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Optimal parameter relations to realize high-power transmission in planar waveguide filled with lossy left-handed material

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Abstract

In a planar waveguide filled with two-layered equal-thickness media, in which one is air and the other is a lossy left-handed medium (LHM) with the relative permittivity $\varepsilon_{r1} = -(1+\delta) + i\gamma_\varepsilon$ and permeability $\mu_{r1} = -1/(1+\delta) + i\gamma_\mu$, we show rigorously that extremely high power densities can be generated and transmitted along the waveguide. In such a lossy super waveguide, the poles in the relevant integrals are complex, whose real parts represent the wavenumbers of guided modes propagating along the waveguide and imaginary parts denote the attenuations of guided modes. We find that optimal values of the retardation parameter δ exist once the loss in LHM is given to make the transmitted power be maximum. Compared with the conventional air-filled waveguide, at an observation point 10 wavelengths away from the source, the transmitted power density in the lossy super waveguide can be 10 000 times larger even when the loss is as high as 10^{-4} and the retardation is as large as -0.0085.

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1. Introduction

In 1968, Veselago first investigated the electrodynamics of a left-handed medium (LHM) with simultaneously negative permittivity and permeability, in which the electric field, the magnetic field, and the wave vector (**E**,**H**,**k**) form a left-handed system [1]. A number of novel properties exhibited by the new material were predicted, such as the negative refraction and reversed Cherenkov radiation in contrast to the conventional right-handed medium (RHM). Pendry followed the pioneering work and proposed the possibility of "perfect lens" using a planar non-dispersive LHM slab with the anti-vacuum condition $\varepsilon_r = \mu_r = -1$ [2]. Although it is impossible to realize such a perfect lens since the anti-vacuum condition is unphysical [3,4], super-resolution can still be achieved when the loss and retardation effects are considered [5–7]. Experimental demonstrations of artificial LHM have been studied by Smith et al. using the combination of metallic rods and split ring resonators (SRR) [8]. An alternative method has also been proposed to realize LHM by the transmission line (TL) network [9], from which novel microwave devices and antennas have been developed with relatively compact structures and high efficiencies [10].

Recently, a super electromagnetic planar waveguide has been proposed to realize the extremely high power generation and transmission [11]. In the super waveguide, two-layered media with equal thickness are filled: one layer is air and the other is a lossless LHM with the relative permittivity $\varepsilon_r = -(1+\delta)$ and permeability $\mu_r = -1/(1+\delta)$. Here, δ is a small parameter, representing a retardation of the perfect anti-vacuum. When a line source is located inside the super waveguide, it has been shown rigorously that several guided modes are excited due to the discontinuity. Unlike in the conventional air-filled waveguide, the electromagnetic fields of guided modes are

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extremely high in the super waveguide, which are inversely proportional to δ. Therefore, extremely high-power densities are generated and transmitted along the waveguide without attenuation [11]. It has also been shown that the power flows in the air and LHM have opposite directions, which ensures the validation of energy conservation.

The lossy effect of LHM on the super waveguide has also been discussed in Ref. [11], where it has been shown that very high-power flow could still be generated and transmitted through the waveguide. However, such a high-power transmission does not always occur in the lossy case. We may have to ask the following questions: How does the loss in LHM affect the high-power generation and transmission in the super waveguide? Is there an optimal relation between the loss and retardation in realizing the high-power generation and transmission? In order to get the answers and gain further insights on the role of loss, we present detailed analysis and numerical results in this paper to describe the physical pictures in the lossy super waveguide.

2. Theoretical analysis and numerical results

We consider a planar waveguide structure filled with right handed (RH) and left handed (LH) media, as shown in Fig. 1. The upper layer, Region 0 ($d_0 \leqslant z \leqslant d_1$), is the air ($\varepsilon_{r0} = \mu_{r0} = 1$), and the lower layer, Region 1 ($d_1 \leqslant z \leqslant d_2$) is a lossy LHM with the relative permittivity $\varepsilon_{r1} = -(1+\delta) + i\gamma_\varepsilon$ and permeability $\mu_{r1} = -1/(1+\delta) + i\gamma_\mu$. Here, the parameter δ describes a retardation of the real part to the perfect anti-vacuum condition, and γ_ε and γ_μ are loss factors. Clearly, $h_0 = d_1 - d_0$ and $h_1 = d_2 - d_1$ represent the thicknesses of Regions 0 and 1, respectively. In this letter, we let $h_0 = h_1$. The perfectly electrically conducting (PEC) boundaries are located at $z = d_0$ and d_2, as shown in Fig. 1. A linear current source is placed at the origin of the Cartesian coordinate system with the current amplitude $I = 1\,\text{mA}$, yielding TE polarized waves in the y direction.

