2(b), see green (a = 2 mm) and pink (a = 2.5 mm) traces. The peak of ET arises at 57 GHz with a maximum level of -13 dB and –7 dB for a = 2 and 2.5 mm respectively, i.e. 10.5 and 4.5 dB below the power measured with the rectangular hole array. In this case it is important to note that, due to the finite size of the incident Gaussian beam, the number of periods illuminated by the beamwaist is restricted to 6 × 6 holes (Fresnel zone), which is much lower than the experimentally found number of 31 × 31 holes required for nearly total transmission in Fraunhofer illumination for these structure's parameters [27]. This result is related to the analytical description of Ref. [33]. Note that this hole array size corresponds to an area of $S/\lambda^2 = 900$, i.e. 36 times greater than that required to achieve a nearly total transmission through the rectangular hole array between dielectric slabs.

Therefore, the measurements confirm that the metal plates embedded in a dielectric material and perforated by rectangular hole arrays with a dense periodicity in one of the

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directions are more efficient for the experimental verification of ET than free standing square hole arrays. Hence, ET phenomena can be observed under Fresnel zone illumination. As the array density in the horizontal dimension increases, the transmitted power level increases as well.

3. LHP through a stack of rectangular hole arrays

A bulk PhC is constructed by periodically stacking the rectangular hole arrays (Fig. 1(d)). In the following numerical and experimental results, the stack period, which is the sum of the thickness of the dielectric and conductor layers $d_z = h + t$, was chosen as 0.525 mm. The vertical periodicity of the hole array was slightly modified to $d_y = 3.4$ mm for reasons explained below. All other parameters were unchanged.

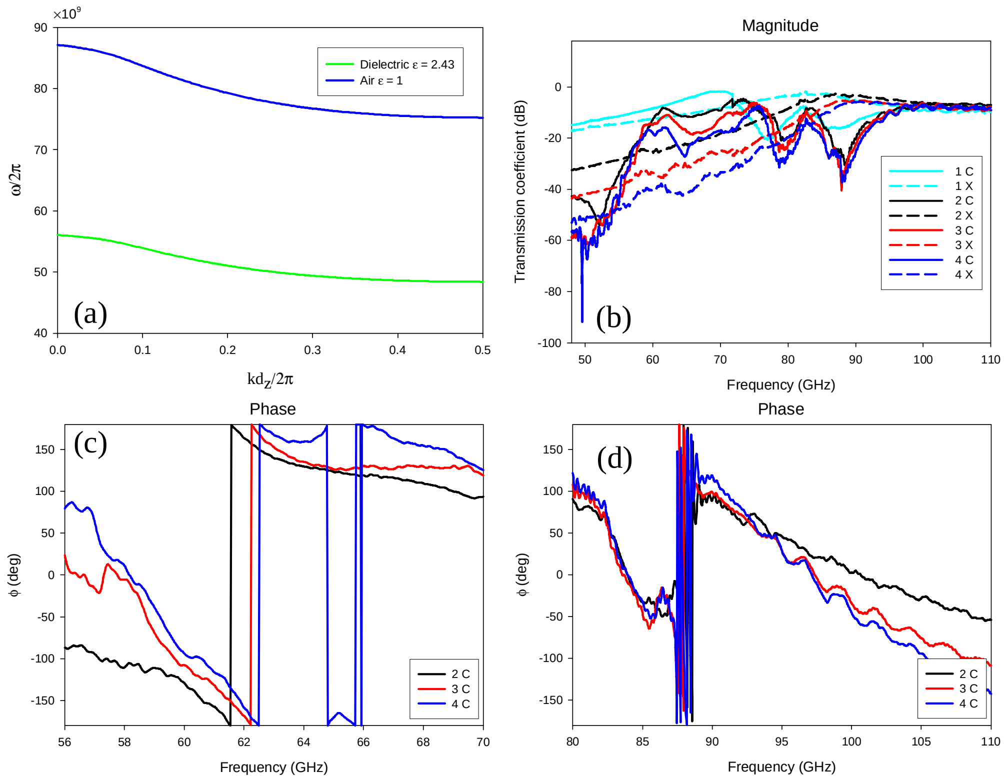

Fig. 4. (a) Dispersion diagram particularized to the first band of the stacked hole array separated by air slabs (blue) and by $\varepsilon_r = 2.43$ dielectric slabs (green). (b) Experimental transmission coefficient magnitude of stacked hole arrays. Solid lines correspond to copolar excitation of the rectangular periodic hole array on the dielectric slab structure, i.e. E-field in the direction of the large periodicity and dashed lines to the orthogonal polarization. (c) and (d) Phase response in and out of the LHM band respectively. In (b), (c) and (d) black is for two plates, red for three plates and blue for four plates

