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# Chirality effects on channel modeling for THz-band wireless communications in LoS/NLoS propagation

Anna Maria Vegni<sup>a,\*</sup>, Valeria Loscri<sup>b</sup>

<sup>a</sup>*Department of Engineering, Roma Tre University, Rome, Italy*

<sup>b</sup>*INRIA Lille-Nord Europe, FUN Research Lab, Lille Nord-Europe, France.*

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## Abstract

Channel modeling in the Terahertz frequency band has become a very hot research field, above all in the context of nano-Internet of Things. Thanks to the exploitation of frequencies in the interval ranging from 0.06 to 10 THz, it is envisioned the possibility to overcome the issues related to the spectrum scarcity and capacity limitation. On the other hand, the design of new channel models, able to capture the inherent features of the phenomena related with this specific field is of paramount importance. Very high molecular absorption, and very high reflection loss are peculiarities phenomena that need to be included in these models. In this paper, we present a *full-wave* propagation model of the electromagnetic field that propagates in the THz band both for Line-of-Sight and Non-Line-of-Sight propagation models. In the full-wave model, we also introduce the chirality effects occurring in the propagation medium, *i.e.*, a chiral metamaterial. Finally, the analysis of path loss in Line-of-Sight and Non-Line-of-Sight propagation models, and for biological and indoor application scenarios, has been carried

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\*Corresponding author

*Email addresses:* annamaria.vegni@uniroma3.it (Anna Maria Vegni ),  
valeria.loscri@inria.fr (Valeria Loscri)

out through simulation results.

*Keywords:* Chirality effects, full-wave model, THz channel modeling, nanoscale communications

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## 1 **1. Introduction**

2       The increasing demand of wireless communication systems based on large-  
3 scale use of nanodevices according to the Internet of Things idea has enhanced the  
4 attention on accurate and more precise channel models working in the Terahertz  
5 frequency band. This was a consequence of new sensing components to be used  
6 in a large variety of applications, including *e.g.* health and life sciences.

7       Nowadays, the Terahertz band [1] has been identified in the range [0.06, 10] THz,  
8 and represents one of the most promising spectrum bands to enable ultra-high-  
9 speed communications. The use of this frequency band is envisioned to address  
10 the spectrum scarcity and capacity limitations of current wireless systems, thus  
11 providing a plethora of applications, like ultra-high-speed wireless communica-  
12 tions.

13       In order to address these needs for an optimal wireless communication net-  
14 works in the THz band, it is necessary to develop new channel models working in  
15 THz band, that include specific phenomenons that are more evident when working  
16 in optic and almost-optic frequencies [2]. Researchers are investigating specific  
17 Terahertz spectrum peculiarities, like the *very high molecular absorption loss* or  
18 the *very high reflection loss*. Indeed, differently from traditional lower frequency  
19 bands, where the propagation is mainly influenced by the spreading loss only,  
20 the physical mechanisms in a THz-band wireless transmission are a very high  
21 molecular absorption loss, and spreading loss. Also, the molecular absorption

1 attenuates the propagated signals in THz-band wireless communications. These  
2 phenomenons are specific for THz band and cause a very high and frequency-  
3 selective path loss for Line-of-Sight (LoS) links, while high reflections occur in  
4 Non-Line-of-Sight (NLoS) propagation due to the type of material and the rough-  
5 ness factor of reflecting surfaces [2, 3, 4].

6 From all these considerations, it follows that existing channel models used for  
7 lower frequency bands cannot be re-used for THz communications, and then the  
8 need to design novel channel models for THz band is a challenge. In this paper,  
9 we omit channel models for lower frequency (*i.e.*, ultra-wideband), but investigate  
10 recent works in channel modeling for THz band.

11 Many works have already investigated all these specific phenomenons occur-  
12 ring in the THz band, and consequently novel channel models for THz band have  
13 been presented so far. One of the main channel models for communications in  
14 THz band is that presented by Jornet and Akyildiz in [5], which includes both  
15 molecular absorption and free space loss. In [6], Llatser *et al.* investigate the  
16 influence of molecular absorption in a short-range THz communication model on  
17 both frequency and time domain. Piro *et al.* [7] address radio propagation mod-  
18 els for nanoscale wireless communications in the field of nanomedicine. Finally,  
19 Boronin *et al.* [8] present a model for describing the phenomena of molecular  
20 noise occurring in THz band. This concept has been broadly surveyed in [9] by  
21 distinguishing from time and frequency dependence.

22 In [3] Moldovan *et al.* present a deterministic channel model working in THz  
23 band, both in case of LoS and NLoS propagation, and by assuming molecular  
24 absorption and spreading loss, together with a ray-tracing approach. In [4] Han  
25 *et al.* deal with a multi-ray channel model that considers not only LoS and NLoS

1 propagation effects, but also reflected, scattered and diffracted paths. This work  
2 represents an accurate channel model, where the use of ray tracing technique is  
3 exploited. Because of the very short wavelength in the THz band, THz waves  
4 propagate quasi-optically and can be modeled highly accurate with a ray optical  
5 approach. Ray tracing has already enabled good capabilities at low Terahertz  
6 frequency *i.e.*, at 0.3 THz.

7 In [10], Sheikh *et al.* use a ray-tracing model to simulate the multipath wave  
8 propagation in a realistic office environment, and include the frequency dependent  
9 atmospheric attenuation.

10 Another feature to be considered is the scattering effect. Piesiewicz *et al.* [11]  
11 study scattering properties of typical building materials, for channel modeling  
12 in THz band. The authors observed that in realistic environments, with rough  
13 surfaces, the modeling of the propagation effects should take into account the  
14 reduction of the reflected power in the specular direction due to diffuse scatter-  
15 ing, even if not extremely large. Also, robust scattering models are needed and  
16 can be implemented in ray-tracing algorithms to enhance the propagation model-  
17 ing. Finally, Kokkonniemi *et al.* [12] consider the scattering effect into the channel  
18 modeling in the THz band. They theoretically analyze multiple scattering effects,  
19 referring to a sequence of scattering events from small particles, such as aerosols.  
20 It is shown that the small particle scattering can result into significant additional  
21 loss that needs to be taken into account with the loss depending on the density and  
22 size distribution of the particles.

