The chiral vacuum in metamaterials

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When an electromagnetic wave is incident on a surface of a medium, it is partially refracted into the medium and partially reflected back. However, at a particular angle of incidence, the reflected wave vanishes completely. With normal dielectric media, this phenomenon occurs only for transverse-magnetic (TM) waves (p waves) and is called the Brewster effect. But if we can prepare a magnetic medium, the no-reflection effect for transverse-electric (TE) waves (s waves) can be observed. The TE Brewster effect was experimentally observed in the metamaterial composed of split-ring resonators [1].

Here we explore the no reflection conditions for isotropic chiral media whose properties are characterized not only by the relative permittivity ε_r and relative permeability μ_r but also by the normalized chirality parameter ξ_r. We find that the no reflection effect arises for elliptically polarized (EP) waves and circularly polarized (CP) waves [2, 3]. In general, EP waves incident at a particular angle satisfy the no reflection condition as in the non-chiral cases. However, when the wave impedance and wavenumber of the chiral medium are equal to the corresponding parameters of vacuum, one of the CP waves is transmitted to the medium without reflection nor refraction for all angles of incidence. In terms of ε_r, μ_r, and ξ_r, the condition can be represented as $\varepsilon_r = 2 - \mu_r^{-1}$, $\xi_r = \pm(1 - \mu_r^{-1})$. An example of FDTD analysis is given in Fig. 1. A cylinder composed of the chiral medium that satisfies the condition is illuminated with a two-dimensional Gaussian beam. While the left circularly polarized (LCP) wave is transmitted straight through the chiral medium with no reflection and no refraction, the right circularly polarized (RCP) wave is scattered by the cylindrical object. We call this effect as the chiral vacuum.

The chiral vacuum can be understood physically as follows. The polarization and magnetization of chiral medium is represented as a sum of electric and magnetic contributions, i.e., $\boldsymbol{P} = \boldsymbol{P}_E + \boldsymbol{P}_M$ and $\boldsymbol{M} = \boldsymbol{M}_M + \boldsymbol{M}_E$. When the condition is satisfied, the electric and magnetic contributions cancel each other out for one of the circular polarizations, and $\boldsymbol{P} = \boldsymbol{M} = 0$ is achieved. Thus the medium is equivalent to a vacuum only for the circular polarization. This effect shares some similarities with electromagnetically induced transparency (EIT), which is widely used to control light propagation in the field of quantum optics.

In order to realize the chiral vacuum, we are now trying to fabricate three-dimensional isotropic chiral metamaterials. As a preparatory stage, we made an array of one-dimensional helical structures with print-circuit boards shown in Fig. 2 and measured the transmission spectra for the vertically polarized microwaves. In Fig. 3, T_{VV} and T_{HV} respectively represent the vertical and horizontal components of the transmitted wave. At around the resonance frequency, f = 6 GHz, a polarization change that indicates the chirality is clearly observed. The next step is to build a three-dimensional structure with this kind of helix as shown in Fig. 4 and its fabrication is underway.

Recently, in the infrared region, the chiral structures are successfully fabricated and circular dichroism is observed [4, 5]. Therefore it may be possible to realize the chiral vacuum in the infrared or visible regions in the near future.

References

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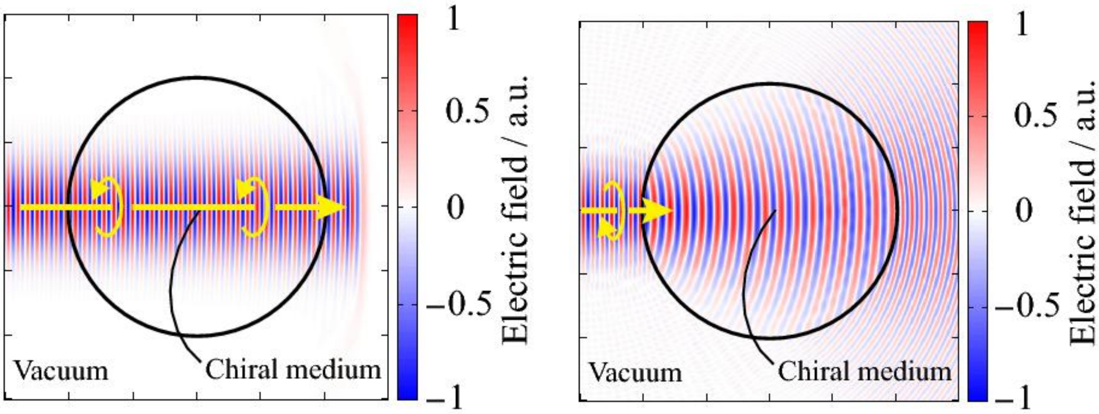

Figure 1: Results of two-dimensional FDTD analysis. A beam of circularly polarized wave is incident on a chiral vacuum medium with cylindrical shape. The LCP wave is not influenced by the object (Left panel) but the RCP wave is scattered (Right panel).

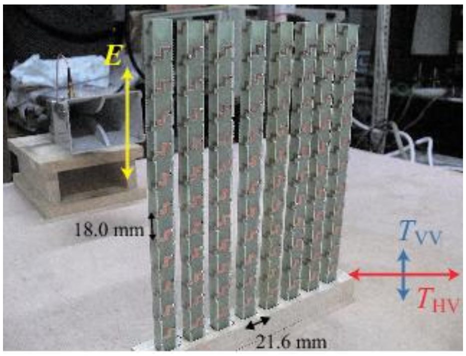

Figure 2: An array of helices made of print-circuit boards as a component of chiral metamaterials.

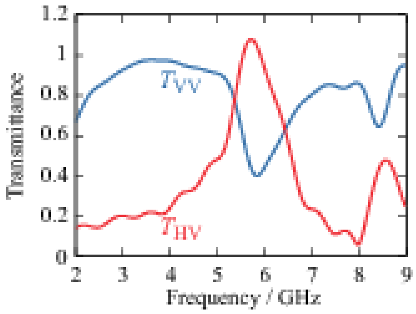

Figure 3: The chirality of helix array is observed as the conversion from the vert ical to horizontal polarizations at around the resonance frequency, 6GHz.

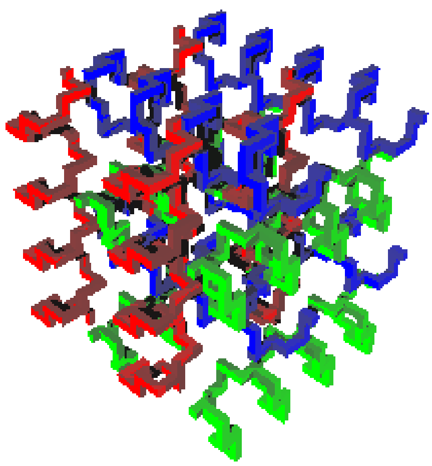

Figure 4: Three-dimensional chirality is realized by a three-dimensional stack of helices.