# Polarized left-handed extraordinary optical transmission of subterahertz waves

**Miguel Beruete[1]\*, Miguel Navarro-Cía[1], Mario Sorolla[1] and Igor Campillo[2]**

[1]*Millimeter Wave Laboratory, Universidad Pública de Navarra, Campus Arrosadía s/n, 31006-Pamplona, Spain*
[2]*CIC nanoGUNE Consolider, Paseo Mikeletegi 56, 301, 20009 Donostia, Spain*
\**Corresponding author: miguel.beruete@unavarra.es*

**Abstract:** In this paper we design and measure a metamaterial polarizing device working in the sub-terahertz range. The polarizer is based on a modified version of our previous miniaturized Stacked Hole Array (SHA) structure, an arrangement that combines Extraordinary Optical Transmission (EOT) and Left-Handed Metamaterial (LHM) propagation even under Fresnel illumination. Here, we use a self complementary screen by connecting the holes of an EOT structure. Importantly, EOT remains and simultaneously total reflection is obtained for the orthogonal component. Moreover, by computing the dispersion diagram, we demonstrate that LHM propagation can be achieved for the principal polarization within the stop band of the orthogonal component, which propagates in other bands as a standard forward wave. Finally, we check our conjectures by measuring the transmission and reflection coefficients of screens milled on a low-loss microwave substrate. Measurements have been taken for 1 to 6 stacked wafers and they show clearly that the stack acts as a polarizer with left-handed characteristic. Our results open the way to design of novel polarization control metamaterials at Terahertz wavelengths..

OCIS codes: (999.9999) Left-handed Metamaterials; (999.9999) Extraordinary Transmission; (999.9999) Photonic Crystals

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## 1. Introduction

After Bose [1] and Glagolewa-Arkadiewa [2], the Terahertz region was only used in astronomy and remote sensing due to the absence of a mature technology. Today, industrial, medical, military and scientific applications start to bridge this spectral gap [3,4]. In the Terahertz, quasioptical (QO) Gaussian beam propagation models geometrical optics and diffraction of light. QO offers broad bandwidth, low insertion losses, high power-handling capability and good polarization purity [3]. Light polarization is relevant in theoretical physics because of the similitude between the formalisms describing elliptically rotating electromagnetic field vectors and spin properties of particles, respectively [5]. For technological applications, the capability to isolate a specific polarization state is essential.

Typical and broadly used polarizing structures are one-dimensional inductive and capacitive grids [3]. Inductive grids are made of thin parallel metallic wires periodically spaced and behave as shunt inductances when the electric field is parallel to the wires, exhibiting a high-pass characteristic. The complementary structures (in the sense of Babinet's principle [6]) namely, capacitive grids made of a periodic array of narrow slits, behave as shunt capacitances for the complementary (orthogonal) polarization, showing a low-pass

characteristic. Capacitive grids were the earliest QO systems: Rittenhouse discovered the filtering principle in 1786! [7]. Later, Bose reported, studying plant physiology, that the pages of a book can polarize light [1,3]. Other classic polarizing structure related with the previously mentioned ones is the two-dimensional grid or mesh array employed in several regions of the electromagnetic spectrum: microwaves [8], millimeter [9], sub-millimeter waves [10], far infra-red [11], and mid infra-red [12].

Recent findings in electromagnetic research have revived the interest in grid and mesh arrays. Explicitly, the phenomenon of Extraordinary Optical Transmission (EOT) [13] consists of strong peaks in the transmittance frequency dependence and happens in metallic plates perforated by arrays of subwavelength holes, which can be viewed as a particular case of the more general mesh arrays [3]. Initially, EOT was identified as the coupling of light with surface plasmons, viz. surface waves that exist on the interface between two media with $Re\{\varepsilon\}$ of opposite sign, like air (positive) and most metals in the optical range (negative). However, theoretical [14] and experimental [9, 15] evidences obtained at other wavelengths soon demonstrated that EOT can take place in the whole electromagnetic spectrum [16,17]. Sparse slit arrays – capacitive grids – were firstly analyzed as the one-dimensional equivalent of Ebbesen's structure (though it is now well-established that the similitude is limited since holes have a cutoff wavelength while slits do not). Anyway, the high transmittance peak observed led to include them as part of the EOT structures [18,19].