23 As can be noticed from previous works, the channel modeling in THz band is  
24 addressed through transfer functions that consider specific effects, like molecular  
25 absorption loss, spreading loss, reflected, diffracted, and scattered rays. However,

1 the *electromagnetic chirality effect* and the particular kind of the medium (also  
2 in terms of power excitation, with respect to the intensity of the electromagnetic  
3 field) are a few aspects that are often neglected in classical modeling of trans-  
4 mission channels. In fact, related works on channel modeling in the THz band  
5 consider the behavior of the channel by assuming molecular absorption loss func-  
6 tion, the signal attenuation due to free space, and the particle scattering effect. All  
7 those aspects are assumed through appropriate functions (*e.g.* the Friis's function,  
8 the directivity of the transmitting antenna) added to the amplitude of the transmit-  
9 ted electromagnetic field. These features can be addressed in terms of constitutive  
10 relations of the electromagnetic medium, where the propagation of the electro-  
11 magnetic signal occurs. On the other side, in this paper, we aim to consider a  
12 punctual setup of the issue, based on the determination of whole structure of the  
13 electromagnetic field that propagates in the channel, and then, a more appropriate  
14 definition of the constitutive relations of the medium should result important for  
15 this aim.

16 To summarize, the main goals addressed in this paper are (*i*) the full-wave  
17 propagation model in a non-conventional material (namely, a chiral metamate-  
18 rial), and (*ii*) how the chirality effects affect the channel transfer functions on LoS  
19 and NLoS propagation. Chiral metamaterials, namely metamaterials that do not  
20 present any mirror symmetry plane, are materials where electric (magnetic) field  
21 generates also magnetic (electric) polarization [13]. They represent a very inter-  
22 esting category of metamaterials, since they offer great possibilities in the control  
23 of polarization such as optical activity. Specifically, they allow the polarization  
24 rotation of a linearly polarized wave.

25 As outlined in [14], another aspect really interesting of chiral metamaterials

1 is the exploitation of chirality property in order to reduce the attractive Casimir  
2 force, which is detrimental in micro- and nano-electromechanical systems. It has  
3 been discovered that chiral metamaterials are very good to realize the repulsive  
4 Casimir force, and this force is strictly dependent on the strength of the chiral-  
5 ity. In particular, the repulsive force leads to nanolevitations and opens up many  
6 opportunities such as frictionless operation of nanomotors. Furthermore, chiral  
7 metamaterials can provide negative refractive index, and this type of materials has  
8 gained a lot of attention in the last few years, since they can be used in all the  
9 applications that require “perfect lenses”, by overcoming diffraction limit.

10 This paper is organized as follows. In Section 2 we introduce a full-wave prop-  
11 agation model of the electromagnetic field that propagates in the THz band. Start-  
12 ing from the concept of electromagnetic chirality [15, 16, 17, 18], this approach  
13 considers the chiral effects following the change in the propagation velocity and  
14 in the refractive index, due to the chiral impurities inside the propagation medium.  
15 These effects are evaluated also in the case when the considered medium exhibits  
16 a Giant Optical Activity (GOA) [19, 20]. Section 3 describes the equivalent chan-  
17 nel model by considering the chirality-affected channel transfer functions, both  
18 for LoS and NLoS propagation. In Section 4 the performances have been as-  
19 sessed in terms of path loss in cases of LoS and NLoS propagation mechanisms,  
20 for biological and indoor applications. Finally, conclusions are drawn at the end  
21 of the paper.

## 22 2. Full-Wave Propagation in THz Band

23 This section is devoted to the design of a full-wave propagation model for  
24 THz band. Starting from the classic harmonic macroscopic Maxwell’s equations,

1 we consider the electromagnetic propagation inside a generic complex material,  
2 under the assumption that it is a linear and chiral medium.

3 Maxwell's equations represent the differential relations between the electric  
4 displacement  $\mathbf{D}$  and the electric field  $\mathbf{E}$ , as well as the magnetic displacement  
5  $\mathbf{B}$  and the magnetic field  $\mathbf{H}$ , combined together with the constitutive relations  
6 characterizing the medium where the electromagnetic field exists according to  
7 assigned electric and magnetic sources.

8 For real-world materials, the constitutive relations are rarely simple, except  
9 approximately, and usually determined by experiment. For materials without po-  
10 larisation and magnetisation effects (*i.e.*, vacuum), the constitutive relations are:

$$11 \quad \mathbf{B} = \mu_0 \mathbf{H}, \quad \mathbf{D} = \varepsilon_0 \mathbf{E}, \quad (1)$$

12 where  $\varepsilon_0$  is the electric permittivity, and  $\mu_0$  is the magnetic permeability.

13 For homogeneous materials, the electric permittivity is  $\varepsilon = \varepsilon_0 \varepsilon_r$ , where  $\varepsilon_r$  is  
14 the relative electric permittivity. Analogously, the magnetic permeability changes  
15 as  $\mu = \mu_0 \mu_r$ , where  $\mu_r$  is the relative magnetic permeability. These quantities  
16 are constant throughout the material, while in inhomogeneous materials they de-  
17 pend on space location within the material. For isotropic materials,  $\varepsilon$  and  $\mu$  are  
18 scalar quantities, while for anisotropic materials they are tensors *e.g.*, in crystal  
19 structures.

20 In this formulation unconventional materials (*i.e.* metamaterials) are also in-  
21 cluded, even if our considerations will be focused essentially on traditional di-  
22 electrics. Materials can be also generally dispersive, so that  $\varepsilon$  and  $\mu$  depend on the  
23 frequency of any incident electro-magnetic (EM) waves. Even more generally, in  
24 the case of non-linear materials  $\mathbf{B}$  and  $\mathbf{D}$  are not necessarily proportional to  $\mathbf{E}$ ,



1 and  $\mathbf{H}$ , respectively. In general,  $\mathbf{D}$  and  $\mathbf{B}$  depend on both  $\mathbf{E}$  and  $\mathbf{H}$ , on location  
2 and time.

3 Now, let us consider a time-harmonic generic linear material, where chiral  
4 (magneto/electric-optical) effects are included in the following constitutive rela-  
5 tions:

$$6 \quad \begin{cases} \mathbf{B} = \underline{\xi} \bullet \mathbf{E} + \underline{\mu} \bullet \mathbf{H} \\ \mathbf{D} = \underline{\varepsilon} \bullet \mathbf{E} + \underline{\zeta} \bullet \mathbf{H} \end{cases} \quad (2)$$

7 where the symbol  $\bullet$  represents the scalar product operator. In (2),  $\underline{\xi}$ ,  $\underline{\mu}$ ,  $\underline{\varepsilon}$ , and  $\underline{\zeta}$   
8 are specific tensor quantities of the material.

9 From (2) we observe the chirality property through the dependence of (i)  $\mathbf{E}$   
10 in  $\mathbf{B}$ , and (ii)  $\mathbf{H}$  in  $\mathbf{D}$ . Furthermore, the displacement field existing inside the  
11 material is generated by an excitation expressed in terms of intensity of the inci-  
12 dent electro-magnetic field. Therefore, the material under consideration is a linear  
13 chiral medium.