Figure 4 shows numerical and experimental results characterizing the field scattering from the stacked structure. Figure 4(a) plots a computed dispersion diagram of the double periodicity structure separated with air and with a dielectric of relative permittivity $\varepsilon_r = 2.43$. By using the eigenmode solver of CST Microwave Studio™, when the structure is embedded in air, the first band appears between 75 and 87 GHz (blue curve), whereas the first band shifts to the range between 48.4 and 56 GHz (green curve) when the structure is embedded in dielectric. The frequency shift for the stacked hole arrays embedded in dielectric as compared to the freestanding stacked arrays (see Ref. 10) is consistent with the shift in a single hole array sandwiched between dielectric slabs.

Figure 4(b) shows the experimental results for the frequency dependence of the transmittance of the stacked rectangular hole arrays embedded in a dielectric material. The transmittance was measured using the previously described Quasi-Optical (QO) bench, in the range from 45 to 110 GHz (V- and W-bands). The solid cyan curve represents the response of a single perforated plate sandwiched between dielectric slabs. Note that the resonance is shifted to 70 GHz as compared to the one in Fig. 2 due to the shorter chosen periodicity d_y. For two stacked plates (solid black curve) a clear ET peak is detected at 60 GHz. As the number of layers is increased, the peak level decreases, likely due to losses and slight misalignments between consecutive layers. However, the resonance frequency remains locked at 60 GHz, below the resonance of a single perforated plate, regardless the number of plates in the stack. The frequency shift is due to the coupling between the perforated plates in the stack. This coupling leads to the fact that the electric field lines are trapped in the dielectric and contribute to a self-capacitance of the single perforated plate and mutual capacitance of adjacent plates [10]. This shift also partially explains the decrease in the transmittance by the fact that the hole diameter / wavelength ratio decreased as well (see e.g. discussions in [25]).

Figure 4(b) also compares the frequency dependence of the co- and cross-polarized transmitted fields. For the cross-polarization, no resonances are observed in any of the measured cases. Instead, the power level increases monotonously with the frequency (as expected). Finally, Figs. 4(c) and (d) show the phase response of the stacked structure. Inside the ET band (Fig. 4(c)) the phase increases with the number of periods (as in [10]), i.e. ET-LHP is obtained. Outside the ET band (Fig. 4(d)), the phase obeys a regular right handed behavior, i.e. it decreases with the number of periods. This behavior shows that ET phenomena in a stack of perforated plates are intimately related with our ability to achieve LHP. It also should be noted that the LHP is obtained only in the regime of ET indicating that the origin of the LHP is not a presence of a Brillouin zone edge as often occurs in conventional PhCs but rather the effects associated with ET resonances.

4. Conclusions

Introducing rectangular double periodicity and a dielectric sandwich in sub-wavelength hole arrays allows obtaining ET transmission phenomena for perforated metal plates of significantly reduced size. It allows nearly total transmission of collimated Gaussian beam when the perforated plate sample is in the Fresnel rather than Fraunhofer zone. This represents an important achievement for the experimental study of enhanced transmission phenomena in the microwave regime.

A novel route for the fabrication of structures allowing controlled right and left handed propagation (transmission) was proposed. This was achieved by means of stacked plates perforated by rectangular arrays of holes and embedded in a dielectric material. The structure allows for a great flexibility in tuning the propagation properties. For instance, the tuning the left right to right handed propagation and vice versa can be achieved by modifying the transversal periodicities, longitudinal periodicities, as well as the dielectric permittivity of the embedding material. The latter option may be attractive as the permittivity of the dielectric can be controlled by incorporating electro-optic materials without modifies the structure dimensions.

Scaling these results to other frequency ranges (e.g. terahertz regime) is now under consideration. Further experiments and theoretical analysis to allow characterization of the introduced structure are under development as well.

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