Today, many studies in progress are devoted to the artificial synthesis of media with exotic properties. In this aspect, wire media – three-dimensional inductive grids – have been proposed to implement artificial electric plasma media ($\varepsilon < 0$ below electric plasma frequency) [20] that combined with split ring-resonator (SRR) arrays [21] ($\mu < 0$ below magnetic plasma frequency) have given the first realization of a Left-Handed Metamaterial (LHM) working in the microwave range [22, 23]. Since then, the characterization and synthesis of LHMs has become one of the most ground-breaking topics in electromagnetic research [20-25], leading to a new class of devices, ranging from perfect lenses [24] to the very recent invisibility cloak [25]. A usual criticism pointed to LHMs constructed with the mentioned wire media + SRR topology is the high losses they exhibit and the difficulty to obtain a LHM working in the optical range.

It has been very recently reported the possibility to obtain a LHM by just stacking several perforated plates showing EOT at subterahertz wavelengths [26,27], and at optical frequencies [28,29]. Plate alignment difficulties for such tiny holes restricted the stacking to a pair of plates for the optical arrangements. It has been also demonstrated that the LHM propagation through Stacked Hole Arrays (SHAs) can be inhibited by means of a Photonic Band-Gap (PBG) [30] and, also, that a zero group band can be achieved, see Ref. 27 where also an artificial waveguide model has been introduced to add more physical insight about SHAs. It is very remarkable that EOT, LHM and PBG are linked phenomena that can be found in the same SHA structure [26,27]. Still, a clear drawback of typical EOT structures is the large number of holes involved in the resonant process, as demonstrated in [31], which leads to very big structures. But this constraint can be overcome by embedding the plates in dielectric slabs and by using rectangular arrays instead of square ones giving as a result a miniaturized prototype working in the Fresnel-zone illumination, a result experimentally confirmed in Ref. 32.

Up to now, previous works dealing with polarization dependence on EOT hole arrays have been usually focused on the hole shape to tune the polarization [33]. In this paper, we design and measure a LHM polarizer by modifying our mentioned miniaturized SHA metamaterial approach. Nevertheless, in order to enhance the fractional hole area and minimize the cross-polarization power level, square holes are used; furthermore, the hole array is modified in such a way that a self-complementary [6] structure is obtained, see Fig. 1. Hence, a step forward in the relation of different electromagnetic phenomena is given by linking miniaturized EOT-based LHM with the concepts of Babinet's self-complementary structures. As a result, an innovative polarizer is obtained with LHM propagation characteristic for the principal polarization and simultaneous forbidden band for the cross-polarization component.

Moreover, it is demonstrated that the latter propagates in the standard right-handed way in the bands where transmission is allowed.

All the simulation results presented throughout the manuscript have been obtained with the Finite Integration Time Domain Method of CST Microwave Studio™ code. The experiments have been carried out with an ABmm™ QO Vector Network Analyzer. The details of the set-up are given in section 4.

