Free-space-matched left-handed metamaterials

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The rich concept of left-handed media (LHM) was theoretically introduced by V. G. Veselago in 1968 (V. G. Veselago, Sov. Phys. Uspekhi, 10, 509-514, 1968.). First experimental demonstrations were developed by David R. Smith and co-workers in for 1D (D. R. Smith et al., Phys. Rev. Lett., 84, 4184-4187, 2000) and 2D structure (R. A. Shelby et al., Science, 292, 77-79, 2001). In those seminal works, it was demonstrated that it is possible to make artificial media with both the electric permittivity ε and magnetic permeability μ simultaneously negative in a certain range of frequency. The samples were composed of split ring resonators, for $\mu < 0$ near the resonance frequency, and straight metallic rods, for $\varepsilon < 0$ below the plasma frequency. However, since the mechanisms giving the effective μ and ε were different, it is not possible to match the wave impedance of the effective medium with the free-space impedance. The mismatch is so important that, for the whole LHM band, most of the impinging energy was reflected just at the interface between the vacuum and the slab. Therefore, the reported low transmission (several decades of decibels below 0 dB) was not only due to the attenuation inside the metamaterial, but also to the strong reflection at the entrance of the slab. Recently, an element like the one shown in Fig. 1(a) was used in (M. Londoño, Phys. Rev. Appl., 10, 034026, 2018) as the building block of a Huygens metasurface. It was demonstrated that it presents very similar functions for the electric and magnetic polaribilities in a wide range of frequencies about the resonance. Now, we have studied the use of the same type of unit cell to make a bulk LHM matched to the free-space impedance. The almost equality of the electric and magnetic polarizabilities implies that the ratio $\mu/\varepsilon \approx 1$ at any frequency, and, therefore, the wave impedance of the effective medium approximately match the free-space impedance. Figure 1(a) shows the geometrical parameters of the simulated unit cell. The corresponding dispersion relation is shown in Fig. 1(b). It demonstrates a LHM band covering from 3.29 to 3.51 GHz, with a bandwidth of 0.22 GHz. The LHM band is surrounded by two narrow stopbands and more far in frequency the structure behaves as a right-handed medium (RHM). These stopbands appear since curves for ε and μ are not crossing the zero level at the same exact frequency. The magnitude of the transmission coefficient for a finite slab of the metamaterial is shown in Fig. 1(c) for the case of 10 cells along the propagation direction. The incident wave is supposed to propagate along the z-axis. It is worth to note that the transmission is relatively high within the LHM band, above 0.8 and 0.9 for most frequencies. The ripples are due to the impossibility of rigorous exact matching. Nevertheless, it is remarkable that the level of impedance matching achieved with this structure overcome previous attempts.

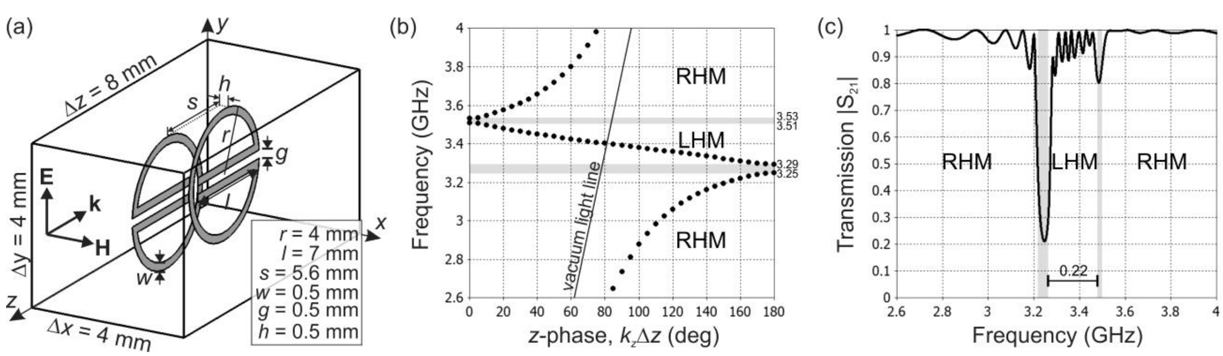

Figure 1. (a) Unit cell made of two SRRs, inverted and laterally shifted, made of perfect conductor. (b) The dispersion relation. (c) The transmission coefficient for a 10 cells deep slab.