TE and TM Guided Modes in Air through a Negative Index Material Waveguide.

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Abstract
We demonstrate that a planar waveguide with an air core and a negative index material cladding can support both transverse electric (TE) and transverse magnetic (TM) guided modes with low losses.

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Negative index materials (NIM s), i.e. materials that have simultaneously negative electric susceptibility and magnetic permeability, seem to challenge several well established concepts in electromagnetism and optics. Perhaps the best known examples are their ability to refract light in the opposite way with respect to what an ordinary material does [1], and the possibility to use them to construct a perfect lens, i.e. a lens that can focus all Fourier components of a 2D image, even those that do not propagate in a radiative manner [2]. The aim of this work is to demonstrate that light can be confined in air by using a waveguide where the bounding medium, or cladding, is made of a NIM. In this case the confinement is due, as in classical waveguides, to total internal reflections. The NIM is described with a lossy Drude model [3]:

$$\varepsilon(\tilde{\omega}) = 1 - \frac{1}{\tilde{\omega}(\tilde{\omega} + i\tilde{\gamma}_e)} \quad , \quad \mu(\tilde{\omega}) = 1 - \frac{(\omega_{pm}/\omega_{pe})^2}{\tilde{\omega}(\tilde{\omega} + i\tilde{\gamma}_m)} \quad , \qquad (1)$$

where $\tilde{\omega} = \omega/\omega_{pe}$ is the normalized frequency, ω_{pe} and ω_{pm} are the respective electric and magnetic plasma frequencies, $\tilde{\gamma}_e = \gamma_e/\omega_{pe}$ and $\tilde{\gamma}_m = \gamma_m/\omega_{pe}$ are the respective electric and magnetic loss terms normalized with respect to the electric plasma frequency. In the transition region of the NIM, i.e. in the region where Re(ε) and Re(μ) have opposite signs, no propagating modes are allowed in the linear regime. The NIM becomes opaque with the complex refractive index that becomes almost a pure imaginary number, $n \cong i\beta$, and the potential barrier is insurmountable. This opaque region represents an intrinsic gap for the electromagnetic radiation different in nature from the gap formed in photonic band gap (PBG) structures, but with similar pictorial characteristics. In PBG structures the formation of the gap is due to destructive interference caused by the periodic arrangement of scattering or diffracting elements whose sizes are on the order of the incident wavelength. In contrast, NIMs are structured on a much finer scale that ranges from $1/10^{th}$ to $1/1{,}000^{th}$ of the wavelength [2], and therefore they respond with an effective dispersion that is essentially due to the bulk properties of the medium. However, while the nature of the gap is different in the two cases, it would be interesting to explore the possibility of using NIMs in the spectral region of opacity as the cladding of a waveguide. Our calculations show that both TE and TM guided modes can exist in the spectral region of opacity of the NIM with losses that vary from 6dB/m for the fundamental mode at ~10μm and an air core of 20μm to 0.01dB/m for a 140 μm core of air. In Fig. 1(a) we show the fundamental TE mode and in Fig 1(b) the fundamental TM mode. While further material development is still needed, recent advancements in the design of meta-materials [2] suggest that this waveguide could operate in the infrared regime with better performances compared to more traditional hollow waveguides.

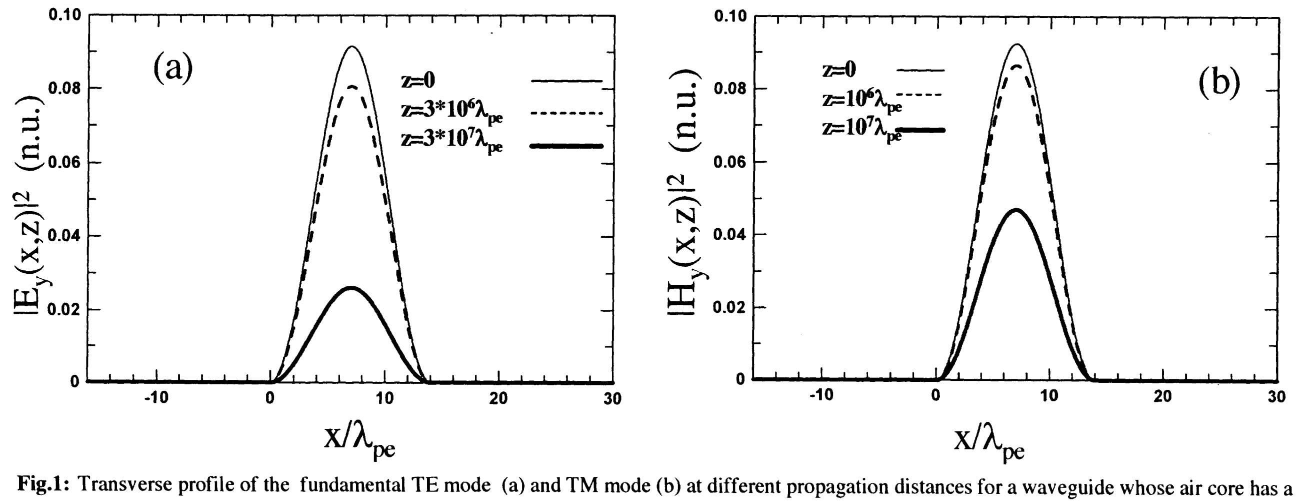

Fig.1: Transverse profile of the fundamental TE mode (a) and TM mode (b) at different propagation distances for a waveguide whose air core has a thickness $d=14\lambda_{pe}$. The frequency of the field is $\omega=0.88\omega_{pe}$. The parameters of the NIM are: $\omega_{pm}/\omega_{pe} = 0.8$ and $\tilde{\gamma}_e \approx \tilde{\gamma}_m \approx 10^{-4}$.

References

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[2] J. Pendry, *Opt. and Photon. News*, **15** , No9, 33 (2004), and references therein.