Experimental verification of backward wave propagation at photonic crystal surfaces

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(Received 5 June 2007; accepted 28 October 2007; published online 20 November 2007)

Backward wave propagation is the true manifestation of left-handed electromagnetism and not negative refraction which occurs also at the interface of right-handed systems. Here we experimentally demonstrate in a direct fashion the backward wave propagation phenomenon, which takes place at the surface of a properly designed photonic crystal. Our microwave experiment could open other venues for the verification of left-handed behavior in optical metamaterials. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2814154]

In 1967, Veselago[1] envisioned a different class of media which possess simultaneously negative permittivity ϵ and permeability μ. If such a medium existed, it would support the propagation of a unique type of electromagnetic (EM) wave, not subject to the known right-hand rule. In particular, the propagation vector **k**, the electric field **E**, and the magnetic field **H** form an orthonormal left-handed coordinate system inside this curious medium, known as left-handed medium (LHM). A direct consequence is backward EM wave propagation,[2] where the flow of EM energy, given by the time averaged Poynting vector **S**, is opposite to the phase propagation direction, given by the wave vector **k**.[1] In turn, this backward type of wave propagation leads to negative refraction[1] at the interface between a conventional right-handed medium (RHM) and a LHM. Much later than conceived, the Veselago medium materialized in an artificial composite metamaterial (CMM) consisting of metallic splitring resonators and wires.[3,4] Some subsequent controversies[5] over the existence of the negative refraction phenomenon were quickly resolved.[6]

While at present the reality of negative refraction is undoubted, recent studies revealed that its existence is not necessarily linked with a left-handed medium. For instance, negative refraction occurs at the ΓM interface of a square photonic crystal (PC),[7] at a frequency range where the PC system is right handed.[8] Interestingly, negative refraction was also demonstrated experimentally at the interface of a properly cut yttrium orthovanadate (YVO_4) bulk slab.[9] YVO_4 is a uniaxial crystal medium without magnetic behavior, so an obviously right-handed substance. Hence, the demonstration of the negative refraction phenomenon inside a material does not provide any information for its "rightness."[1,8,10] In fact, it is backward wave propagation that is the fingerprint of left-handed electromagnetism and not negative refraction.[2,8]

Thus far, the type of EM wave propagation (backward or forward) was probed experimentally[4] only indirectly. An EM wave is launched through a wedge made of a CMM. Then, the reversal or none reversal of the phase velocity inside the wedge, and accordingly the "rightness,"[1,10] is inferred from the position of the final beam relative to the wedge normal. However, this method would be hard to implement[11] for visible CMMs.[12] Accordingly, an alternative method for unveiling the existence of left-handed electromagnetism is of particular interest.

In this letter, we apply a modification of the attenuated total reflection (ATR) technique to experimentally identify in a direct manner the backward wave propagation phenomenon. The ATR setup was used widely in the past to examine surface states in metals[13] or guided modes in dielectric slabs.[14] It also led lately to the experimental discovery of surface waves at PC structures.[15] Although such structures are a periodic arrangement of a positive permittivity material, they can support surface waves which resemble surface-plasmon polaritons in metals. Very recently, Foteinopoulou *et al.*[16] theoretically demonstrated the existence of backward PC surface waves for an original PC design with a surface defect. These emanate from a surface PC band with a negative slope, just like backward bulk PC waves arise from a negative-slope bulk PC band.[8] We shall employ this special PC design[16] in our subsequent investigations.

Overall, we utilize three different configurations of a microwave setup consisting of an HP 8722ES network analyzer (HP-NA), standard gain horn antennas, and a monopole antenna.[17] All configurations are outlined together in Fig. 1. A right angle isosceles Plexiglas prism is placed symmetrically at distance d_{ATR} above the structure to be examined. The first configuration does not make use of the monopole

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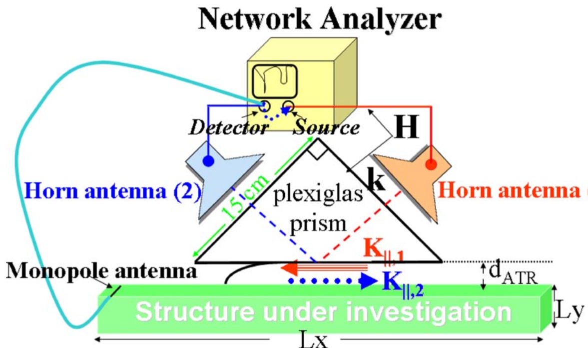