## 2. LHM Polarizer based on self-complementary SHAs.

EOT is a self-resonance of the hole array that can be modeled as an L-C tank [11, 26]. A hole array has inductive character for large $\lambda$, hence transmittance is negligible when $\lambda \to \infty$ [see solid red trace of Fig. 2(a)]. The main contribution to inductance are the conduction currents concentrated in the narrow wire between holes, see Fig. 2(c). At EOT resonance inductance and capacitance are balanced (at least in a first order approach [11]). In Fig. 2(c), the current lines are closed through displacement currents connecting the upper and lower sides of the hole. Now, a narrow vertical slit can be introduced connecting consecutive holes [see Fig. 1(b)] with almost no perturbation of the current distribution, as Fig. 2(d) demonstrates. Therefore, the EOT resonance remains in the new structure when the electric field is vertically polarized ($E_y$): note that the solid blue trace of Fig. 2(a) is superimposed to the solid red one.
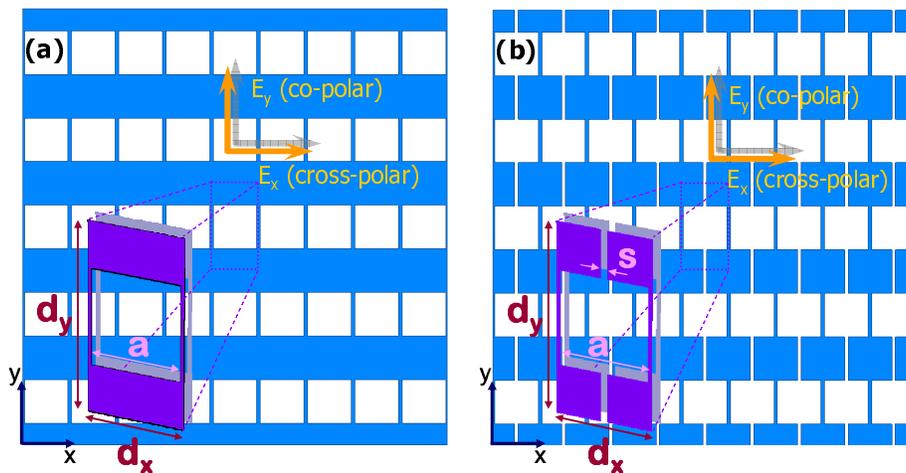


Fig. 1. Schematic representation and unit cell of a rectangular EOT hole array (a) and self-complementary EOT polarizer (b). Parameters: dx = 2.7 mm, dy = 5.0 mm, a = 2.5 mm, s = 0.2 mm. The metal thickness is t = 0 and conductivity $\sigma \to \infty$.

This slight structural modification has very significant consequences. First: It demonstrates EOT through a screen of connected apertures, at difference with typical unconnected EOT structures up to date. Next, a self-complementary [6] screen can be achieved if: $d_x = a + s$; $d_y = 2a$; metal thickness $t \to 0$. Strictly speaking, the structures should be lossless and single layered to guarantee complementariness. Obviously, the complementary structure of the EOT hole array is precisely the small patch array whose spectrum presents a resonant rejection band at the EOT frequency (Extraordinary Reflection) [34], provided the excitation is orthogonal, viz. electric and magnetic fields interchange their roles. In the new structure of Fig. 1(b), the patches are connected through narrow wires being complementary to the aforementioned narrow slits, thus, by symmetry with the connected hole array case, they do not perturb very much the response and Extraordinary Reflection remains.

Mixing all together, when polarization is vertical ($E_y$, co-polar), the transmission and reflection coefficients of the EOT hole array [Fig. 1(a)] and the new self-complementary screen [Fig. 1(b)] are almost indistinguishable, see blue and red solid lines in panels (a) and (b) of Fig. 2. Simultaneously, being the new structure self-complementary, Extraordinary