14 We remind that the chiral effects mean that:

- 15 • an electric field applied on the material provides not only an electric induc-  
16 tion, but also a magnetic displacement,
- 17 • a magnetic field applied on the material provides not only a magnetic in-  
18 duction, but also an electric displacement,

19 unlike other non-chiral materials.

20 We assume this specific material with the aim of assessing the performance  
21 (*i.e.*, transmission of the electromagnetic power) of an optical channel. This per-  
22 formance is linked to the channel transfer function. Also, this formulation allows  
23 a more rigorous assessment of the channel properties, that is verified for all the  
24 frequency range (*i.e.*, from 0 to infinity).

1 For this aim, in our proposed approach we need to define the expressions of  
 2 the EM field generated by a transmitter that is assumed as an impressed source  
 3 distribution in a given volume  $V$ , characterized by assigned electric and magnetic  
 4 vector functions  $\mathbf{J}_{i,e}(\mathbf{r})$  and  $\mathbf{M}_{i,m}(\mathbf{r})$ <sup>1</sup>, respectively, where  $\mathbf{r}$  is the observation  
 5 vector. In the following, the spatial dependence  $\mathbf{r}$  will be omitted.

6 The computation of the EM field in the channel is carried out through the  
 7 solutions of linear differential equations, arising from the following Maxwell's  
 8 equations:

$$9 \quad \begin{cases} \nabla \times \mathbf{E} = -j\omega\mathbf{B} - \mathbf{M}_{i,m} \\ \nabla \times \mathbf{H} = j\omega\mathbf{D} + \mathbf{J}_{i,e} \end{cases} \quad (3)$$

10 where Kong's vector  $\nabla$  in Cartesian space has been used *i.e.*,

$$11 \quad \nabla = \partial_x \hat{\mathbf{x}} + \partial_y \hat{\mathbf{y}} + \partial_z \hat{\mathbf{z}} = \frac{\partial}{\partial x} \hat{\mathbf{x}} + \frac{\partial}{\partial y} \hat{\mathbf{y}} + \frac{\partial}{\partial z} \hat{\mathbf{z}} \quad (4)$$

12 The system in (3) can be written as in the following form:

$$13 \quad \begin{cases} (\underline{\nabla} + j\omega\underline{\xi}) \bullet \mathbf{E} = -j\omega\underline{\mu} \bullet \mathbf{H} - \mathbf{M}_{i,m} \\ (\underline{\nabla} - j\omega\underline{\zeta}) \bullet \mathbf{H} = j\omega\underline{\varepsilon} \bullet \mathbf{E} + \mathbf{J}_{i,e} \end{cases} \quad (5)$$

14 where Kong's operator  $\underline{\nabla}$  is defined as a  $3 \times 3$  matrix:

$$15 \quad \underline{\nabla} = \begin{pmatrix} 0 & -\partial_z & \partial_y \\ \partial_z & 0 & -\partial_x \\ -\partial_y & \partial_x & 0 \end{pmatrix} \quad (6)$$

---

<sup>1</sup>The index  $i$  means impressed source distribution,  $e$  and  $m$  mean electric and magnetic, respectively.

1 and the solving differential equations for  $\mathbf{E}$  and  $\mathbf{H}$  are given, respectively:

$$2 \quad \begin{cases} [(\nabla - j\omega\underline{\zeta}) \bullet \underline{\mu}^{-1} \bullet (\nabla + j\omega\underline{\xi}) - \omega^2\underline{\varepsilon}] \bullet \mathbf{E} = \mathbf{f}_e(\mathbf{J}_{i,e}, \mathbf{M}_{i,m}) \\ [(\nabla + j\omega\underline{\xi}) \bullet \underline{\varepsilon}^{-1} \bullet (\nabla - j\omega\underline{\zeta}) - \omega^2\underline{\mu}] \bullet \mathbf{H} = \mathbf{f}_m(\mathbf{J}_{i,e}, \mathbf{M}_{i,m}) \end{cases} \quad (7)$$

3 Equation (7) derives from well-known Maxwell's equations [21]. In this paper,  
 4 we apply classical electromagnetic theory to the THz band, by assuming a signal  
 5 generated by a linear polarized electric field propagating in a complex medium  
 6 described by  $\underline{\xi}$ ,  $\underline{\mu}$ ,  $\underline{\varepsilon}$ , and  $\underline{\zeta}$ . Thus, from the authors' best knowledge, the follow-  
 7 ing equations represent novel results, useful to derive the electromagnetic field in  
 8 a complex medium. However, the proposed equations can be appropriately ap-  
 9 plied to both traditional and non-conventional (non-traditional) materials, under  
 10 the assumption of specific material constitutive relations.

11 The solutions of the problem can be obtained via (7), together with the diver-  
 12 gence equations. Following this approach, we obtain the expression of the total  
 13 electromagnetic field, but in order to give a simplified formulation for every reg-  
 14 ular observation point P, that is  $\forall P \notin V$ , we pose the condition of electric linear  
 15 polarization (e.g.,  $\hat{\mathbf{x}}$ ). Under this hypothesis, we get:

$$16 \quad \begin{cases} \mathbf{E} = E_1 \hat{\mathbf{x}} \\ \mathbf{H} = -(\rho_{R1} \bullet \xi_{R1} E_1) \hat{\mathbf{x}} + \left( j \frac{\rho_{23}}{\omega} \frac{\partial E_1}{\partial z} - \rho_{R2} \bullet \xi_{R1} E_1 \right) \hat{\mathbf{y}} + \left( j \frac{\rho_{33}}{\omega} \frac{\partial E_1}{\partial y} + \rho_{R3} \bullet \xi_{R1} E_1 \right) \hat{\mathbf{z}} \end{cases} \quad (8)$$

17 where  $\rho_{R1}$ ,  $\rho_{R2}$ , and  $\rho_{R3}$  are the row vectors of  $\underline{\rho} = \underline{\mu}^{-1}$  tensor,  $\xi_{R1}$  is the first row  
 18 vector of  $\underline{\xi}$  tensor, and  $\rho_{23}$ ,  $\rho_{33}$  are elements of  $\underline{\rho}$  tensor. Notice that  $\mathbf{E}$  satisfies the

1 following partial differential equation:

$$2 \quad f_1(\mathbf{r}) E_1 + f_2(\mathbf{r}) \frac{\partial E_1}{\partial x} + f_3(\mathbf{r}) \frac{\partial E_1}{\partial y} + f_4(\mathbf{r}) \frac{\partial E_1}{\partial z} + f_5(\mathbf{r}) \frac{\partial^2 E_1}{\partial y^2} + f_6(\mathbf{r}) \frac{\partial^2 E_1}{\partial z^2} = 0, \quad (9)$$

