Metamaterials for omnidirectional reflectors and hollow-core waveguides

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Abstract: We show that metamaterials have omnidirectional reflecting properties in the frequency region between the magnetic plasma frequency and the electric plasma frequency. These properties are useful for reflectivity control, low loss mirrors, and hollow-core waveguides.

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Negative Index Materials (NIMs) are a class of metamaterials that have a negative electric permittivity and a negative magnetic permeability over a particular frequency range yielding a negative index of refraction. The emphasis of most researchers is on the frequency region of negative indices. In this paper we investigate the frequency range just above the negative refractive index in the region where the real part of the refractive index is very close to zero. This is somewhat analogous to a metal at optical frequencies where the real part of the refractive index is much less than unity. These interesting properties have a range of applications including waveguiding with the core being composed of air.

The overall development of NIMs has occurred at an astounding pace due to the potential applications [1]. A recent publication[2] illustrated the striking similarities in the optical properties of NIMs and 1D Photonic Band Gap (PBG) materials. The similarities are due to the fact that the dispersion relation for the NIM in a spectral range around the electric plasma frequency mimics that of the Bloch's vector for a 1D, infinite periodic structure[2].

A typical 1D-PBG consists of a multilayer stack of alternating high and low index materials. The transmittance spectrum of the 1D-PBG has a gap (sometimes called a stop band or reflecting band) whose width and depth depend primarily on the index contrast of the layers and number of periods, respectively. The high reflecting properties of 1D-PBGs are a result of the constructive interference of smaller reflections at each interface.

The transmittance spectrum of a single layer of NIM also has a band gap. The width of the gap in a NIM is dependent upon the separation of the electric and magnetic plasma frequencies and its depth depends on the thickness of the layer. The high reflecting properties of NIMs are not due to interference effects and are a result of a refractive index being very close to zero at frequencies between the electric plasma frequency and the magnetic plasma frequency. We are assuming that the unit cell of the NIM is small enough that the optical properties can be described by the macroscopic parameters ε and μ, the electric permittivity and magnetic permeability, respectively.

Other similarities between a single layer of a NIM and a 1D PBG are superluminal group velocities inside the gap where the transmittance is small and low group velocities at the band edges where the transmittance is large[2].

Not all the properties of NIMS and 1D PBGs are similar, for instance the 1D PBG has a strong field localization at both band edges while the NIM has field localization at one band edge and field delocalization at the other. If nonlinearities are incorporated, the 1D PBG will support bright solitons while the NIM will support both bright and dark solitons[3].

Another feature of the NIM which sets it apart from a 1D PBG is the angular dependence of the transmittance spectrum[2]. In a 1D PBG the stop band blue shifts with increasing angle due to the change in the optical path through each layer as the refraction angle changes. The stop band in a NIM does not shift and actually widens with increasing angle. The angular dependence of the stop band in a NIM and its omnidirectional reflecting properties are the topics of this paper.

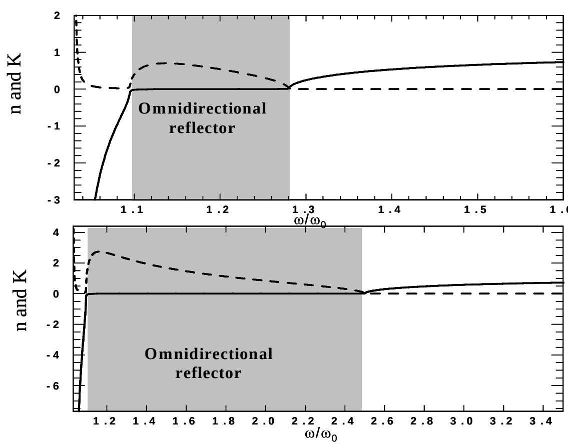
Omnidirectional reflectors have been made in 1D PBGs by forming an extra wide gap[4-6]. The idea is to make the normal incidence gap extremely wide so that the shift with angle is not large enough to completely move the entire stop band to a new range of frequencies. The gap in a 1D PBG can be widened by having a very large index contrast and/or by adding more periods with different lattice constants. Omnidirectional NIMs do not have these constraints since the gap does not shift and actually widens with increasing angle of incidence.