Reflection for the cross-polar ($E_x$) component appears exactly on the EOT resonance, see dashed blue curve of Fig. 2(a). Compare this with the crosspolar curve of the hole array (dashed red curve) where, logically, the dip of rejection is not present. Therefore, the new structure, Fig. 1(b), behaves as a polarizer, see [35]. The superposition of a narrow slit array and a hole array forms our polarizer. It works for the polarization orthogonal to that of slit arrays, since at the EOT frequency it operates as a hole array. For the cross-polarization (slit arrays) a low pass response appears, see the green curves of Fig. 2(a).
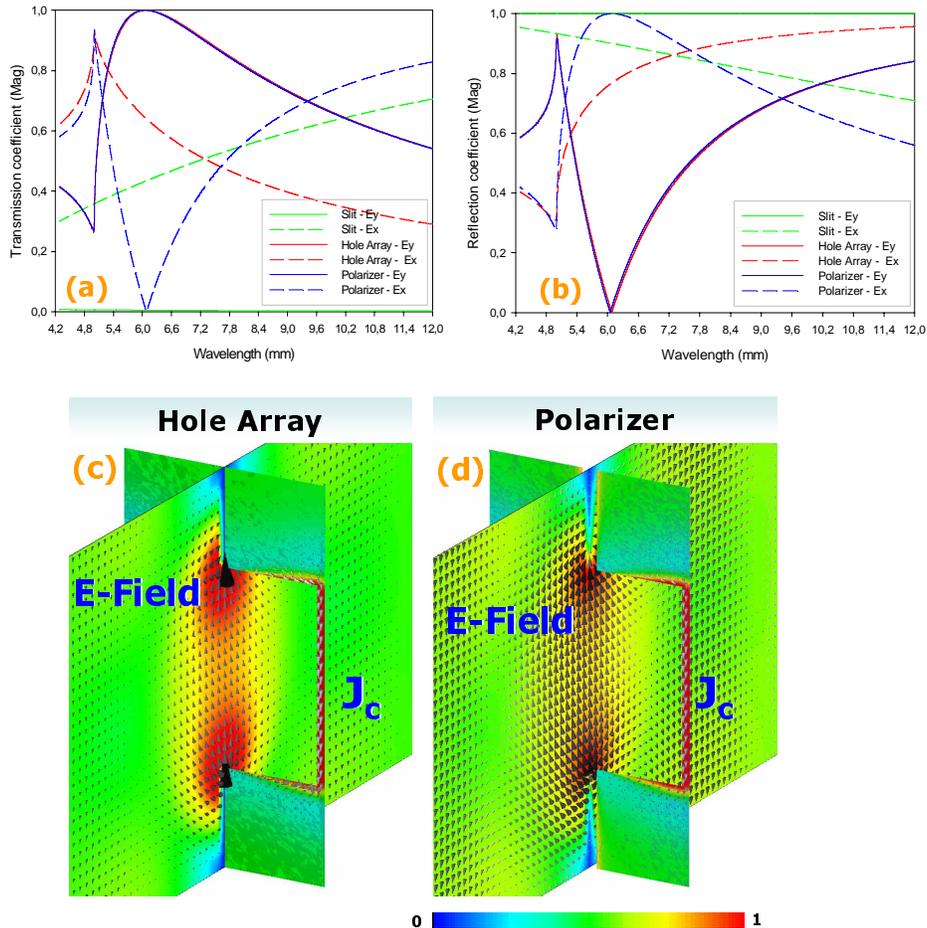


Fig. 2. Simulation results of the polarization dependent transmission (a) and reflection (b) coefficients (continuous trace for co-polar and dashed one for cross-polar) for a slit array along the y-axis, corresponding to the cuts made on the self-complementary structure (green), hole array (red) and for the proposed polarizer (blue). The dimensions of the analyzed structures are given in Fig. 1(a) for the slit array (removing the thin metal lines of width s) and for the hole array. Fig. 1(b) gives the dimensions of the polarizer. Plot of the conduction and displacement currents at the resonance enhanced transmission peak with vertically polarized ($E_y$) light. Hole array case (c) and polarizer (d). The E-field is depicted in a perpendicular cutting plane through the middle of a hole and the scale is normalized to the maximum in each case.

## 3. Simulation results of the stacked structure.

It is shown in Fig. 3 the calculated dispersion diagram of an infinite stack of self-complementary screens (parameters given in the caption). Solid and dashed lines are for co- and cross-polarization respectively. The structure exhibits LHM propagation at the EOT band,

