The Filtering Function of a Completely Open Resonance Cavity Including Left-Handed Materials

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A numerical simulation is performed to study a completely open cavity based on left-handed materials. This cavity can restrict electromagnetic waves with no surrounding reflective wall. A closed path with zero optical paths is formed. Due to the effect of resonance, this cavity can be used as a filter.

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Recently double negative refraction (DNG) materials, i. e., left-handed materials (LHM) with simultaneously negative permittivity and negative permeability have attracted considerable attention because of their peculiar properties, such as the reversal of Doppler shift and the famous negative refraction [1 – 11]. The concept of open cavity was firstly suggested by Notomi [2]. The open cavity consists of four alternating rectangular blocks of two materials with opposite refractive indices. A simple ray-trace analysis can show that there exist many closed ray paths (with zero value of the optical path) running across the four interfaces and thus a kind of an open cavity with no surrounding reflective wall is formed. But the realization of such cavity has not been reported until Z. Ruan and S. He suggested a completely open cavity basing on the negative refraction effect of photonic crystal. But in order to decrease the reflection, the cavity is formed by three 60-degree wedges of a photonic crystal with negative effective index [12]. In the present letter, we report the realization of such cavity using LHM. Moreover, we find this cavity can function as a filter due to resonance. A finite-difference time-domain (FDTD) method is used to study the electromagnetic wave propagation in this cavity.

The sketch map of the cavity is shown in Figure 1. The two square grey areas stand for LHM with refraction index $n = -1$ and the two square white areas stand for air with refraction index $n = 1$. The calculation field is chosen as Figure 1 with 400×400 cells and bounded by perfect-matched layers. Each special cell was $\Delta h = 0.05$m on a side and the time step interval $\Delta t = \frac{0.5h}{\sqrt{2}c} = 58.926$ps (Courant condition). To avoid the divergence as time marches in the FDTD simulation, the following Drude's dispersion model [13] for the permittivity and permeability of the LHM slab is

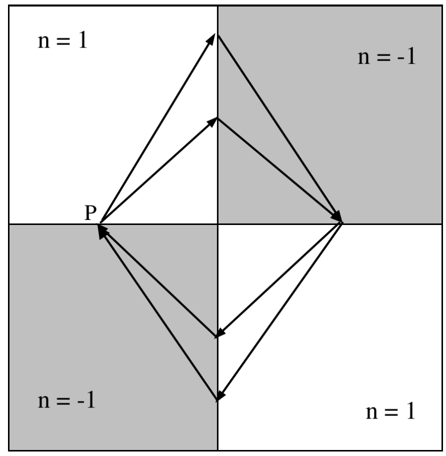


Fig. 1. Sketch map of the cavity.

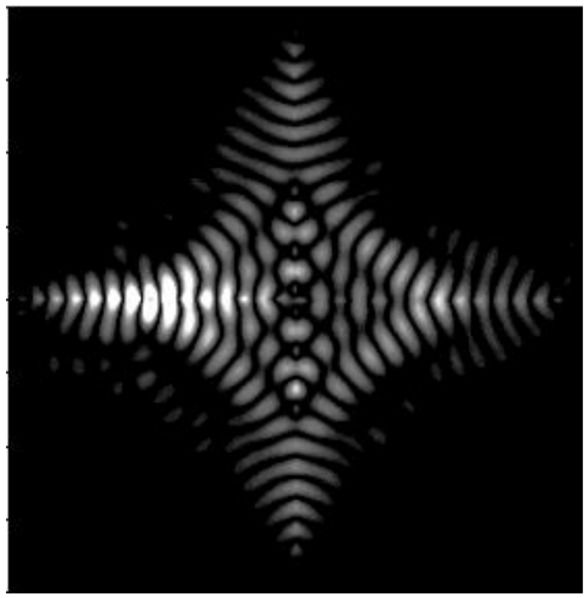


Fig. 2. Field intensity distribution for a point source with the form $f(t) = \sin(\omega_0 t)$.

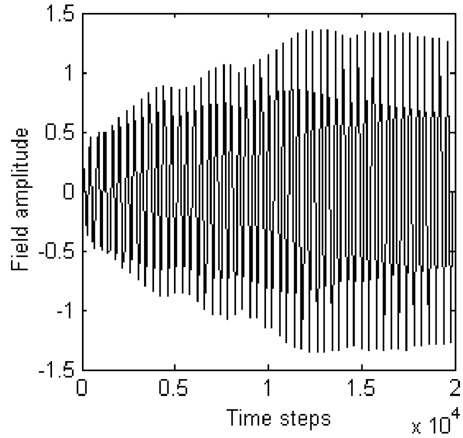


Fig. 3. Instantaneous field of source point vs. time steps.