3 where functions  $f_i(\mathbf{r})$  with  $i = \{1, 2, \dots, 6\}$  depend on the elements of  $\underline{\xi}$ ,  $\underline{\mu}$ ,  $\underline{\varepsilon}$ ,  
4 and  $\underline{\zeta}$  tensors, and assume complicated expressions. As an instance, we present  
5 the  $f_1(\mathbf{r})$  term under the condition of spatial homogeneity of  $\underline{\xi}$ ,  $\underline{\mu}$ ,  $\underline{\varepsilon}$ , and  $\underline{\zeta}$  tensors:

$$6 \quad f_1(\mathbf{r}) = (\rho_{23} + \rho_{32}) \det \underline{\Omega}_{1,1} + \omega^2 \left( \mathbf{v}_1 \bullet \underline{\xi}_{C1} - \varepsilon_{11} \right) \det \underline{\Omega}_{1,2}, \quad (10)$$

7 with

$$8 \quad \underline{\Omega}_{1,1} = \begin{bmatrix} -\rho_{32} & \rho_{33} & \omega^2 \left( \underline{\zeta}_{R2} \bullet \underline{\rho}_{C1} \xi_{11} + \underline{\zeta}_{R2} \bullet \underline{\rho}_{C2} \xi_{21} + \underline{\zeta}_{R2} \bullet \underline{\rho}_{C3} \xi_{31} - \varepsilon_{21} \right) \\ \rho_{22} & -\rho_{23} & \omega^2 \left( \underline{\zeta}_{R3} \bullet \underline{\rho}_{C1} \xi_{11} + \underline{\zeta}_{R3} \bullet \underline{\rho}_{C2} \xi_{21} + \underline{\zeta}_{R3} \bullet \underline{\rho}_{C3} \xi_{31} - \varepsilon_{31} \right) \\ \left( \underline{\zeta}_{R1} \bullet \underline{\rho}_{C2} \right) & \left( -\underline{\zeta}_{R1} \bullet \underline{\rho}_{C3} \right) & 0 \end{bmatrix}, \quad (11)$$

$$10 \quad \underline{\Omega}_{1,2} = \begin{bmatrix} \rho_{13} & \rho_{32} & -\rho_{33} \\ -\rho_{12} & \rho_{22} & -\rho_{23} \\ \left( \underline{\zeta}_{R2} \bullet \underline{\rho}_{C2} - \underline{\zeta}_{R3} \bullet \underline{\rho}_{C3} \right) & \left( \underline{\zeta}_{R1} \bullet \underline{\rho}_{C2} \right) & \left( -\underline{\zeta}_{R1} \bullet \underline{\rho}_{C3} \right) \end{bmatrix}, \quad (12)$$

$$11 \quad \mathbf{v}_1 = \underline{\zeta}_{R1} \bullet \underline{\rho}_{C1} \hat{\mathbf{x}} + \underline{\zeta}_{R1} \bullet \underline{\rho}_{C2} \hat{\mathbf{y}} + \underline{\zeta}_{R1} \bullet \underline{\rho}_{C3} \hat{\mathbf{z}}, \quad (13)$$

12 where the indexes  $C1$ ,  $C2$ , and  $C3$  represent the column vectors.

13 According to this approach, the Poynting's vector defined as:

$$14 \quad \mathbf{P} = \frac{\mathbf{E} \times \mathbf{H}^*}{2}, \quad (14)$$

1 can be split into two components *i.e.*,  $\mathbf{P} = P_y \hat{\mathbf{y}} + P_z \hat{\mathbf{z}}$ , whose expressions are

$$2 \quad \begin{cases} P_y = -\frac{E_1}{2} \left( j \frac{\rho_{33}}{\omega} \frac{\partial E_1}{\partial y} + \rho_{R3} \bullet \xi_{R1} E_1 \right)^* \\ P_z = \frac{E_1}{2} \left( j \frac{\rho_{23}}{\omega} \frac{\partial E_1}{\partial z} - \rho_{R2} \bullet \xi_{R1} E_1 \right)^* \end{cases} \quad (15)$$

3 From (15), we can easily distinguish that Poynting's vector is formed by two  
 4 components that are orthogonal to each other (*i.e.*,  $P_y$  and  $P_z$ ), and to the electric  
 5 polarization axis (*i.e.*,  $\hat{\mathbf{x}}$ ). Therefore, if we refer this solution to the case of a  
 6 transmission channel, where a giant optical activity could be activated, we can  
 7 deduce that one of these terms is responsible of LoS power ( $W^{\text{LoS}}$ ), that is the  
 8 power at the receiver traveling along the direct (LoS) path, and the other one  
 9 contributes to the NLoS power ( $W^{\text{NLoS}}$ ), that is the power at the receiver traveling  
 10 along the indirect (NLoS) path, according to the receiver location. Obviously,  
 11 similar considerations hold for a  $\hat{\mathbf{y}}/\hat{\mathbf{z}}$ -axis electric polarization.

12 In the following, we attribute the presence of the indirect path as due at re-  
 13 flection/scattering/diffraction centers located at  $z = h$ . Therefore, the reflec-  
 14 tion/scattering/diffraction characteristics of the transmissive channel can be eval-  
 15 uated through the specific knowledge of the local planar geometry associated to  
 16 these centers. In this paper, we consider the effects of the reflection generated  
 17 by these centers allocated in the generic S points, while diffraction coefficient re-  
 18 quires the knowledge of the canonical geometry of the diffraction points. This  
 19 consideration limits the cases of real geometry that can be examined, and imposes  
 20 a statistical approach to the problem more than a deterministic one we are dealing  
 21 with. Finally, scattering effects can be inserted either at the level of constitutive  
 22 relations or added in dB as a global term to the power flow evaluation.

23 By assuming Figure 1, where the transmitter and the receiver are aligned along

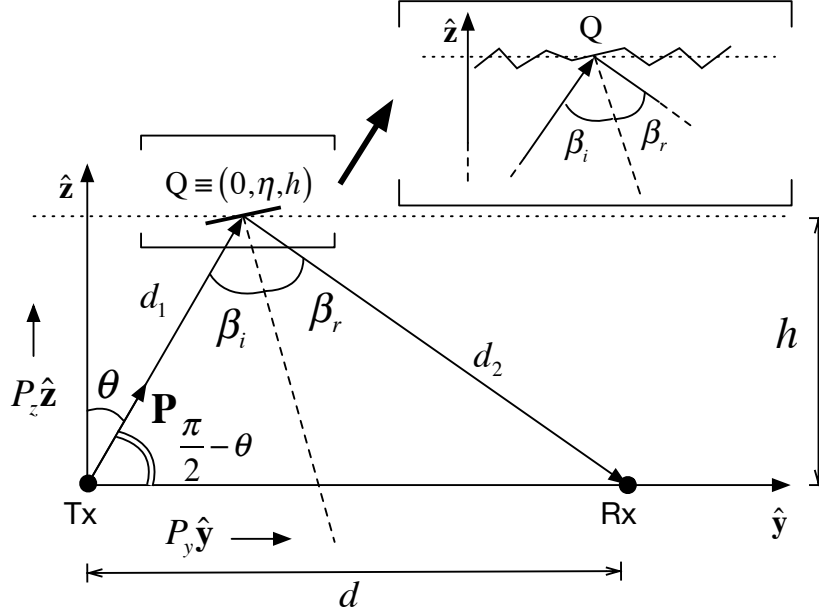


Figure 1: Schematic of the reference geometry, where the transmitter (Tx) and the receiver (Rx) lay along the  $\hat{y}$ -axis with the generic reflecting point Q belonging to  $\{x = 0, z = h\}$ .

