Experimental polarization-independent dual-band metamaterial with a negative refractive index in the millimetre range

C. García-Meca[1], M. Navarro-Cía[2], M. Beruete[2], A. Martínez[1], and M. Sorolla[2]

[1]Valencia Nanophotonics Technology Center, Universidad Politécnica de Valencia
46022 Valencia, Spain
email: cargarm2@ntc.upv.es
[2]Millimeter and Terahertz Waves Laboratory, Universidad Pública de Navarra
31006 Pamplona, Spain
email: miguel.navarro@unavarra.es

Abstract

We fabricate and characterize a fishnet-like polarization-independent (for normal incidence) metamaterial displaying two different negative-index bands at millimetre wavelengths. These bands are linked to the first- and second-order resonances of the electromagnetic mode supported between metals. The backward-wave nature of both bands is confirmed by direct measurement of the structure phase response. The effective negative index of both bands is further verified by the excellent agreement between the retrieved index for the fabricated finite structures and that associated to the propagating modes of the ideal periodic (in the propagation direction) structure. Finally, we numerically show the existence of negative refraction in a prism made up of this metamaterial.

1. Introduction

Practical realization of negative-index media (NIM) have been extensively addressed because of their potential application in the construction of super-lenses. Due to its high performance, the so-called fishnet metamaterial has been widely studied as a main candidate to implement NIM. The main physical phenomena involved in the existence of an effective negative index in the fishnet structure are well-known, with slightly different interpretations [1-4]. Specifically, its magnetic response is ascribed to the excitation of resonances related to an internal mode running between the two metal layers that compose each fishnet functional layer (FL). This internal mode is usually associated with SPPs at optical frequencies and leaky waves in the microwave range [1-4]. Recently, it was shown that not only the first-order resonance of this mode, i.e., the (±1,0) or (0,±1) order, could be exploited to achieve a backward-wave band, but also the (±1,±1) second-order one [4]. This fact has been experimentally demonstrated at visible wavelengths [5]. Unfortunately, direct phase measurements are extremely difficult at such high frequencies and the experimental verification is limited to the amplitude response of the medium. To overcome this drawback, we fabricated several fishnet structures with multiple functional layers that were engineered so that the first- and second-order resonances give rise to negative-index propagating bands at millimetre wavelengths. This allowed us to experimentally confirm the above mentioned backward-wave nature of both bands (the physical phenomenon is essentially the same as in the optical spectrum) by measuring the structure phase response.

2. Experiment and simulations

In Fig. 1(a) we depict the geometric dimensions of the considered fishnet metamaterial. It consists of $2N+1$ alternating metal (m) and dielectric (d) stacked circular hole arrays resulting in N functional layers ($N = 1$ corresponds to m–d–m, $N = 2$ to m–d–m–d–m, . . .). In our experiment, we use an in-plane square lattice with periodicity $d = 2.5$ mm (notice that the symmetry of the structure implies polarization independence for normal incidence), a periodicity in the propagation direction $d_z = 0.525$ mm, a hole diameter $a = 1.1$ mm, and a metal thickness $t = 0.035$ mm. Employing these dimensions, we fabricated several samples with N varying from 1 to 4 by using an ARLON CUCLAD 250 LX and a laser-based PCB production. The permittivity of the dielectric spacer is $\varepsilon_r = 2.43 + j\ 0.022$. An AB-Millimetre™ vector network analyzer and a quasi-optical bench were used for characterization. A linearly polarized Gaussian beam (spatial power distribution) is launched by a corrugated horn antenna. After reflecting onto two elliptical mirrors, the beam is incident on the prototype with a beam spot diameter ranging from 28 mm to 18.4 mm. The transmitted beam is then guided by two other elliptical mirrors to another corrugated horn antenna acting as a receiver. The fabricated sample and experimental setup are shown in Fig. 1 (b-c).