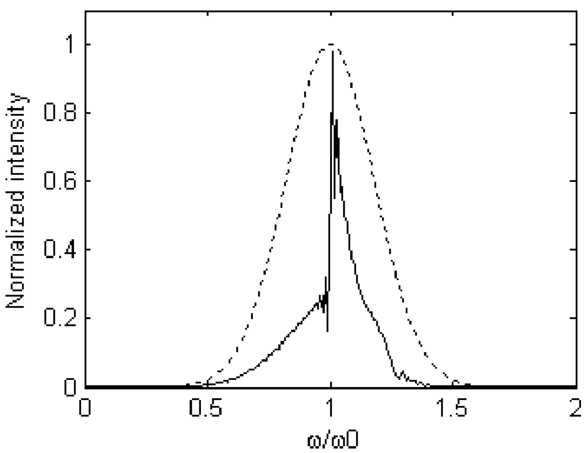


Fig. 4. Spectrum of a pulse source with the form $f_1(n\Delta t) = \exp[-\frac{(n-5000)^2}{100^2}]\sin[\omega_0(n-5000)\Delta t]$ (dotted curve) and the spectrum of a field point near source obtained by simulation (solid curve).

used:

$$\varepsilon(\omega) = \varepsilon_0(1-\omega_{pe}^2/\omega^2),\ \mu(\omega) = \mu_0(1-\omega_{pm}^2/\omega^2). \quad (1)$$

The permittivity and permeability take negative values for frequencies below ω_{pe} and ω_{pm}, respectively. Here we assume $\omega_{pe} = \omega_{pm} = 1.885$ GHz. When $\omega = \omega_0 = \omega_{pe}/\sqrt{2}$, $\varepsilon(\omega)/\varepsilon_0 = \mu(\omega)/\mu_0 = -1$. A point source with a form $f(t) = \sin(\omega t)$ is placed at point P that is just at the interface of air and LHM, and only $\boldsymbol{E}$ polarization wave is considered. Firstly, we give the source frequency $\omega = \omega_0$. Figure 2 plots the field intensity distribution, from which we clearly find a resonance effect and many closed ray paths. Figure 3 further shows how the instantaneous field of source point changes with time steps. We notice that the field amplitude increases with time steps, which is just the result of resonance.

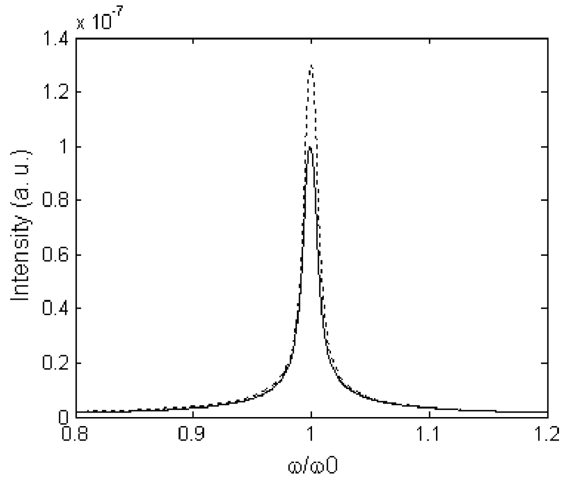


Fig. 5. Spectrum of a pulse source with the form $f_2(n\Delta t) = \exp[-\frac{(n-10000)^2}{5000^2}]\sin[\omega_0(n-10000)\Delta t]$ (dotted curve) and the spectrum of a field near source obtained by simulation (solid curve).

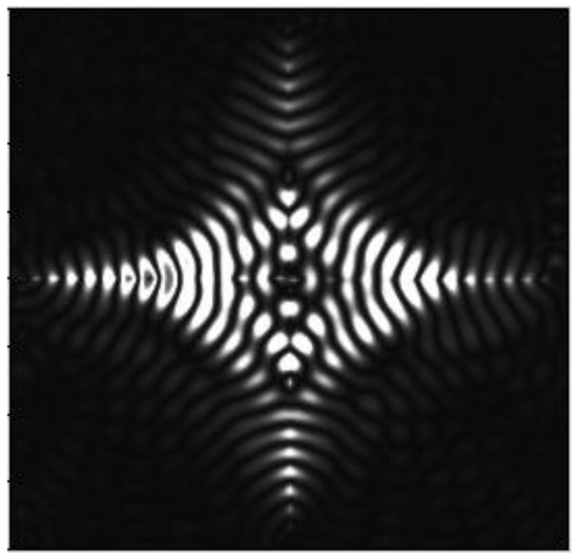
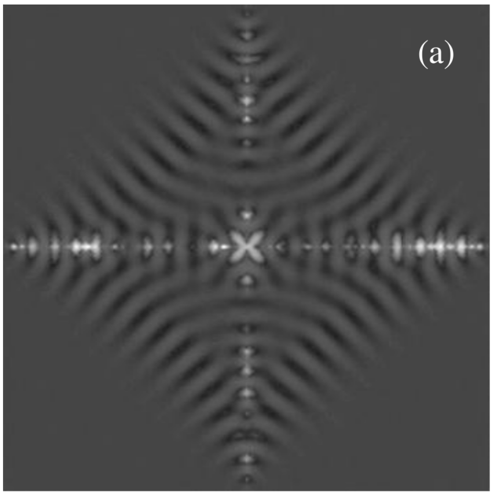


Fig. 6. Field distribution corresponding to pulse source f_2.

