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14. ABSTRACT
We have demonstrated that an anisotropic metamaterial prism comprises both positive and negative indices. Such a prism can split an incident beam refractively. The values of the positive and negative index and the apex angle of the prism determine the separation angle of the output beams. The positive and negative indices are accessible by the choice of polarization of the incident radiation. Using linearly polarized radiation with the electric field vector parallel to the posts in the prism, negative refraction is observed. Rotating the polarized beam 90^0 yields a positively refracted signal. Intermediate angles of polarization can achieve refraction in both negative and positive directions simultaneously.

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Negative Index Metamaterial for Selective Angular Separation of Microwaves by Polarization

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1 Introduction

When Veselago predicted [1] the properties of material with simultaneously negative electric permittivity and magnetic permeability, he assumed the medium was isotropic and homogeneous. Although no such material has been discovered or constructed, the effects he predicted including negative index of refraction have been measured in anisotropic, discontinuous media. The materials, which Veselago referred to as left handed, are also called backward wave and double negative media. The first experimental demonstration by Schultz [2] used a metamaterial that combined metallic split ring resonators with posts etched on opposite sides of dielectric boards. The boards are usually stacked in parallel planes with insulating spacers to form highly anisotropic prisms. For incident microwaves polarized so the electric field is parallel to the posts and the magnetic field is perpendicular to the boards, negative refractive index effects can be observed in a narrow frequency range.

We have observed that if the incident radiation is rotated 90 degrees (the electric field and magnetic fields change places but the direction of propagation remains the same), such a prism has a positive index of refraction of nearly unity at the same frequencies for which the original polarization has a negative index. For the rotated polarization, the magnetic field is parallel to the substrates, which minimizes coupling to the resonators. The electric field is perpendicular to the posts and therefore is nearly unaffected by them. The dielectric substrate has some effect, but the boards are usually less than ten percent of the prism volume and the spacers are nearly transparent to microwaves. An incident beam using this rotated polarization is barely deflected, although some loss of magnitude occurs. The use of intermediate polarizations can split the incident signal into two simultaneous output signals, one refracted negatively and one positively. The angular separation of the two output signals is determined by the prism angle and the negative index of refraction at the particular frequency.

2 Fabrication

The prism used for measurements was previously reported by Greegor et al. [3] and provided by them for this study. The unit cell shown in Figure 1 includes two posts on separate substrates. The posts are joined at top and bottom of each cell to form continuous columns. The dielectric boards are Rogers 5880, 0.254mm thick. These are spaced with 2.3mm thick Rohacell HF foam.

The wedge shaped prism is made from parallel sheets of substrate and foam stacked side by side so the flat, entrance face of the prism is formed by the substrate edges. The entrance face of the prism is a square 28cm on a side. The prism thickness increases from 8 unit cells to 14 and the wedge angle is 12°.

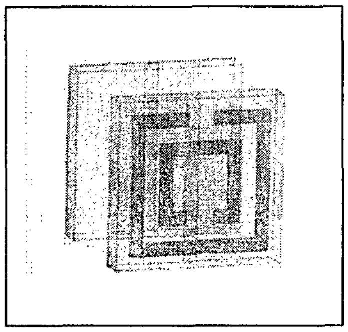

Figure 1. The unit cell. Line widths are 0.25mm, spaces are 0.3mm and the azimuthal gaps 0.46mm. The outer side of the ring is 2.63mm. The distance between cell centers is 3.3mm.

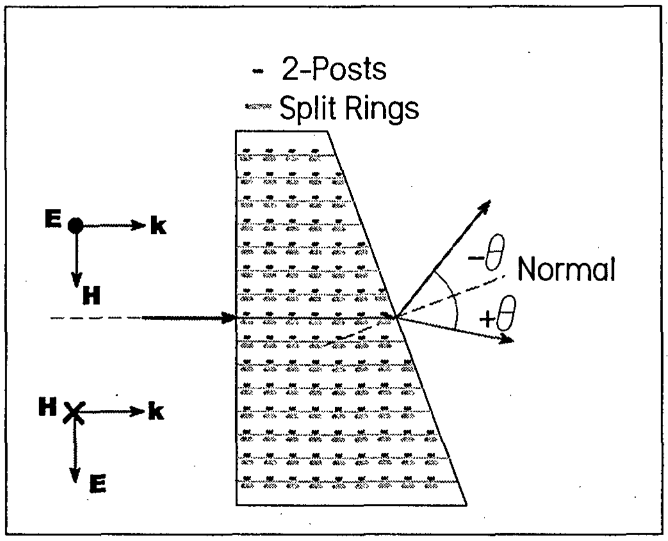

Figure 2. Top view of the prism measurement.

3 Measurements

In the diagram of the experiment shown in Figure 2, the vertical posts are out of the page and the direction of propagation through the prism is along their width. Free space measurements were made using square polarized transmit and receive horns that are 20cm on a side. The transmit horn has a 3dB width of 7° and was mounted 3.73m from the prism. The prism fits into a 28cm aperture in an absorbent baffle 1.5m across. The receive horn was mounted on an arm 2.58m from the prism and was rotated about the exit face normal in 0.5 degree steps. Note that for the frequency band and apertures used, the transmit and receive distances are both beyond the reactive near-field distance, $0.62(D^3/\lambda)^{1/2}$, where D is the diagonal of the source aperture and λ is wavelength.

