Resonant Excitation of Plasma Waves in Near-Zero Index Metamaterials

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A detailed understanding of the propagation of electromagnetic waves in various kinds of metamaterials plays a crucial role in the development of efficient photonic devices. Electromagnetic waves incident on a metamaterial fabricated using metals or semiconductors can induce different kinds of plasma waves in the free electron plasma inside the medium. We are especially interested in the excitation of volume plasma waves in inhomogeneous metamaterials, where the effective refractive index vanishes in a small resonance region, and the mode conversion or inverse mode conversion phenomena associated with it. It is possible to excite longitudinal plasma waves in the resonance region, where the energy of incident transverse electromagnetic waves can be converted into that of volume plasma waves [1, 2]. In the presence of a small damping in the resonance region, this mode conversion leads to a resonant absorption of wave energy [3]. On the other hand, in the presence of a small gain maintained by an external pumping, the energy of incident transverse waves can be resonantly enhanced due to an inverse mode conversion phenomenon. We point out that this is a new phenomenon which has never been studied before.

We study the resonant absorption and amplification phenomena in both uniform and one-dimensionally inhomogeneous metamaterials theoretically, using the invariant imbedding method developed by us recently [4, 5]. Starting from Maxwell's equations and the constitutive relations, we derive the wave equations satisfied by linearly or circularly polarized waves in stratified media. These equations are transformed into a set of first-order ordinary differential equations called the invariant imbedding equations, using which we calculate the reflectance R, the transmittance T and the amount of the absorbed or amplified energy, as well as the electromagnetic field profiles inside the media in a numerically exact manner.

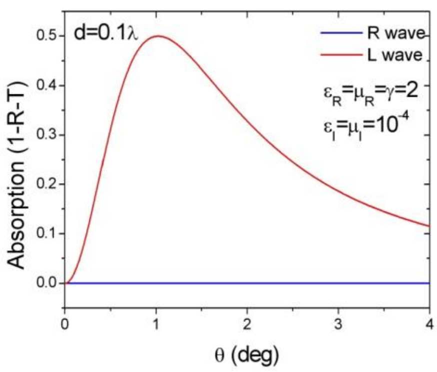

Fig. 1

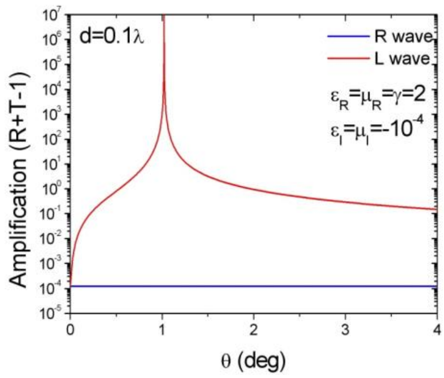

Fig. 2

First, we consider uniform slabs made of metamaterials with almost zero real parts of the dielectric permittivity ε or/and the magnetic permeability μ. We find that mode conversion occurs when s (p) polarized waves are incident if μ (ε) is almost zero. When both ε and μ are almost zero, both s and p waves can induce mode conversion. If the small imaginary parts of ε and μ are positive (negative), mode conversion leads to resonant absorption (amplification) of incident waves. We also make a novel generalization of these interesting concepts to chiral metamaterials, inside which circularly polarized waves are eigenmodes [4]. The effective refractive indices for right-hand and left-hand circularly polarized waves are $\sqrt{\varepsilon\mu}+\gamma$ and $\sqrt{\varepsilon\mu}-\gamma$ respectively, where γ is the so-called chirality parameter. It turns out that mode conversion occurs when the effective refractive index is zero in this case. In Fig. 1, we plot the absorptance versus incident angle when circularly polarized waves are incident on a thin chiral slab with small positive imaginary parts of ε and μ. We find that the maximum value of the absorptance is about 50 %, even when the slab is very thin and the imaginary parts of ε and μ are extremely small. The resonant behavior is even more dramatic if the small imaginary parts of ε and μ are negative, as shown in Fig. 2. We observe that left-hand circularly polarized waves are almost infinitely amplified at a certain critical angle.

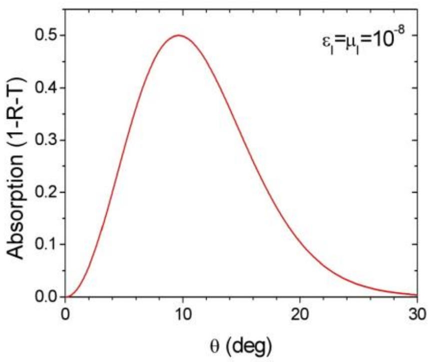

Fig. 3

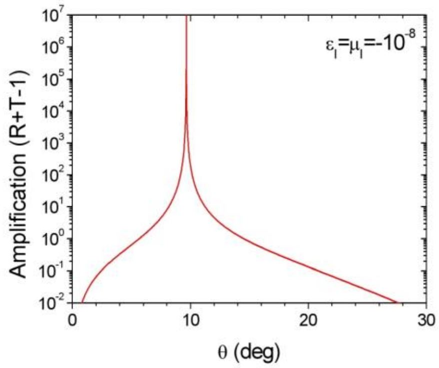

Fig. 4

Second, we consider nonuniform slabs where ε and/or μ change from positive to negative values in a continuous manner. For instance, this situation can describe a transient region between positive index and negative index media. Specifically, we consider a model where both ε and μ change from 1 to -1 in a distance 5λ. In Figs. 3 and 4, we plot the absorption and the amplification of incident waves when the imaginary parts of ε and μ are 10^{-8} and -10^{-8} respectively. We find again the resonant absorption and giant amplification phenomena, which exist even in the limit where the imaginary parts of ε and μ go to zero.

In conclusion, we have studied theoretically the resonant absorption and amplification phenomena due to the excitation of longitudinal plasma waves in various kinds of uniform and nonuniform metamaterials. The results obtained here can be useful in designing efficient absorbers and amplifiers. They are also useful in the development of enhanced nonlinear optical devices.

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References

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