1 the  $\hat{y}$ -axis, we can derive that the LoS power (*i.e.*,  $W^{\text{LoS}}$ ) is determined by  $P_y$ ,  
 2 while the NLoS power (*i.e.*,  $W^{\text{NLoS}}$ ) is contributed both by  $P_y$ , and  $P_z$ .

3 So, at the receiver the  $W^{\text{LoS}}$  can be written as

$$\begin{aligned}
 W^{\text{LoS}} &= \int_{S_R} \hat{\mathbf{n}} \bullet P_y \hat{\mathbf{y}} dS = \\
 &= \frac{1}{2} \int_{S_R} \left[ j \frac{\rho_{33}^*}{\omega} E_1 \frac{\partial E_1^*}{\partial y} - \rho_{R3}^* \bullet \xi_{R1}^* E_1 E_1^* \right] dS,
 \end{aligned} \tag{16}$$

5 being  $\hat{\mathbf{n}}$  the normal vector to the  $S_R$  receiving surface *i.e.*,  $\hat{\mathbf{n}} = -\hat{\mathbf{y}}$ .

6 We observe that (16) is a general formula that can be applied in the case of  
 7 conventional and/or unconventional materials. In this way it can be applied ei-  
 8 ther to biological propagation media, as well as indoor wireless communications.  
 9 Moreover, (16) is expressed in terms of the electric field and depends on the ele-

1 ments of the constitutive tensors. The explicit representation of the electric field  
 2 can be obtained after integration of (9), as it will be indicated below.

3 On the other side, in order to obtain the  $W^{\text{NLoS}}$ , we need to evaluate the indi-  
 4 rect path followed by the Poynting's vector through the generic reflection/ scatter-  
 5 ing/ diffraction point S laying in the  $z = h$  plane, to reach the receiving point.

6 We distinguish these points S into two classes *i.e.*, (i) Q points belonging to  
 7 the straight line ( $x = 0, z = h$ ), and (ii) all the remaining R points in the  $z = h$   
 8 plane. In this paper, we refer to the first class Q points, as shown in Figure 1.

9 Let us consider the effect of the local mirror reflection in points Q in  $z = h$ . In  
 10 this generic reflection point, the dielectric discontinuities in the permittivity give a  
 11 local specular reflection coefficient that acts on the two incident Poynting's vectors  
 12  $\mathbf{P}^{(i)}$  components *i.e.*,  $\mathbf{P}^{(i)} = P_y^{(i)}\hat{\mathbf{y}} + P_z^{(i)}\hat{\mathbf{z}}$ , and is depending on the specific  
 13 location of point Q and the reflecting local plane. This local specular reflection  
 14 coefficient generates the reflected Poynting's vector  $\mathbf{P}^{(r)} = P_y^{(r)}\hat{\mathbf{y}} + P_z^{(r)}\hat{\mathbf{z}} =$   
 15  $P_y^{\text{NLoS}}\hat{\mathbf{y}} + P_z^{\text{NLoS}}\hat{\mathbf{z}}$ , in the NLoS path, contributing to  $W^{\text{NLoS}}$ .

16 From Figure 1, it is easy to verify that for Q points belonging to the  $z = h$ -  
 17 plane, the incident/reflected  $\beta$  angle, related to the incident Poynting's vector, is  
 18 connected to the elevation angle  $\theta$  by the following simple relation:

$$19 \quad \frac{\cos \theta}{\cos(\theta - 2\beta)} = \frac{d_2}{d_1}, \quad (17)$$

20 where  $d_1$  and  $d_2$  are the distances of these points from the transmitter and the  
 21 receiver, respectively. Notice that for R points, a similar formula for the NLoS  
 22  $\hat{\mathbf{y}}$ -axis Poynting's vector component can be established as well.

23 Let us now determine  $\mathbf{P}^{(r)}$  in Q points. With reference to Figure 2 (a), we can

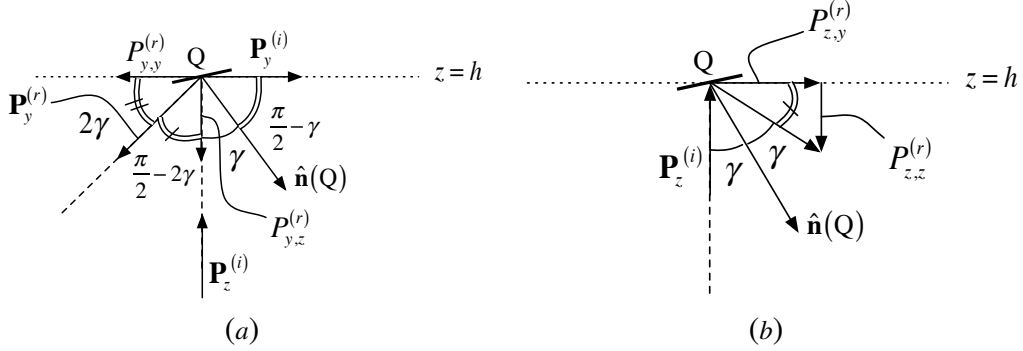


Figure 2: Schematic of the reference geometry for  $\mathbf{P}^{(r)}$  evaluation, in the case of (a)  $\mathbf{P}_y^{(i)}$ , and (b)  $\mathbf{P}_z^{(i)}$  components.