for the vertical (co-polar) component (y-axis of Fig. 1): notice that the first band (49.2 GHz to 56.3 GHz) has a negative slope, i.e. phase and group velocities are antiparallel, hence the term left-handed since electric, magnetic and wave vectors form a left-handed triplet. For the horizontal (cross-polar) component the bands shown have both positive slope (i.e. are RHM) and a forbidden band appears from 49.1 GHz to 64.6 GHz covering the range of co-polar LHM propagation. Clearly a LHM polarizer is feasible with modified SHAs. A more developed study of the propagation characteristics dependence on $d_z$ of a standard EOT hole array can be found in [26, 27, 30]. For close stacked hole arrays the propagation is left-handed and for large $d_z$ is right-handed with a zero-group velocity band in the limit between both regimes. The current modified self-complementary screen is expected to have a similar behavior.
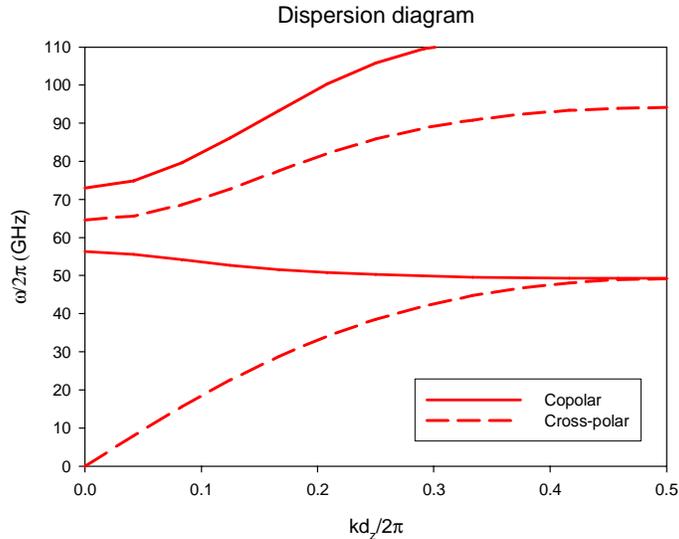


Fig. 3. Dispersion diagram for the co-polar (continuous red line) and cross-polarization (dashed red line) corresponding to the parameters $d_x = 1.8$ mm, $d_y = 3.4$ mm, $a = 1.2$ mm, $s = 0.2$ mm (for nomenclature check caption of Fig. 1(b)). The metal thickness is $t = 35$ microns and Cu conductivity $\sigma = 5.8 \cdot 10^7$. The substrate has the next characteristics: dielectric permittivity $\varepsilon = 2.43$ and thickness $h = 0.49$ mm The longitudinal lattice of the stack is $d_z = 0.525$ mm.

A graphical picture of the operation is given in the animation, where 20 infinite plates have been stacked, see in Fig. 4 a frozen image from the given animation. Notice that a single unit cell is sufficient to characterize infinite structures, by means of the proper boundary conditions [27]. The excitation is made by means of a circularly polarized plane wave. Only the vertical component emerges and unambiguously, the wave inside the stack has anti-parallel phase and group velocities. Moreover, in the input region, an elliptically polarized wave is obtained, due to interference of the reflected horizontal component with circularly polarized excitation wave.

## 4. Experimental results

The built prototype, consisting in modified self-complementary SHAs [Fig. 1(b)], must move away from the ideal Babinet's principle [6]. Firstly, proceeding as in [32], the arrangement is milled on the copper layer of a low loss microwave substrate with parameters: dielectric permittivity $\varepsilon = 2.43$ and thickness $h = 0.49$ mm. The dielectric loading affects distinctly to each polarization and, therefore, a fine parameter tuning is mandatory. Secondly, LHM operation is accomplished by stacking plates, leading to a multilayer structure, departing from ideal Babinet's principle. The parameters are then: $d_x = 1.8$ mm, $d_y = 3.4$ mm, $d_z = 0.525$ mm, $a$

= 1.2 mm, $s$ = 0.2 mm [for nomenclature check caption of Fig. 1(b)]. Metal thickness t = 35 microns and Cu conductivity $\sigma$ = 5.8·10$^7$.

