STSM REPORT

STSM Application number: COST-STSM-BM1205-041115-068542

STSM Grantee: Vitomir Milanovic

STSM title: Advanced modelling of delay times in terahertz chiral metamaterils slab

Home Institution: School of Electrical Engineering, University of Belgrade, Belgrade(RS)

Host Institution: School of Electronic and Electrical Engineering, University of Leeds, Leeds (UK)

STSM period: 04/11/2015 - 2/12/2015

STSM purpose: The objective of this short term scientific mission is to develop and test a model of influence chirality magnitude on reflection and transmission group and dwell delays in terahertz chiral metamaterials in collaboration with Quantum Electronics group from the School of Electronic and Electrical Engineering , University of Leeds, UK.

Description of the work carried out during the STSM:

The collaboration between the Quantum Electronic group in the School of Electronic and Electrical Engineering (SEEE), University of Leeds, and Quantum Devices group in the School of Electrical Engineering (ETF), University of Belgrade, Serbia fits very well in the BM1205 COST Action's aims, in particular in development and optimisation of THz sources and detectors, as well as in analysing interaction of THz radiation with the targets. During my visit, we shall consider a propagation of THz pulse through chiral metamaterials slab which be controlled by group delay. Then we shall investigate the wave propagation and energy flow, later used for obtaining dwell time in chiral slab. In this analysis we shall focus on transmission and reflection in chiral metamaterials -- air interfaces and analyse dependence group and dwell delays vs. frequency in THz range.

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Description of the main results obtained:

Nowadays, terahertz (THz) technology is receiving more and more attention due to huge range of important applications, such as information and communication technology, biomedical sensing and imaging, analytical chemistry spectroscopy, materials characterization and imaging. Due to weak signal, which conventional materials have in interaction with THz radiation, they are not appropriate for application in this range. However, artificially made materials, metamaterials, can provide unprecedented manipulation of THz radiation [1,2]

As the THz technology is considered very important for wireless and sensing applications, there exists necessity for the development of the high-speed optical components.

Recently, the group delay has proved to be very convenient for control of the THz electromagnetic signal used for filters, waveguides and polarization components [3]..

Here, we consider a model, which consists of barrier made of chiral metamaterial which thickness is L = 100μ and it is surrounded with air (as shown in Fig. 1).

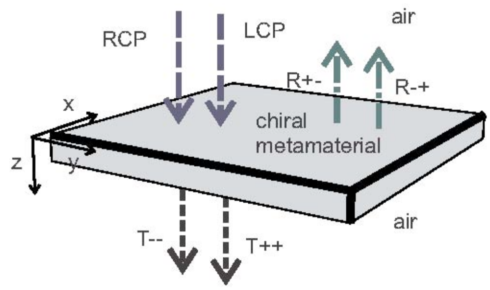

FIG. 1. The model of THz interaction with the material used for the calculation

We did the calculation for the case without substrate, although the influence of substrate is here negligible because the resonance elements are embedded far away from the substrate. The parameters which were used for our model are [4]: ω_0 = 1.8713 THz, ω_p= 0.394ω_0 , Γ = 0.05463 ω_0 and F = 0.0625, where ω_0 is resonance frequency of the resonators, Γ is the dissipation coefficient related to the power loss, , ω_p is characteristic frequency of the medium and F is filling factor of resonators in the one unit cell. Our results included the frequency range from 1 to 2.5 THz. We firstly investigated electric and magnetic field propagation, then density of energy in the slab and at the end the dwell time [5]. As in chiral media exists different wave vectors for left circularly polarized (LCP) and right circularly polarized (RCP) wave, there are also different propagations of electric and magnetic fields through the chiral slab (Fig. 2). This calculation was done at the resonant frequency. The higher amplitude of electric field for the case of LCP wave in chiral media is due to the lower value of imaginary component of k_- then for the case of RCP wave Im(k_+).This means that LCP has longer propagation path then RCP wave (Fig. 2, inset). The electric field of the incident RCP wave E_+ has huge attenuation in the chiral slab and it has near zero value after reaching 30 μm (Fig. 2 (a)). In the case of LCP wave, the electric field decreased a bit in the slab but on the second interface it increased. On the other side, the magnetic fields H_+ and H_- have small amplitudes in comparison with the amplitudes of the electric fields (Fig. 2 (b)).

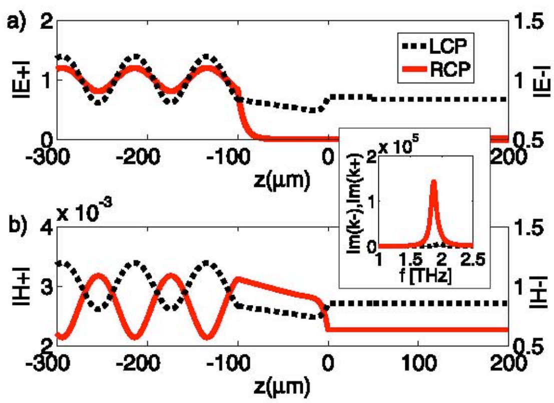

FIG. 2. (a) Electric field propagations of LCP and RCP waves, inset: imaginary parts of wave vectors k_+ and k_-, (b) magnetic field propagations LCP and RCP waves.

