FDTD Simulation of Perfect Lens Imaging System

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The ability of the Finite-Difference Time-Domain (FDTD) method to model a perfect lens made of a slab of homogeneous left-handed material (LHM) is investigated. It is shown that because of the frequency dispersive nature of the medium and the time discretization, an inherent mismatch in the constitutive parameters exists between the slab and its surrounding medium. This mismatch in the real part of the permittivity and permeability is found to have the same order of magnitude as the losses typically used in numerical simulations. Hence, when the LHM slab is lossless, this mismatch is shown to be the main factor contributing to the image resolution loss of the slab.

Using the Auxiliary Differential Equation (ADE) method to implement the frequency dispersive permittivity and permeability for Drude model, we show that after the FDTD discretization, the numerical permittivity (so as permeability) can be described as

$$\epsilon_r = 1 - \frac{\omega_{pe}^2}{4\sin(\omega_o \Delta t/2)/(\Delta t)^2} \tag{1}$$

It is clear that Eq. 1 approaches the Drude model $\epsilon_r = 1 - \omega_{pe}^2/\omega_o^2$ in the limit of $\Delta t \to 0$, which gives a value of -1 when $\omega_{pe} = \sqrt{2}\omega_o$. However, for a finite Δt used in an actual simulation, ϵ_r presents a slight deviation from exactly -1 at the same ω_{pe}. As an example, the value of ϵ_r from Eq. 1 is about -1.000297 for a typical grid size of $\lambda/100$, which is also the value of the refractive index since we choose here a magnetic plasma frequency identical to the electric one. This small perturbation does not affect the propagating waves significantly. However, the resolution of a subwavelength imaging system is critically dependent on the reconstruction of the evanescent waves, or part of the evanescent wave spectrum, by the LHM slab. This reconstruction is in turn critically dependent on the slab's constitutive parameters, and the slight mismatch of 0.03% in the real part has an important impact on the resolution of the image as we shall see hereafter. It is important to note that this small perturbation in the real part of the constitutive parameters has often been overlooked and the imaginary parts with a value in the same order are typically considered to be the main contributor for limiting the image resolution. By comparing the simulation results and analytical calculations, we demonstrate that the simulated image resolution of an LHM perfect lens is mainly limited by this mismatch. In other applications such as the simulation study of surface plaritons at LHM/RHM interfaces where the matching condition is required, the understanding of this limitation in FDTD can also be very important.