Metamaterial in the quasi-static regime

Jonghwa Shin* and Yong-Hee Lee
Department of Physics, KAIST, Daejeon, Korea
**E-mail:qubit@kaist.ac.kr*

Most of metamaterial structures proposed or fabricated previously have been directly based on resonances of metallic inclusions. In the vicinity of the resonance wavelength, the amplitude and phase of the local electromagnetic fields around the resonant elements have a strong dependence on the wavelength. Therefore, the effective material parameters, such as permittivity and permeability, swing over a large range of values for small changes in wavelength. This strongly pronounced dispersion of effective material parameters can be beneficial when one tries to design metamaterial with extreme values of permittivity and permeability combinations. That is because slight changes in shape and size of the inclusion result in large effective parameter changes and desired combinations of parameters can be easily obtained by a few trial and errors, starting from a structure with known resonance frequency.

However, the resonance-based scheme has several, rather severe problems in real applications. First, the very fact that it is strongly dispersive around the resonance wavelength, which helped the design process, places a fundamental limit on the bandwidth over which the system shows the intended effective material properties. The effective properties assume values quickly deviating from the design values as the operating wavelength detunes from the design wavelength. This may be ok if one is only interested in a single wavelength, but becomes a problem if the device needs to operate over a broad bandwidth.

The optical loss is also a problem. In common with diverse range of resonance phenomena in other areas of physics, the local field shows large amplitude near the resonance wavelength. Since metallic inclusions of metamaterial has intrinsic material loss due to the non-zero imaginary component of its complex permittivity, metamaterial is optically lossy system. This loss becomes especially problematic in the spectral vicinity of resonance wavelength because the local field intensity is higher for the same input power and the phase of electric current is such that it efficiently absorbs optical power. This loss may limit device sizes, for example the cloaked volume in invisibility cloak, or it may severely degrade the performance of the device.

Another problem is fabrication tolerance. The effective parameters are sensitive to the relative detuning of the operation wavelength and the resonance wavelength of the inclusions. Thus, slight perturbations in the shape and size of inclusion structures induce large swing of effective properties by influencing the resonance wavelength. In real situations, one always has to consider the errors from fabrication steps and strict requirement of element size and shape tolerance may limit the fabrication methods to only those which are slow and costly.

On the other hand, it was shown that metamaterial in the quasi-static regime can possess very interesting effective properties [1–3]. One example is metamaterial with a high refractive index over a broad bandwidth [2–3]. The authors theoretically and experimentally demonstrated that a high index metamaterial with weak dispersion can be realized. Another example is metamaterial with much more internal degrees of freedom than typical metamaterial that can be parameterized with effective permittivity and permeability [1].

Metallic elements used in these 'quasi-static' metamaterial also exhibit resonant behavior at shorter wavelengths. However, the key difference of these metamaterial and other metamaterial is that operation wavelength range of the 'quasi-static' metamaterial can span a couple of octaves or more while the wavelength range for the latter is typically a few percent of center wavelength or smaller. This dramatic difference in potential operation bandwidth comes from the differences in the design principles. The resonance-based design approach directly utilizes the strong dispersion around the resonance wavelength to achieve desired set of effective parameters through slight structural tuning, starting from a known structure. This approach has the advantage that it does not require of the designer a deep insight into the mesoscopic field distribution and its effect on macroscopic properties since the desired values can be obtained from diverse range of initial structure design through parameter sweeps or optimizations. The disadvantages of this approach are already outlined above. The design principles of the quasi-static metamaterial require consideration of the electromagnetic field distribution around metallic element in the quasi-static regime. But once understood, the principles can be applied almost universally to any application of quasi-static metamaterial.

The main limitations of quasi-static metamaterial are two-fold. First, some permittivity-permeability combinations, such as doubly-negative media, are fundamentally limited to dispersive systems and, hence, are not accessible by quasi-static, nearly-dispersion-free metamaterial. Another disadvantage is that the resonance wavelength should be much shorter that the operation wavelength if one intends the metamaterial to be very non-dispersive. This imposes constraints on the minimum feature size that needs to be fabricated. However, even with these considerations, quasi-static metamaterial provides a unique and potentially more realistic alternative to the current, resonance-based metamaterial and needs to be studied more extensively.

References

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