We continued our investigation with the calculation of the energy density flow and dwell time. For the case of LCP incident wave, energy increased in the slab, mainly at the resonant frequency. τ_{d-} has the maximum of 19.78 ps at the resonant frequency. The absorption and the group delay have a similar shape but frequency shifted. On the other side, the energy density map shows that the losses are very large in the case of RCP wave, because very small part of energy passed through the slab, especially at the resonant frequency . On the Fig. 3(a) and (b) are presented the dwell time dependency of frequency and the dwell time dependency of thickness of the slab. We see that τ_{d+} saturates after reaching 30 μm. That is the reason for small values of the dwell time, which is 0.78 ps at resonant frequency. The absorption is the largest at the resonant frequency.

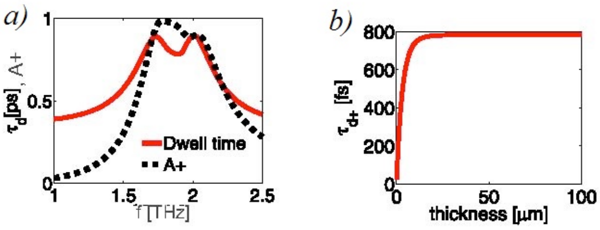

Fig. 3 (a) Disribution of dwell time and absorption for LCP wave, (b) dwell time dependence of thickness

For considering group delays it is useful firstly to discuss the results obtained for transmission and reflection coefficients (Fig. 4). When we look from lower to higher frequencies, transmission coefficient T_{++} decreased to the minimum, which is close to zero at the resonant frequency. This is indicating on the existence of the stop band. For frequencies higher then resonant, T_{++} increased what presents a pass band (Fig. 5 (a)). On the other side, T_{--} has a minimum value 0.64 at the frequency 1.95 THz and after reaching this point, it increased what indicate a pass band (Fig. 4 (b)). Reflection coefficients R_{-+} and R_{+-} have a maximum 0.336 at the frequency 1.975 THz and the minimum nearly zero for at the frequency 1.28 THz (Fig. 5 (c)).

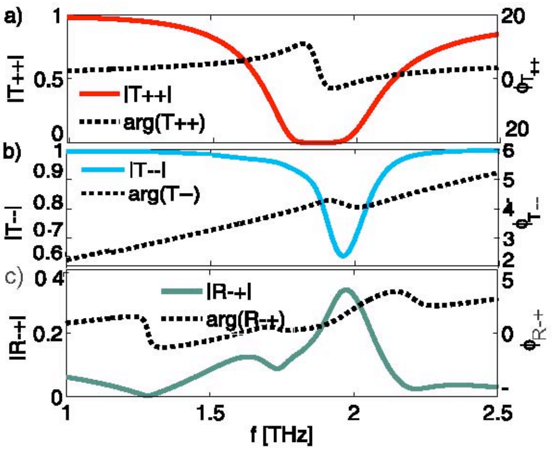

FIG. 4. (a) Transmission coefficient amplitude τ_{T++} and phase as a function of frequency, (b) transmission coefficient amplitude T_{--} and phase as a function of frequency, (c) reflection coefficient amplitude R_{-+} and phase as a functions of frequency.

The group delay in transmission τ_{T++} have a minimum at resonant frequency and it is a negative value (Fig. 5 (a)). At the same point, τ_{T--} has a maximum (Fig. 5 (b)). The maximum of the imaginary part of k_- is at the frequency 1.95 THz where is the minimum of τ_{T--} what is indicating the largest attenuation. We can observe a negative group delay in transmission what means that the peak of the output pulse appears before the input pulse[24]. In the regions of negative transmission group delays, there is attenuation of the phase of the transmission (see Fig. 4).

A negative range of the real part of wave vector, real(k_+), as well as of the index of refraction is in between 1.88 THz and 2.06 THz. From Fig. 5 (a), it can be seen that in the region 1.92 THz -- 2.06 THz, real(k_+) is negative and τ_{T++} is positive what implies that the phase velocity remains negative and group velocity is positive. This means that there exists backward wave propagation. On the other hand, the group delays in reflection,

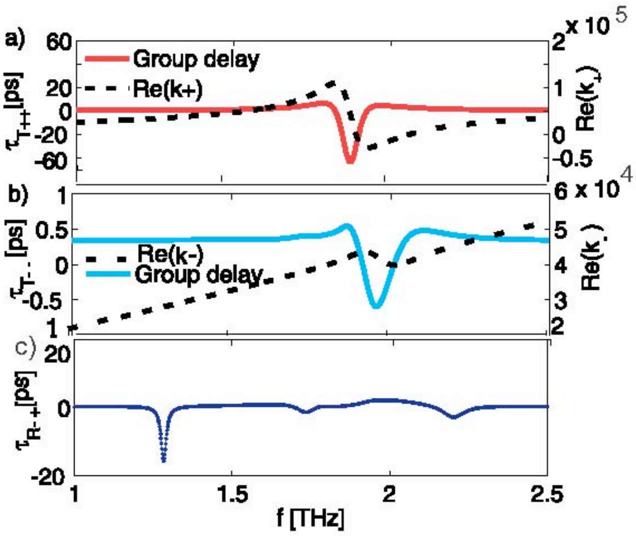

FIG. 5. (a)τ_{T++} and real(k_+) as a function of frequency, (b) τ_{T--} and real(k_-) as a function of frequency, (c)τ_{R-+} as a function of frequency