Next, we excite a pulse with the form $f_1(n\Delta t) = \exp[-\frac{(n-5000)^2}{100^2}]\sin[\omega_0(n-5000)\Delta t]$ at point P (Δt is one time step length and n is the number of time steps). The spectrum of the source is shown in Figure 4 with a dotted curve. The pulse consists of many monochromatic waves with different frequencies, but Figure 4 shows that the most intensity of the pulse concentrates on the wave with $\omega = \omega_0$. It is obvious that only the



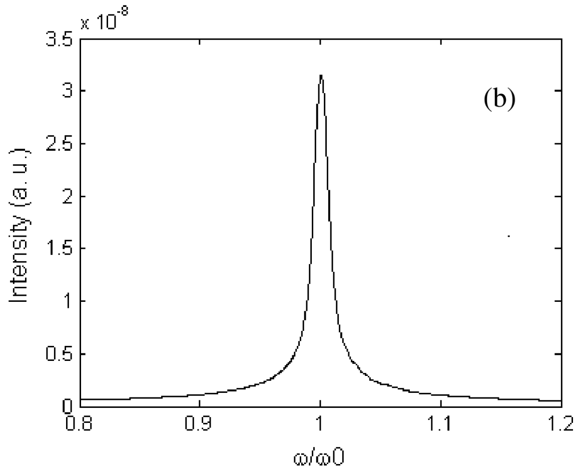


Fig. 7. Field intensity distribution obtained from the Lorentz model for point source with the form $f(t) = \sin(\omega_0 t)$ (a) and the spectrum of instantaneous field near source point (b).

wave with $\omega = \omega_0$ can resonance in the open cavity and other waves gradually fade away. We also record the change of the field intensity of one point near the source with time steps and transform it to the frequency domain by a Fourier transform. The solid curve in Figure 4 is the result, from which we find that the maximum value is still at $\omega = \omega_0$. Furthermore, the width of the solid curve is much narrower than that of the dotted curve, which means that the open cavity can also function as a filter.

Finally, we excite a pulse with another form $f_2(n\Delta t) = \exp[-\frac{(n-10000)^2}{5000^2}]\sin[\omega_0(n-10000)\Delta t]$ at point P. Figure 5 shows its spectrum (dotted curve). Clearly, it is much narrower than that of f_1 and mainly focuses on $\omega = \omega_0$. As a result, the width of the spectrum of instantaneous field near source point (solid curve) is the same as that of the source and its intensity at $\omega = \omega_0$ is lower than that of the source. The reason is that the energy of the wave with $\omega = \omega_0$ has little loss due to the effect of resonance. Figure 6 shows the corresponding field distribution for source f_2. We clearly find that there still exist many closed ray paths running across the four interfaces.

As is known, (1) is an ideal model for LHM materials. In a real implementation of a LHM, we should consider the effect of loss. Thus the Lorentz model for the permittivity and the permeability including losses in the optical parameters should be applied and is shown as [14]

$$\begin{aligned}\varepsilon(\omega) &= 1 + \frac{\omega_{\mathrm{pe}}^2}{\omega_{1\mathrm{e}}^2 - \omega^2 - \mathrm{i}\gamma_{\mathrm{e}}\omega},\\ \mu(\omega) &= 1 + \frac{\omega_{\mathrm{pm}}^2}{\omega_{1\mathrm{m}}^2 - \omega^2 - \mathrm{i}\gamma_{\mathrm{m}}\omega}.\end{aligned} \tag{2}$$

In calculations, we keep $\omega_{\mathrm{pe}} = \omega_{\mathrm{pm}} = 1.885$ GHz and $\omega = \omega_0 = \omega_{\mathrm{pe}}/\sqrt{2}$. The items γ_{e} and γ_{m} refer to the loss. We set $\omega_{1\mathrm{e}} = \omega_{1\mathrm{m}} = 0.1$ GHz and $\gamma_{\mathrm{e}} = \gamma_{\mathrm{m}} = 0.001$ GHz. A point source with the form $f_2(n\Delta t) = \exp[-\frac{(n-10000)^2}{5000^2}]\sin[\omega_0(n-10000)\Delta t]$ is also placed at point P, and only $\boldsymbol{E}$ polarization wave is considered. The result is shown in Figure 7a. Although the resonant effect is decreased due to the loss, the closed ray paths clearly exist. Also we find that there is some localized field on the interface between the RHM materials and LHM materials. The spectrum of the instantaneous field near the source point is also plotted in Figure 7b. Compared with Figure 5, the intensity at $\omega = \omega_0$ is much decreased, but the energy still focuses at $\omega = \omega_0$. Thus the filtering function still exists.

In conclusion, we perform a FDTD simulation to realize an open cavity. This open cavity does restrict electromagnetic wave with a special frequency. In addition, it can be used as a filter.

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