1 write:

$$\begin{aligned}
 \mathbf{P}^{(r)}|_Q &= P_y^{(r)}|_Q \hat{\mathbf{y}} + P_z^{(r)}|_Q \hat{\mathbf{z}} = \\
 2 \quad &= \left( -P_{y,y}^{(r)} + P_{z,y}^{(r)} \right) |_Q \hat{\mathbf{y}} - \left( P_{y,z}^{(r)} + P_{z,z}^{(r)} \right) |_Q \hat{\mathbf{z}} = \quad (18) \\
 &= P_y^{\text{NLoS}}|_Q \hat{\mathbf{y}} + P_z^{\text{NLoS}}|_Q \hat{\mathbf{z}},
 \end{aligned}$$

3 and from the Snell's law, we obtain:

$$4 \quad P_y^{(r)}|_Q = \left( -P_y^{(i)}|_Q \cos(2\gamma) + P_z^{(i)}|_Q \sin(2\gamma) \right) c_{\parallel}(\gamma) = P_y^{\text{NLoS}}|_Q, \quad (19)$$

5 and

$$6 \quad P_z^{(r)}|_Q = \left( -P_y^{(i)}|_Q \sin(2\gamma) + P_z^{(i)}|_Q \cos(2\gamma) \right) c_{\perp}(\gamma) = P_z^{\text{NLoS}}|_Q, \quad (20)$$

7 where  $c_{\parallel}(\gamma)$  and  $c_{\perp}(\gamma)$  are the reflection coefficients on the local plane reflecting  
 8 surface centered on Q point for parallel and orthogonal incidence, respectively.



1 From (19) and (20), we observe that the components along  $\hat{y}$  and  $\hat{z}$  of the  
 2 incident Poynting's vector contribute to the mirror reflection in point Q. The  
 3 new reflection components *i.e.*,  $P_{y,y}^{(r)}$ ,  $P_{y,z}^{(r)}$ ,  $P_{z,y}^{(r)}$ , and  $P_{z,z}^{(r)}$ , propagate towards the  
 4 receiver with the same propagation characteristics of the incident components, as  
 5 the propagation medium is the same of the direct path (LoS path). Therefore, such  
 6 components will arrive at the receiving end with an amplitude proportional to that  
 7 of the incident waves, as influenced from the reflection in point Q, but with the  
 8 same propagation characteristics.

9 To determine  $W^{\text{NLoS}}$  for the generic Q point, we observe that if the receiv-  
 10 ing surface is  $(-\hat{y})$ -oriented, only  $P_{y,y}^{(r)}$  and  $P_{z,y}^{(r)}$  will contribute, while  $W^{\text{LoS}}$  is  
 11 determined via  $P_y$  (see Figure 1). These two quantities can be written implicitly  
 12 as functions of the electric field, but to give an explicit form of these, the partial  
 13 differential equation in (9) satisfied by the electric field must be solved. This can  
 14 be done by writing the electric component as a factorized expression that is

$$15 \quad E_1 = e_1(x) e_2(y) e_3(z). \quad (21)$$

16 Under this hypothesis, the expression of  $W^{\text{LoS}}$  in (16) becomes:

$$17 \quad W^{\text{LoS}} = j \frac{e_2(d)}{2\omega} \left( \frac{de_2^*(y)}{dy} \right) \Big|_{y=d} N_1 - \frac{|e_2(d)|^2}{2} N_2, \quad (22)$$

18 where  $N_1$  and  $N_2$  are two scalar quantities *i.e.*,

$$19 \quad \begin{cases} N_1 = \int_{x_1}^{x_2} \int_{z_1}^{z_2} \rho_{33}^* |e_1(x)|^2 |e_3(z)|^2 dx dz \\ N_2 = \int_{x_1}^{x_2} \int_{z_1}^{z_2} \underline{\rho}_{R3}^* \bullet \underline{\xi}_{R1}^* |e_1(x)|^2 |e_3(z)|^2 dx dz \end{cases} \quad (23)$$

1 where  $x_1, x_2, z_1,$  and  $z_2$  are the extension limits of  $S_R$ .

2 Finally, to determine  $W^{\text{NLoS}}$  at the receiving end, we observe that it can be  
 3 written as the sum of infinite individual contributions of Q and R reflecting points  
 4  $P_{y,k}^{\text{NLoS}}$ , but can be approximated to  $N_T$  element with  $k = \{1, 2, \dots, N_T\}$ , over  
 5  $S_R$ :

$$6 \quad W^{\text{NLoS}} = \sum_{h=1}^{N_T} \int_{S_R} \hat{\mathbf{n}} \bullet \mathbf{P}_h^{(r)} dS = \sum_{h=1}^{N_T} \int_{S_R} \hat{\mathbf{n}} \bullet (P_{y,h}^{\text{NLoS}} \hat{\mathbf{y}} + P_{z,h}^{\text{NLoS}} \hat{\mathbf{z}}) dS. \quad (24)$$

7 To give a simplified example, we can consider the case of a single reflecting Q  
 8 point (*i.e.*,  $h = 1$ ), by assuming again that the  $\hat{\mathbf{x}}$ -polarized electric field is written  
 9 in a factorized form. Following this hypothesis, we obtain:

$$10 \quad W^{\text{NLoS}}|_{h=1} = e_2(d) \int_{x_1}^{x_2} \int_{z_1}^{z_2} \left[ \frac{j}{\omega} \left( \rho_{33}^* \frac{de_2^*(y)}{dy} \Big|_{y=d} + \rho_{23}^* \frac{de_2^*(y)}{dz} \Big|_{y=d} \right) + \right. \\ \left. - \left( \rho_{R3}^* + \rho_{R2}^* \right) \bullet \underline{\xi}_{R1}^* e_2^*(d) \right] |e_1(x)|^2 |e_3(z)|^2 dx dz. \quad (25)$$

11 Finally, from (16) and (25), the total power  $W$ , due to the contribution of a  
 12 single generic reflection point, at the receiver is computed as  $W|_{h=1} = W^{\text{LoS}} +$   
 13  $W^{\text{NLoS}}|_{h=1}$ .

14 We can conclude that all the remarks regarding the specific features of chiral  
 15 metamaterials permit us to characterize them as perfect candidates for nanosystem  
 16 applications realization, and more specifically, they represent the ideal candidates  
 17 for operations in the THz and also higher frequencies. In fact, in comparison to  
 18 natural materials, chiral metamaterials show strong response to the THz radiation  
 19 that shows a very great technological potential in several sectors such as imag-  
 20 ing, sensing and also communications. Also, materials exhibiting a giant tunable

1 optical activity show a very great potential in the achievement of active THz po-  
2 larization components (such for example tunable polarizers, polarization filters,  
3 etc.). As outlined by Kenanakis *et al.* in [22], giant optical activity is a very im-  
4 portant property particularly in the THz regime where there is a lack of optical  
5 components.

### 6 **3. Equivalent Channel Model**

7 In this section, we will present a channel model for THz band, based on  
8 ray tracing technique, and that considers the chirality effects of the EM field by  
9 taking advantage of the results in Section 2. Indeed, we firstly derived the re-  
10 ceived electric power in LoS and NLoS propagation in a chiral metamaterial from  
11 Maxwell's equations for the specific material. In this section we keep on exploit-  
12 ing Maxwell's equations to obtain the chirality dependence of the channel transfer  
13 functions in LoS and NLoS scenarios. More details on how the chirality affects  
14 the channel transfer functions are provided in the Appendix at the end of the paper.