FIG. 1. (Color online) The microwave experimental setup in three functional configurations: (I) Horn antennas (1) (source) and (2) (detector) are connected to the HP network analyzer (HP-NA) (conventional ATR setup). II) Horn antenna (1) (source) and the monopole antenna (detector) are connected to the the HP-NA (forward signal detecting scheme). (III) Horn antenna (2) (source) and the monopole antenna (detector) are connected to the HP-NA (backward signal detecting scheme).

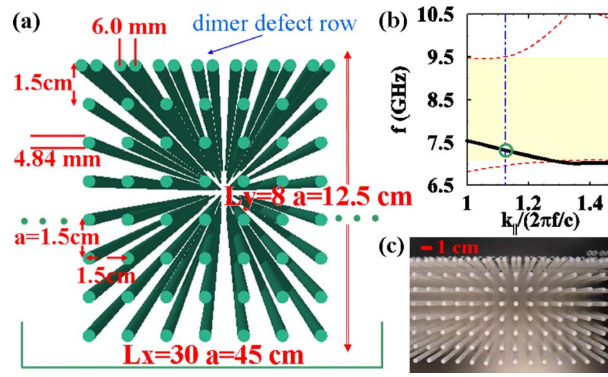

FIG. 2. (Color online) (a) The PC design under study. (b) Surface band (solid line) for the PC shown in (a). The band edges (dotted line) and full band gap (shaded region) of the bulk PC are also indicated. The Plexiglas prism fixes the lateral wave vector $k_{\parallel}$ (dot-dashed vertical line) and so excites the mode indicated with the open circle. (c) Picture (top view) of the real PC structure.

antenna, and is the familiar ATR setup.[13] The EM wave launched from horn antenna (1) couples through an evanescent wave in the bottom prism region to any existing surface or guided mode. Therefore, these modes will reveal themselves as dips in the spectra detected by horn antenna (2).

In order to obtain the rightness of these modes, two more experiments must be performed using the same setup in two variations. In the second (third) configuration we connect only horn antenna (1) [(2)] to the HP-NA as a source. The launched EM wave would couple to a mode with a phase velocity pointing toward the left (right) of the figure, as shown by the solid (dotted) arrow. This is because the lateral wave vector $k_{\parallel}$ is always conserved. The monopole antenna is placed on the structure at the prism's left side and is oriented parallelly to the electric field, which is normal to the plane of incidence. Apparently, in the second (third) configuration, the monopole antenna would detect only a forward (backward) type of propagating signal arriving laterally to its location.

The PC system under study is designed based on the theoretical findings in Ref. 16. Alumina rods (dielectric constant equal to 9.3) with a high aspect ratio (127:1) are placed in a square PC lattice of 30×8 cells, with the rods aligned with the electric field (E polarization). A dimer consisting of the same rods with the bulk PC rods substitutes the single rod in the upper row. The exact design parameters are denoted in Fig. 2(a), while in Fig. 2(c) the actual structure is seen (top view). The surface band dispersion, i.e., the frequency f versus the lateral wave vector $k_{\parallel}$, is calculated with the supercell finite difference frequency domain method.[16] It is shown in Fig. 2(b) with the bold solid line. The prism fixes $k_{\parallel}$ to the value of $(2\pi f/c)n_{\mathrm{pl}}\sin 45°$, with c being the velocity of light. (n_{pl} is the Plexiglas refractive index, determined from phase shift measurements[18] to be $\sim$1.59.) This $k_{\parallel}$ value is depicted in Fig. 2(b) with the vertical dot-dashed line, implying that the experimental ATR setup can couple only to the mode marked with the open circle at 7.32 GHz.

In the experiment, we span the frequency region from 6.8 to 9.6 GHz which just encompasses the directional band gap of the bulk PC. Outside this region, the ATR setup can also couple to bulk PC modes. We also benchmark our microwave setup with a conventional system known to support only forward EM waves. This is a Plexiglas slab with thickness $L_y=2$ cm, which has a guided mode in the pertinent frequency interval, at 8.49 GHz. Our results with the traditional ATR configuration,[19] are shown for the Plexiglas slab in Fig. 3(a) and for the PC in Fig. 3(d). In both cases, we find a dip which is strong for a shorter prism-structure distance ($d_{\mathrm{ATR}}=5$ mm). However, this dip becomes quite weaker for a larger prism structure distance ($d_{\mathrm{ATR}}=10$ mm).