A convincing experimental demonstration of negative refraction was made by Shelby, Smith, and Schultz[7]. They constructed a 2D NIM consisting of metal wires for the electric response and split ring resonators (SRRs) for the magnetic response. According to their experimental results, the complex, frequency dependent electric susceptibility ε and the magnetic permeability μ of the NIM can be modeled as follows[7, 8]:

$$\varepsilon(\omega) = 1 - (\omega_{ep}^2 - \omega_{eo}^2)/(\omega^2 - \omega_{eo}^2 + i\gamma\omega) \quad (1)$$

$$\mu(\omega) = 1 - (\omega_{mp}^2 - \omega_{mo}^2)/(\omega^2 - \omega_{mo}^2 + i\gamma\omega) \quad (2)$$

where ω_{ep} is the electric plasma frequency, ω_{eo} is the electric resonance frequency, ω_{mp} is the magnetic plasma frequency and ω_{mo} is the magnetic resonance frequency and γ the loss term. The parameters are taken according to the experimental results reported in Ref. 7, i.e.: $\omega_{ep}=2\pi\times12.8$GHz, $\omega_{eo}=2\pi\times10.3$GHz, $\omega_{mp}=2\pi\times10.95$GHz, $\omega_{mo}=2\pi\times10.05$GHz, $\gamma=2\pi\times10$MHz.



1(a)

1(b)

Fig.1

Fig. 1) Optical constants of a broadband omnidirectional reflector. Index of refraction n (solid line) and extinction coefficient K (dashed line) vs. ω/ω_0 where $\omega_0=2\pi\times10$GHz. Fig. 1a, optical constants based on the experimental parameters of Ref. 7. In Fig.1(b) we use the same parameters as in Fig.1(a) except that $\omega_{ep}=2\pi\times25$GHz.

The optical constants for a material can be defined as $N = (\varepsilon\mu)^{1/2} = n + iK$, where N is the complex index of refraction, n is the index of refraction, and K is the extinction coefficient. The sign in front of the square root must be chosen in a way that ensures the Poynting vector of the light, refracted into a semi-infinite slab of NIM, will always be directed away from the interface and into the refracting material itself[2, 3]. Fig. 1a shows the optical constants for the material parameters described above. Fig. 1b shows the optical constants for the same material parameters as in Fig. 1a with the exception that the electric plasma frequency has been moved to $\omega_{ep} = 2\pi\times25$GHz. Notice that a gap forms between the electric and magnetic plasma frequencies. On the low frequency side of the gap is the region of negative index. Inside the gap, the optical constants of the NIM are similar to a metal at optical frequencies with a small index of refraction and a small but finite extinction coefficient. For comparison, the optical constants of silver at λ = 620 nm are n=0.131 and K=3.88 (Ref. 9). Metals are good reflectors at optical frequencies because the refractive index is close to zero and K is reasonably large. NIMs reflect radiation more efficiently than metals because the refractive index is essentially zero inside the gap.

Comparing Figs 1a with 1b illustrates the dependence of the gap on the choice of ω_{ep} and ω_{mp}. Increasing the separation of the electric and magnetic plasma frequencies has expanded the width of the gap by a factor of five. It has been previously shown that the width and center frequency of the gap can be written as $\Delta\omega\sim|\omega_{ep}-\omega_{mp}|$ and $\omega_c\sim(\omega_{ep}+\omega_{mp})/2$, respectively[2], therefore, the larger the separation between the electric and magnetic plasma frequency the wider the spectral region where the NIM behaves as an omni-directional reflector.

From the optical constants plotted in Fig 1 we can show by that the reflectivities inside the gap are on the order of 98% for all polarizations and angles of incidence. At normal incidence, the highly reflecting band occupies the region between the magnetic plasma frequency and the electric plasma frequency of the NIM. At the steeper angles of incidence, the low frequency side of the reflecting band remains fixed at the magnetic plasma frequency. On the high frequency side of the gap where the NIM has a positive index of refraction, the reflecting band begins to widen as the angle of incidence increases. In this frequency region, the optical constants of the NIM are similar to a low loss dielectric with the exception that the index of refraction is less than unity. The radiation is propagating from a high index region to a low index region and the highly reflecting band terminates when the angle of incidence is less than the angle required for total internal reflection. Also, the reflection is not overly sensitive to losses. If we double the loss term of Eqns 1 and 2, the reflectivity drops by only 1%. The high reflectivities at very steep angle are ideal for applications in hollow-core waveguides.

In summary we have demonstrated that a single layer of a NIM has omnidirectional reflecting properties in the region between the electric and magnetic plasma frequencies. In this frequency region, the optical constants of a NIM are similar to real metals at optical frequencies. However, the reflecting properties of “metallic NIMs” are superior to ordinary metals as a result of the real part of the index of refraction being nearly zero.

The wide range of applications for NIMs in general and for metallic NIMS in particular, such as hollow core waveguides[10,11] and highly efficient back-reflectors for common light fixtures, give additional motivation to develop these unique metamaterials. High reflectivity from metamaterials having a refractive index near zero has been reported for low loss waveguide applications by Schwartz and Piestun[11]. The results show that waveguiding in air using silver/dielectric metamaterials as cladding layers provide lower propagation loss than solid silver reflectors.

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