15  
16 The use of ray tracing techniques for channel modeling in THz band has been  
17 already adopted in [4], where the authors present a multi-ray propagation model  
18 consisting of LoS, reflected, scattered, and diffracted paths. Indeed, due to the  
19 very short wavelength in the THz band, the ray tracing approach allows accu-  
20 rate modeling. We refer to the work in [4], and consider the chirality effects  
21 on the channel impulse response, affecting both the LoS and NLoS ray propaga-  
22 tion in the simplified case of spatial homogeneous chirality. The channel model  
23 will be the combination of many individual narrow sub-bands with a flat-band re-  
24 sponse. In the  $i$ -th frequency sub-band, the narrow-band channel impulse response

1 is expressed as a superposition of  $N_i$  rays, among which the  $n$ -th ray experiences  
 2 frequency-dependent attenuation  $\alpha_{i,n}$  that is also affected by chirality effects of  
 3 the propagation medium.

4 In the case of stationary environment, with a fixed transmitter and receiver, the  
 5 channel response of the multi-ray model is given as

$$6 \quad h_i(\tau) = \sum_{n=1}^{N_i} \alpha_{i,n} \delta(\tau - \tau_n), \quad (26)$$

7 where  $\tau$  and  $\tau_n$  are the propagation delays for the direct ray, and the  $n$ -th NLoS  
 8 ray, respectively.

9 Analogously in [4], by assuming a homogeneous chirality-affected LoS prop-  
 10 agation, and  $N_{\text{Ref}}^{(i)}$  reflected rays, the multi-ray channel model in the  $i$ -th frequency  
 11 sub-band can be described as:

$$12 \quad h_i(\tau) = \alpha_{i,\text{LoS}} \delta(\tau - \tau_{\text{LoS}}) \mathbf{I}_{\text{LoS}} + \sum_{l=1}^{N_{\text{Ref}}^{(i)}} \alpha_{i,l}^{(\text{Ref})} \delta(\tau - \tau_l^{(\text{Ref})}), \quad (27)$$

13 where  $\mathbf{I}_{\text{LoS}}$  is the indicator function that is equal to 1 or 0 for the presence of  
 14 LoS path or not, respectively. For the LoS path,  $\alpha_{\text{LoS}}$  and  $\tau_{\text{LoS}}$  refer to the atten-  
 15 uation and the delay, respectively. For the  $l$ -th reflected path,  $\alpha_{i,l}^{(\text{Ref})}$ , and  $\tau_l^{(\text{Ref})}$   
 16 correspond to the attenuation and the delay, respectively.

17 Through the use of Wiener-Khinchin theorem, the attenuations and delays in  
 18 the  $i$ -th frequency sub-band can be expressed by the module of transfer func-  
 19 tions  $H_{\text{LoS}}$ , and  $H_{\text{NLoS}}$ , respectively as LoS, and NLoS (*i.e.*, reflected) propagation  
 20 paths.

1 The chirality-affected LoS channel transfer function can be expressed as:

$$2 \quad H_{\text{LoS}}(f) = H_{\text{Abs}}(f) H_{\text{Spr}}(f) e^{-j2\pi f \tau_{\text{LoS}}}, \quad (28)$$

3 where  $H_{\text{Abs}}$  is the transfer function due to the molecular absorption loss that ac-  
 4 counts for the attenuation that part of the wave energy is converted into internal  
 5 kinetic energy to the molecules in the propagation medium [4], *i.e.*

$$6 \quad H_{\text{Abs}} = e^{-\frac{1}{2}k(f)d}, \quad (29)$$

7 while  $H_{\text{Spr}}$  is the transfer function due to the spreading loss, when the chirality is  
 8 active *i.e.*,

$$9 \quad H_{\text{Spr}} = \frac{\nu_{\text{Chir}}}{4\pi f d}, \quad (30)$$

10 by assuming  $d$  as the distance between the transmitter and the receiver. In (30),  
 11  $\nu_{\text{Chir}}$  is the propagation velocity of the EM field in a chiral homogeneous isotropic  
 12 medium *i.e.*,

$$13 \quad \nu_{\text{Chir}} = \frac{c}{n_{\text{Chir}}}, \quad (31)$$

14 where  $n_{\text{Chir}}$  is the refractive index, and being  $c = 1/(\sqrt{\varepsilon_0\mu_0})$ , we can write

$$15 \quad n_{\text{Chir}} = \sqrt{\mu_r \varepsilon_r + \xi_{cr}^2}. \quad (32)$$

16 where  $\xi_{cr}$  is the relative chirality parameter, and  $\varepsilon_r$  ( $\mu_r$ ) is the relative electric  
 17 (magnetic) permittivity (permeability), respectively. From (32), the expression in  
 18 (31) becomes

$$19 \quad \nu_{\text{Chir}} = \frac{c}{\sqrt{\varepsilon_r \mu_r + \xi_{cr}^2}}. \quad (33)$$

1 Finally, it follows that  $\tau_{\text{LoS}} = d/\nu_{\text{Chir}}$  is the time-of-arrival of the direct ray.

2 For the NLoS case, by considering  $d_1$  as the distance between the transmitter  
 3 and a generic reflecting point Q, and  $d_2$  as the distance between Q and the receiver,  
 4 the frequency-dependent transfer function of the NLoS ray propagation affected  
 5 by the homogeneous chirality effect, *i.e.*  $H_{\text{NLoS}}$ , is given by [4]

$$6 \quad H_{\text{NLoS}}(f) = \left( \frac{\nu_{\text{Chir}}}{4\pi f (d_1 + d_2)} \right) e^{-j2\pi f \tau_{\text{Ref}} - \frac{1}{2}k(f)(d_1 + d_2)} \cdot R(f), \quad (34)$$

7 where  $\tau_{\text{NLoS}} = \tau_{\text{LoS}} + (d_1 + d_2 - d)/\nu_{\text{Chir}}$  is the time-of-arrival of the reflected  
 8 ray, and  $R(f)$  is the rough surface reflection loss of EM waves at THz band. It  
 9 depends on the material, the shape and the roughness of the surface on which EM  
 10 field has been reflected.