From the electromagnetic theory and the boundary conditions, we obtain the electric fields in different regions

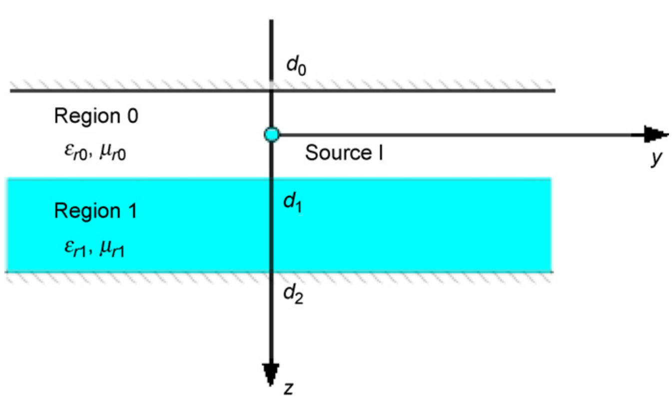

Fig. 1. An x-directed linear current source located in a planar waveguide filled with two-layered media.

of the RHM–LHM filled waveguide

$$E_{0x} = \int_0^{+\infty} dk_y 2\zeta[e^{ik_{0z}|z|} + A_0 e^{ik_{0z}z} + B_0 e^{-ik_{0z}z}] \times \cos(k_y y), \tag{1}$$

$$E_{1x} = \int_0^{+\infty} dk_y 2i\zeta[A_1 e^{ik_{1z}z} + B_1 e^{-ik_{1z}z}] \sin(k_y y), \tag{2}$$

where $\zeta = -\omega\mu_0 I/(4\pi k_{0z})$, $k_{iz} = \sqrt{k_i^2 - k_y^2}/(i = 0, 1)$; A_0 and A_1 are coefficients of forward waves in Regions 0 and 1, and B_0 and B_1 are coefficients of backward waves in the two regions.

After simple derivations, we have [11]

$$A_0 = -(pa^- c^+ + a^+ c^-)/D, \tag{3}$$

$$A_1 = -1 - A_0 e^{i2k_{0z}d_0}, \tag{4}$$

$$B_1 = (a^- b^+ - a^+ b^-)/D, \tag{5}$$

$$B_0 = -B_1 e^{-i2k_{1z}d_2}, \tag{6}$$

where $p = \mu_{r0}k_{1z}/(\mu_{r1}k_{0z})$, $D = pb^- c^+ + b^+ c^-$, $a^\pm = e^{ik_{0z}d_1} \pm e^{-ik_{0z}d_1}$, $b^\pm = e^{ik_{0z}d_1} \pm e^{-ik_{0z}(d_1 - 2d_0)}$, $c^\pm = e^{-ik_{1z}d_1} \pm e^{ik_{1z}(d_1 - 2d_2)}$.

As has been discussed in Ref. [11], when the anti-vacuum condition is satisfied, i.e., $\delta = \gamma_\varepsilon = \gamma_\mu = 0$, continuously infinite modes could be guided by the waveguide and infinitely high-power density could be generated and transmitted. Obviously, this is unphysical. When a small retardation δ exists and the LHM is lossless, i.e., $\gamma_\varepsilon = \gamma_\mu = 0$, a number of guided modes are excited if the guidance condition is satisfied [11]. In this case, the propagation constants of guided modes correspond to the poles along the integration path, the real k_y axis. It has been shown that extremely high power densities are generated and transmitted without attenuation along the lossless super waveguide.

Now we consider a general case where all of δ, γ_ε, and γ_μ are not zero. In such a lossy case, we investigate the denominator D. Using the Taylor expansion and neglecting higher-order terms of δ, γ_ε, and γ_μ, we obtain

$$D = \frac{e^{i2k_{0z}d_1}}{k_{0z}^2}\{[k_0^2(\gamma_\mu + \gamma_\varepsilon) - 2k_{0z}^2\gamma_\mu]\sin 2k_{0z}h_0 - 2k_0^2 k_{0z}h_0(\gamma_\mu + \gamma_\varepsilon) + i2k_{0z}^2\delta \sin 2k_{0z}h_0\}. \tag{7}$$

Clearly, the denominator D is a linear function of $\gamma_\mu + \gamma_\varepsilon$, γ_μ, and δ. Note that Eq. (7) reduces to Eq. (14) in Ref. [11] when $\gamma_\varepsilon = \gamma_\mu = 0$, which has only accounted for the effect of small retardation. Hence, both the denominator and integrands will be affected even though the loss is very small.

We take a rough look at the denominator shown in Eq. (7). It is clear that D will be small when $|\delta|$, γ_ε, and γ_μ are small. If the losses γ_ε and γ_μ are fixed, D decreases as $|\delta|$ decreases, which seems to result in larger field values and higher power densities inside the waveguide. However, the real physical picture is not so simple. In order to show the lossy and retardation effects on the power densities directly, we make a computation of the real part of the