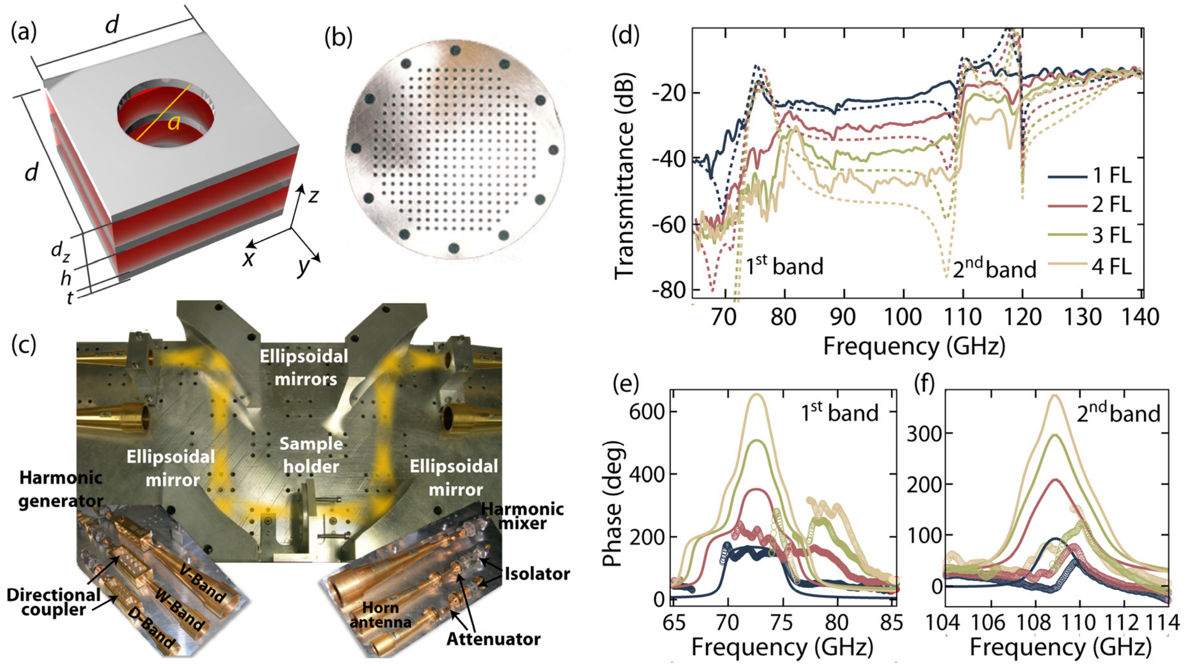

Fig. 1: (a) Fishnet geometrical dimensions (picture of two unit cells). (b) Fabricated prototype. (c) Experimental setup. (d) Measured (solid lines) and simulated (dashed lines) transmission spectra. (e) First and (f) second band measured (circles) and simulated (solid lines) phase response on transmission [same color legend as in (b)].

The amplitude and phase response on transmission of all fabricated structures are shown in Fig. 1(d-f). There is a good agreement between measurements and simulations (performed with CST Microwave Studio™). In Fig. 1(d) we can clearly observe both bands in the measured transmission, whose spectral position coincide with the numerical calculations except for a slight frequency blue-shift of the first band for $N > 1$. This can be ascribed to non-perfect assembly of the FLs. To verify the backward-wave nature of both bands from experimental data, we inspect the phase response. For backward-wave/forward-wave propagation, the phase increases/decreases with the number of FLs because of the $\exp(-jk_z\Delta l)$ dependence of the transmission, where Δl is the length of the stack, and k_z is the wavenumber in the stack, which in the case of an effective negative index n_z is $k_z < 0$. According to this description, the measured phase response is in accordance with backward-wave propagation (negative n_z) and exhibits the same tendency as in the simulations. Notice that the phase response of very low values of transmittance, where the phase measurement is really challenging, has been removed from the plot to avoid misinterpretation. The effective n_z of the fabricated structures was also calculated from simulations [6]. Remarkably, the retrieved n_z is almost independent of the number of FLs as corresponds to a homogeneous medium, although the effective behavior is only valid for a limited angular range around normal incidence. We also calculated the dispersion diagram of the ideal infinite structure (infinite FLs) through an Eigen-mode analysis. The first two propagation bands are plotted in Fig. 2(b), where we can see their backward nature. The effective n_z derived from the dispersion diagram is also plotted in Fig. 2(a), which is in excellent agreement with the n_z retrieved from the finite structure. Losses are not taken into account in the Eigen-mode analysis, so the low-frequency part of each band

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in Fig. 2(a) is a forbidden region in Fig. 2(b), since at these frequencies propagation is dominated by losses. Finally, we render in Fig. 2(c-d) the propagation in a 2D prism based on the considered metamaterial. The beam exits the prism following the rules of negative refraction for both bands.