To observe negative refraction, the electric fields of the transmit and receive horns were first oriented parallel to the posts and the magnetic field was normal to the plane of the substrates. The incident beam is normal to the entrance face of the prism and not refracted there. The beam then strikes the second face at 12° and does refract. The frequency for which the index of refraction equals -1 was found experimentally to be 14.1GHz. This frequency was used for succeeding measurements with the field polarization rotated.

4 Results

Plots of the measured data are shown in Figure 3. Labels on the plots for the transmit and receive horns refer to the electric field polarization. Thus vertical means the electric field is parallel to the posts and horizontal means the electric field is perpendicular to the posts. As Figure 3a shows, with vertical electric field the incident beam is refracted to -12° and the index of refraction is -1 from Snell's Law. With horizontal electric field the beam exits the prism at positive 12°, which is in line with the transmit horn, and the index of refraction is +1. The transmitted signal is larger for the horizontal polarization than the vertical, possibly due to decrease of reflection or absorption. In Figure 3b, when the electric fields of both the transmit and receive horns are oriented at 45° to the posts, the incident beam is split into two signals at positive and negative 12°. The angular separation between the two beams is twice the wedge angle and determined solely by the gross geometry of the prism. Figure 3c shows that with the transmit horn oriented at 45° to the posts, a vertically oriented receiver only detects the negatively refracted signal at −12°. A horizontally oriented receiver as in Figure 3d only detects the positively refracted signal at +12°. The magnitude of these signals is approximately 0.71 or $\sqrt{2}/2$ times the signals in Figure 3a. This ratio is the cosine of 45°, consistent with the projection of the signal onto the vertical and horizontal axes. The magnitude of the signals in 3b is about one half, or $\cos^2(45°)$ times the originals in 3a.

5 Conclusions

We have demonstrated that this anisotropic prism exhibits both positive and negative refractive indices and can split an incident beam into two components. The positive and negative indices are accessible by the choice of polarization of the electric field. Using an electric field parallel to the posts, negative refraction is observed. Rotating the electric fields 90^0 yields a positively refracted signal. Intermediate angles of polarization can achieve refraction in both negative and positive directions simultaneously, or the receiver polarization can be chosen to select either signal separately. The values of the positive and negative index and the wedge angle of the prism determine the separation angle of the output beams. This effect has potential application for a unique type of angular beam splitter.

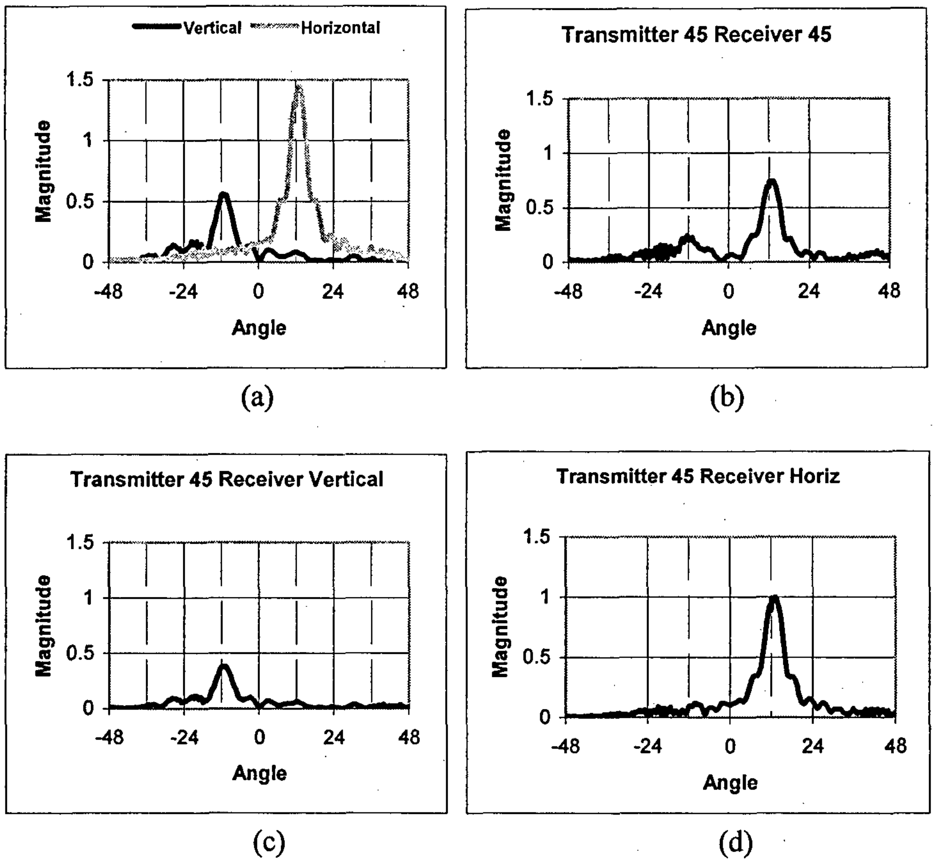

Figure 3. Measurements of refracted signal with the electric field rotated relative to vertical posts. Angle is measured in degrees from the normal to the exit face. Magnitude is a linear scale with 1=20μW.

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[3] R. B. Greegor, C. G. Parazzoli, K. Li, B. E. C. Koltenbah and M. Tanielian, "Experimental determination and numerical simulation of the properties of negative index of refraction materials," *Optics Express,* vol. 11, pp. 688-695, April 7, 2003.

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