A photograph of the built structure is shown in Fig. 5. The measurements, Figs. 6(a)-6(h), were performed with an ABmm™ QO Vector Network Analyzer which can operate up to 260 GHz, see Fig. 5. This instrument is based on a solid state multiplier that generates the millimetre-submillimeter wave frequencies which are detected by harmonic mixer heterodyne downconversion. The phase detection is done by an original concept based upon a phase reference oscillator in the MHz frequency range that eliminates the need of complex interferometric techniques operating in this part of the spectrum [36]. In this way, this instrument bridges the gap between conventional microwave spectroscopy using standard vector analyzers and far-infrared spectroscopy with Fourier transform interferometers.
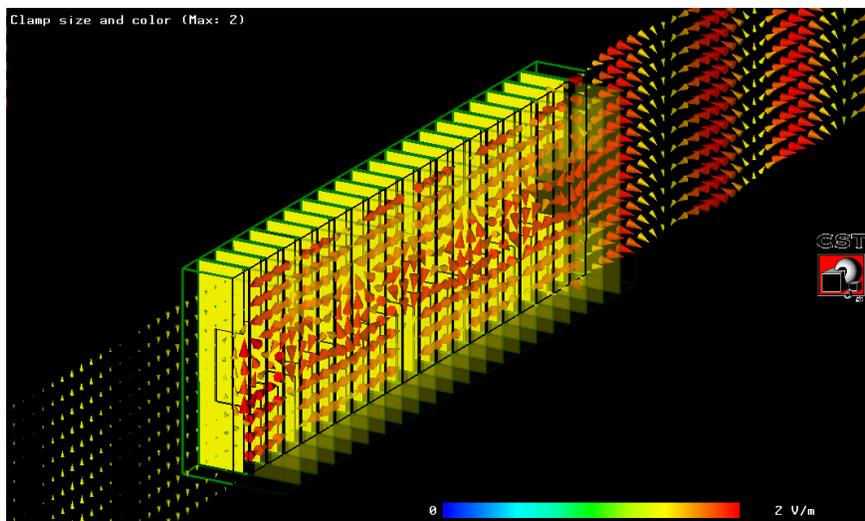