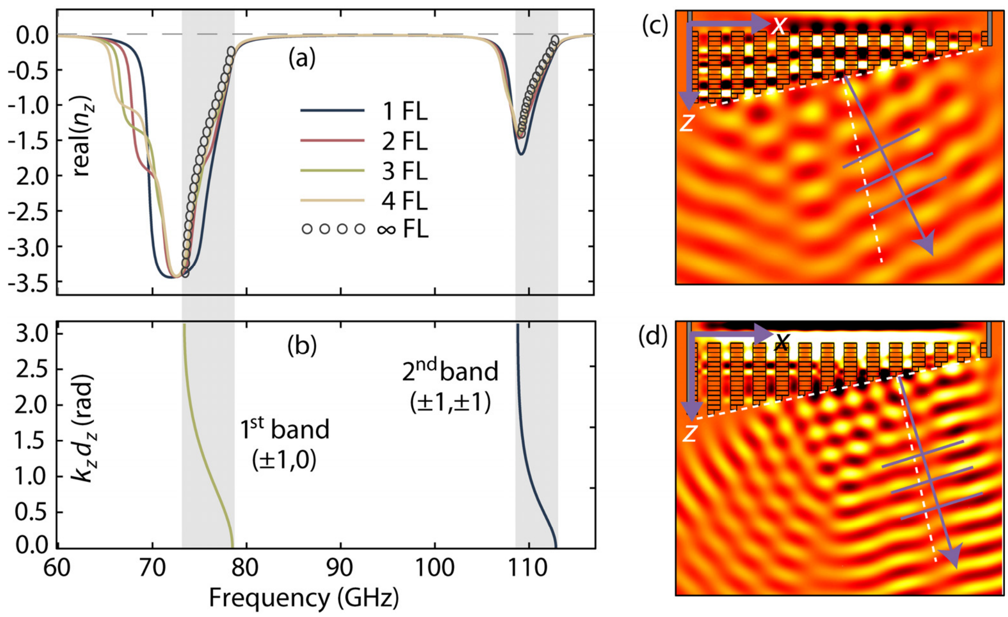

Fig. 2: (a) Retrieved effective index for different number of FLs. The circles correspond to the index derived from the dispersion diagram (infinite FLs). (b) Calculated dispersion diagram. (c) Negative refraction in a simulated prism based on the studied metamaterial at the (c) first and (d) second band. The interface and its normal have been plotted in dashed lines, and the power flow direction with a purple arrow.

3. Conclusion

We experimentally confirmed a polarization-independent dual-band negative-index metamaterial at millimetre wavelengths. Direct phase measurements allowed us to verify backward-wave propagation at both bands for different number of functional layers. The retrieved index for normal incidence is in excellent agreement with that derived from the dispersion diagram of the ideal infinite structure. Finally, we numerically demonstrated negative refraction in a prism based on this metamaterial. Work supported by Spanish Government and E.U. FEDER funds (contracts CSD2008-00066, TEC2008-06871-C02-01, and TEC2008-06871-C02-02), and Valencian Government (contract PROMETEO-2010-087). C. G.-M. acknowledges financial support from grant FPU of MICINN.

References

[1] M. Beruete, M. Sorolla and I. Campillo, Left-handed extraordinary optical transmission through a photonic crystal of subwavelength hole arrays*, Opt. Express*, vol. 14, p. 5445, 2006.

[2] M. Beruete, M. Sorolla, M. Navarro-Cía, F. Falcone, I. Campillo and V. Lomakin, Extraordinary transmission and left-handed propagation in miniaturized stacks of doubly periodic subwavelength hole arrays, *Opt. Express,* vol. 15, p. 1107, 2007.

[3] A. Mary, S.G. Rodrigo, F.J. García-Vidal, L. Martin-Moreno, Theory of negative-refractive-index response of double-fishnet structures, *Phys. Rev. Lett.*, vol. 101, p. 103902, 2008.

[4] C. García-Meca, R. Ortuño, F. J. Rodríguez-Fortuño, J. Martí, and A. Martínez, Double-negative polarization-independent fishnet metamaterial in the visible spectrum, *Opt. Lett*., vol. 34, p. 1603, 2009.

[5] C. Garcia-Meca, J. Hurtado, J. Marti, A. Martinez, W. Dickson, and A.V. Zayats, Low-loss multilayered metamaterial exhibiting a negative index of refraction at visible wavelengths, *Phys. Rev. Lett.* vol. 106, p. 067402, 2011.

[6] X. Chen, T. M. Grzegorczyk, B. Wu, J. Pacheco, Jr., and J. A. Kong, Robust method to retrieve the constitutive effective parameters of metamaterials, *Phys. Rev. E*, vol. 70, p. 016608, 2004.