Subsequently, we run the experiment with the monopole antenna positioned at the left side of the prism as shown in Fig. 1. The experimental outcome[20] with the forward configuration (configuration II in Fig. 1) is seen in Fig. 3(b) for the Plexiglas slab case and in Fig. 3(e) for the PC case. Correspondingly, the results[20] with the backward configuration (configuration III in Fig. 1) are plotted in Figs. 3(c) and 3(f). For the Plexiglas slab case, we measure, as expected, a strong forward signal in comparison to a weak backward signal. On the contrary, for the PC case, we witness a prominent backward signal and a weak forward signal. These findings constitute an unambiguous direct experimental observation of backward EM wave propagation. We note that the backward to forward (forward to backward) signal ratio in the Plexiglas slab (PC) case is of the order of 10%. The weak

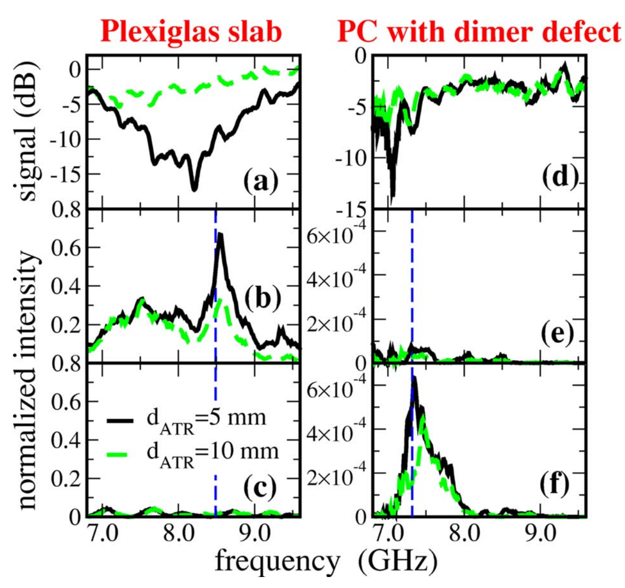

FIG. 3. (Color online) Experimental results with the microwave setup of Fig. 1 for a Plexiglas slab (left panel) and the PC system (right panel), in configurations I [(a) and (d)], II [(b) and (e)], and III [(c) and (f)].

backward (forward) signal for the Plexiglas (PC) case is due to the reflections at the left (right) prism face and at the Plexiglas (PC) slab edge, which induce a secondary signal propagating reversely to the primary signal.[16]

The theoretically expected frequencies for the Plexiglas slab guided mode and, the PC surface mode are seen in Fig. 3 as dashed vertical lines in the left and right panels, respectively. We observe a remarkable agreement with the calculated frequencies for the forward or backward signal peaks [Figs. 3(b) and 3(f), respectively]. On the other hand, the ATR dips [Figs. 3(a) and 3(d)] are slightly off from the expected frequency values. Moreover, the dips' strength reduces more quickly with increasing prism-structure separation in comparison to the peaks' strength. There is a unique reason behind both these effects. The very same prism used to excite the surface modes inevitably perturbs the system. This means that the surface or guided mode frequency in the structure directly below the bottom prism face is different from the one in the free part of the structure. This allows also other frequencies slightly away from the mode for the free-standing structure to couple. However, these disperse into free space when the prism edge is encountered, and so they do not arrive at the monopole antenna.

In conclusion, we experimentally demonstrated directly the backward wave propagation phenomenon. This occurs at the surface of a suitable photonic crystal design. Our proposed modified microwave ATR setup could be also applied at visible frequencies to test the directionality (forward or backward) of guided modes[21] in CMM designs.[12] This could provide an alternative way to verify experimentally left-handed behavior in such structures.

We thank Th. Koschny for stimulating discussions. This work was supported by Ames Laboratory (Contract No. DE-AC0207CH11385), EU-NOE-PHOREMOST, EU-NOE-METAMORFHOSE, and EU-Molecular Imaging (LSHG-CT-2003-503259).

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