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τ_{R-+} and τ_{R+-}, have the same characteristics because these two reflections for the both circular polarisations are the same (Fig. 5 (c)). This comes from the reason that incident RCP wave becomes LCP in reflection and contrary [4].

In the final part we observed the influence of chirality on the group delays (Fig. 6). The used values of chirality are κ (from the equation 5), the half of that value 0.5κ and κ=0. We

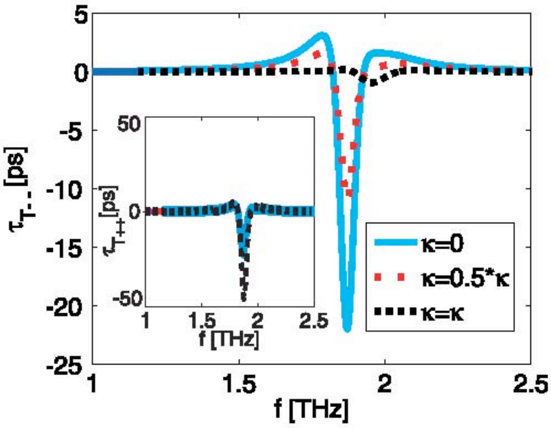

FIG. 6. τ_{T--} dependency of frequency for different values of chirality parameter. Inset:τ_{T++} dependence of frequency for different values of chirality parameter

concluded from the calculation that there is no influence of chirality on the group delays in reflection τ_{R+-} and τ_{R-+}. When it comes to group delays in transmission, there exists a huge changes with variation of the chirality parameter. If we observe the τ_{T--} at resonant frequency, it is increasing with increasing chirality. τ_{T++} manifests the opposite behavior (Fig.6, inset).

The difference in group delay characteristics of RCP and LCP waves in the chiral media is the main tool for manipulating and controlling the light. This fact gives a great potential for variety of THz devices.

Mutual benefits for the Home and Host institutions:

Collaboration with the host, Dr Dragan Indjin from the School of Electronic and Electrical Engineering, University of Leeds, was very useful and stimulating, with many aspects of modelling of terahertz radiation interaction with chiral metamaterials discussed between the visitor and host. A draft of joint manuscript was difficult to complete without possibility to have discussions in person, as it requires having about 10 such meetings during 1-month period. The working visit was the most efficient way to accomplish this objective. By discussing challenges encountered and the work completed to date, both groups have a better understanding of possible critical areas, which require further elucidation.

Future collaboration with the Host institution (if applicable):

ETF and SEEE will continue their collaboration on this topic. In the short-term it is desirable to complete the manuscript for publication.

Foreseen journal publications or conference presentations expected to result from the STSM (if applicable):

An outcome of this STSM, specific program codes will be developed and a paper we will be submitted to international journal.

References

[1] B. Ferguson and X.-C. Zhang, "Terahertz magnetic response from artificial materials," Nature Materials 1, 26–33 (2002).
[2]T. J. Yen, W. J. Padilla, N. Fang, D. C. Vier, D. R. Smith, J. B. Pendry, D. N. Basov, and X. Zhang, "Terahertz magnetic response from artificial materials," Science 303, 1494–1496 (2004).
[3] F. M. Miyamaru, N. Hiroki, N. Yohei, N. Tsubasa, K. Toshihiro, Masao T., and W.Mitsuo, "Ultrafast optical control of group delay of narrow-band terahertz waves,"Scientific Reports 4, 43461–5.
[4]R. Zhao, T. Koschny, and C.M. Soukoulis, "Chiral metamaterials: retrieval of the effective parameters with and without substrate," Opt. Express 18, 14553–14567 (2010).
[5]H. G. Winful, "Tunneling time, the Hartman effect, and superluminality: A proposed re solution of an old paradox," Physics Reports 436, 1 – 69 (2006).

STSM outcome form

STSM application number	Home institution & country	Host institution & country	BM1205 WG	Objective of the collaboration	Results of the collaboration
COST-STSM-BM1205-041115-068543	School of Electrical Engineering, University of Belgrade, Serbia	School of Electronic and Electrical Engineering, Leeds, United Kingdom	WG 3	Development and test a model of influence chirality magnitude on group and dwell delays in terahertz chiral metamaterials.	Theoretical analysis and numerical simulations of interacion of THz radiation with material. Possible ways of model improvement was found.

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I acknowledge that the described short-term scientific mission (STSM) was successfully carried out in the conditions here specified. Prospects of potential further collaborations on topics related to the THz radiation interaction with materials are expected in the coming months out of the agreements reached.

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