Fig. 4. Frozen image extracted from the given animation where an impinging circular polarized wave (upper right side) is transmitted through the LHM-polarizer and a pure vertically polarized wave emerges at the output side of the device (bottom left side).
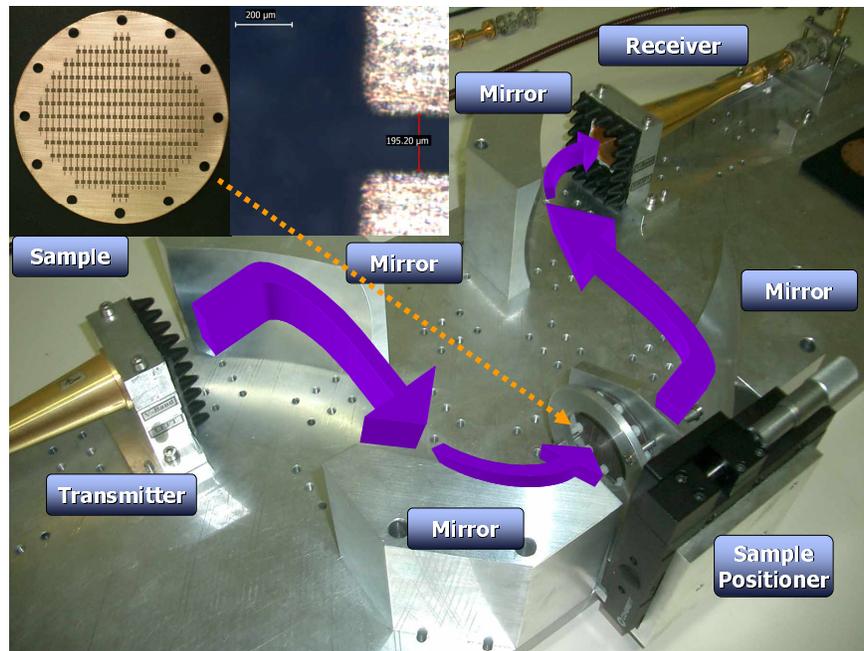
Fig. 5. Picture of the quasioptical measurement set-up where operates our AB MILLIMETRE vector network analyzer and a picture of the fabricated prototype. A detail of the fine fabrication process is also given.
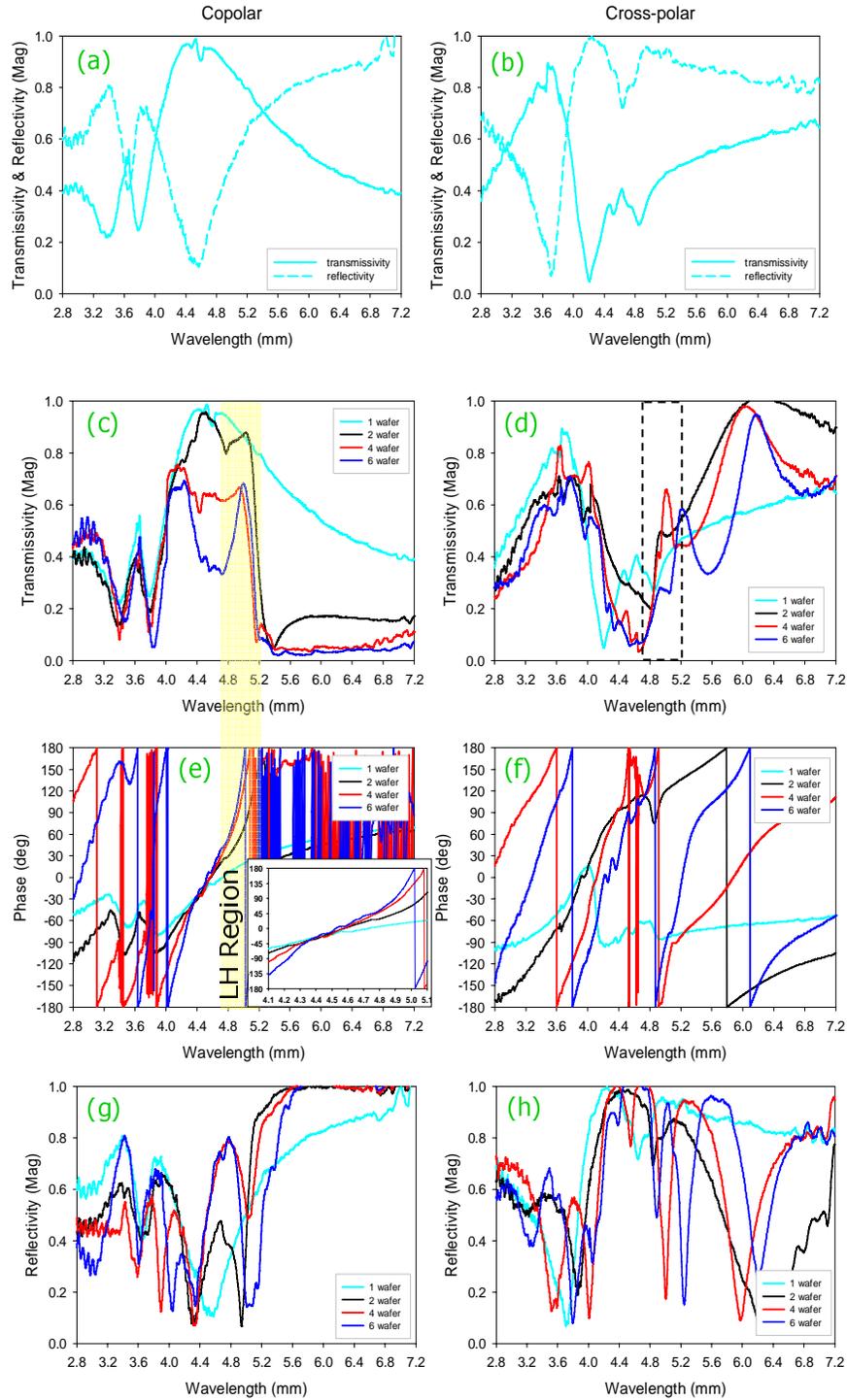
Fig. 6. Magnitude of the transmission and reflection coefficient of one wafer: co-polar (a) and cross-polar component (b) Magnitude of the transmission coefficient for several stacked wafers: co-polar (c) and cross-polar component (d) Phase of the transmission coefficient for several stacked wafers: co-polar (e) and cross-polar component (f) Magnitude of the reflection coefficient for several stacked wafers: co-polar (g) and cross-polar component (h)

The QO set-up consists of a corrugated horn antenna that generates a very well linearly polarized Gaussian beam which, after two ellipsoidal mirrors, is focused over the sample under test. There, the transmitted and reflected beams are obtained. The transmitted beam passes through another pair of identical mirrors and reaches the receiver antenna. This antenna is another corrugated horn which is very sensitive to polarization and well matched to the Gaussian beam. The transmitting antenna works as a receiver for the reflected power, and the detection is done through a directional coupler that steers the signal to the receiver. This QO set-up can be seen as a Beam Waveguide [3] capable to work up to 1 THz.

The experimental results of a single plate embedded between dielectric slabs are represented in panels (a) and (b) of Fig. 6, where a clear resonance around 4.6 mm emerges with practically total transmission for the co-polar polarization, followed by the Rayleigh-Wood's anomaly null [9] at 3.8 mm. The cross-polarization level at 4.6 mm is negligible, which results in a very efficient polarizer. Note the nearly complementary response in reflection.

For several stacked plates, panels (c)-(h), the first band is located around 5.0 mm with a reasonable co-polar transmission level, panel (c) and cross-polarization rejection, panel (d). Attending to the phase behavior of the co-polar component in that region, panel (e), a clear LHM propagation is demonstrated, i.e. the phase increases as plates are stacked. From that point on, the phase evolution returns to the conventional RHM propagation, i.e. the phase decreases as plates are stacked. Comparing with the dispersion diagram of Fig. 3, a frequency shift is noticed, probably due to inherent tolerances in the fabrication process. Besides, the gap between the LHM and the RHM band is not as clear in the experiment as in the simulation because a larger stack (ideally infinite) is necessary to observe it.

Co-polar reflection coefficients, panel 6(g), show the reflection caused by this gap. Finally, two minima at 3.4 mm and 3.8 mm appear in the response shown in Fig. 6(c). They are originated in the input interface, since they also appear in the single plate response and, consequently, are not due to the periodic stacking. The rejection band for the cross-polarization, panel 6(d), is around 4.6 mm, i.e. is somewhat detuned with respect to the LHM band and is also shifted compared to Fig. 3, likely due to the aforementioned tolerances that affect differently to both polarizations. Besides, the phase measurement confirms the conventional RHM character, in good agreement with simulations, panel 6(f). Again, the cross-polar reflection coefficients, panel 6(h), show a gap, in agreement with the dispersion diagram of Fig. 3.

For the sake of completeness we have calculated the extinction ratio (ER) between the co- and cross-polar components from the experimental data. For a wavelength of 4.7 mm in the case of 1 wafer the ER is around 10 dB whereas for 4 stacked wafers it presents a clear peak of 25 dB.

## 5. Conclusion

In summary, by using Babinet's self-complementary EOT subwavelength structures on a single wafer, an innovative sub-terahertz left-handed metamaterial polarizer is obtained. It consists of subwavelength connected holes which, very significantly, still can work at EOT resonance, in contrast with typical EOT hole arrays where the holes remain unconnected. Then, by stacking several wafers, a novel LHM polarizer is tailored. It behaves as a LHM for the co-polar component of the impinging electric field, and reflects simultaneously the cross-polar component, which propagates in other bands as a standard forward wave. The measured extinction ratio has been calculated and a reasonably high value has been obtained. These exotic properties could be used for the design of novel polarization control metamaterials at Terahertz wavelengths.

### Acknowledgments