11 According to the Kirchhoff scattering theory, the reflection coefficient for a  
 12 rough surface can be obtained by multiplying the smooth surface reflection co-  
 13 efficient derived from the Fresnel equations,  $\Psi(f)$ , with the Rayleigh roughness  
 14 factor  $\varsigma(f)$ , as

$$15 \quad R(f) = \Psi(f)\varsigma(f), \quad (35)$$

16 where  $\Psi$  is chosen according to the polarization of the incident Poynting's vector,  
 17 and can be approximated as:

$$18 \quad \Psi(f) \approx -\exp\left(\frac{-2 \cos(\beta_i)}{\sqrt{n_{\text{Chir}}^2 - 1}}\right). \quad (36)$$

19 and the Rayleigh roughness factor is defined as:

$$20 \quad \varsigma(f) = \exp\left(-\frac{8\pi^2 f^2 \sigma^2 \cos^2(\beta_i)}{\nu_{\text{Chir}}^2}\right), \quad (37)$$

1 with  $\sigma$  as the rough surface height standard deviation, commonly assumed as  
 2 Gaussian-distributed.

3 By combining the aforementioned models in (28) and (34), the channel model  
 4 in the  $i$ -th frequency sub-band in (27) becomes as:

$$\begin{aligned}
 h_i(\tau) = & \left| \frac{\nu_{\text{Chir}}}{4\pi f_i d} e^{-\frac{1}{2}k(f_i)d} \right| \delta(\tau - \tau_{\text{LoS}}) \mathbf{I}_{\text{LoS}} + \\
 5 & + \sum_{l=1}^{N_{\text{Ref}}^{(i)}} \left| \frac{\nu_{\text{Chir}}}{4\pi f_i (d_1 + d_2)} e^{-\frac{1}{2}k(f_i)(d_1 + d_2)} e^{-\frac{2 \cos(\beta_i)}{\sqrt{n_{i,\text{Chir}}^2 - 1}}} e^{-\frac{8\pi^2 f_i^2 \sigma^2 \cos^2(\beta_i)}{\nu_{\text{Chir}}^2}} \right| \\
 & \cdot \delta(\tau - \tau_l^{(\text{Ref})}).
 \end{aligned} \tag{38}$$

6 Now, we are able to compute the total path loss, *i.e.*  $A$  [dB], both in the case  
 7 of LoS and NLoS propagation. In the first case, it is contributed by the spreading  
 8 path loss (*i.e.*,  $A_s$ ), and the absorption path loss (*i.e.*,  $A_a$ ), and it can be expressed  
 9 as:

$$10 \quad A_{\text{LoS}} = A_s + A_a = 20 \log_{10} \left( \frac{4\pi d}{\lambda_{\text{Chir}}} \right) + 10\gamma d \log_{10} e, \tag{39}$$

11 where  $\lambda_{\text{Chir}} = \nu_{\text{Chir}}/f$  is the wavelength in the considered medium affected by the  
 12 homogeneous chirality, and  $\gamma$  is the absorption coefficient measuring the amount  
 13 of absorption loss of the EM field in the medium.

14 On the other hand, from (34) we can derive the total path loss for NLoS prop-  
 15 agation *i.e.*,  $A_{\text{NLoS}}$ , as follows:

$$\begin{aligned}
 A_{\text{NLoS}} = & 20 \log_{10} \left( \frac{\nu_{\text{Chir}}}{4\pi f (d_1 + d_2)} \right) + \\
 16 & + 20 \log_{10} \left( e^{-\frac{1}{2}\alpha(d_1 + d_2)} e^{-\frac{2 \cos(\beta_i)}{\sqrt{n_{\text{Chir}}^2 - 1}}} e^{-\frac{8\pi^2 f^2 \sigma^2 \cos^2(\beta_i)}{\nu_{\text{Chir}}^2}} \right).
 \end{aligned} \tag{40}$$

## 1      4. Simulation Results

2            In this section, we distinguish simulation results for LoS and NLoS propaga-  
3            tion models, in the case of (i) biological (for very small distances, in the order of  
4            millimeters), and (ii) indoor (for small distances, in the order of meters) wireless  
5            communications, and w.r.t. the chirality effects on these two types of propagation  
6            models. Since in this paper our aim is basically addressed to the path loss behavior  
7            in LoS and NLoS propagation (assuming reflected paths only) in a chiral affected  
8            medium, in the simulation results, we focus only on LoS and NLoS transfer func-  
9            tions with chirality effects, assuming a flat behavior for the molecular absorption  
10           loss (*i.e.*, frequency independent behavior). Thus, the following results represent  
11           the behavior of transmitted signals propagating along LoS and NLoS directions  
12           in a chirality-affected channel, by omitting the frequency-dependent molecular  
13           absorption effect.

14           In this framework, we discuss the influence of low values of chirality parame-  
15           ter *i.e.*,  $\xi_{\text{Chir}} = 1$ , separately from the higher values occurring in the GOA medium  
16           *i.e.*,  $\xi_{\text{Chir}} = 10$ .

17           Simulation results have been obtained under the assumption of homogeneous  
18           chirality and with a linear electric polarization. Standard values of the chiral pa-  
19           rameter  $\xi_{\text{Chir}}$  have been chosen varying in the range  $0 \leq |\xi_{\text{Chir}}| \leq 1$ . However  
20           higher values for  $\xi_{\text{Chir}}$  have been considered [19, 20, 23, 24] to evaluate the ef-  
21           fects of this parameter in the particular media such as the chiral complex materials  
22           where a giant optical activity with strong circular dichroism takes place. In this  
23           special media,  $|\xi_{\text{Chir}}|$  can be extended up to  $|\xi_{\text{Chir}}| \approx 5 \div 10$ .

24           Table 1 collects the parameters used in the simulation results in the cases of  
25           LoS, NLoS, and GOA scenarios. Distance values are (i)  $d = [1, 10]$  mm (m), and



Table 1: Parameters used in the simulations for LoS, NLoS, and GOA cases. Common parameters are  $f = [0.06, 60]$  THz,  $\varepsilon_0 = 8.85 \times 10^{-12}$ ,  $\mu_0 = 4\pi 10^{-7}$ .

Scenario	Parameters
LoS	$\varepsilon_r = [1, 3, 12]$ $\mu_r = 1$ $\xi_{\text{Chir}} = 1$ $\gamma = 0.6$
NLoS	$\varepsilon_r = [1, 3, 12]$ $\mu_r = 1$ $\xi_{\text{Chir}} = 1$ $\beta_1 = \pi/6, \sigma = 10^{-6}$
GOA	$\varepsilon_r = [40, 60, 80]$ $\mu_r = 40$ $\xi_{\text{Chir}} = 10$

1 (ii)  $d_1 = d_2 = [1, 10]$  mm (m), for biological (indoor) LoS and NLoS scenarios,  
2 respectively. In GOA scenario, the values of  $\varepsilon_r$  have been chosen in accordance  
3 with [19]–[24]. In the following, we describe the simulation results for LoS, NLoS  
4 and GOA scenarios.

5 Figure 3 depicts the total path loss for LoS propagation in a biological environ-  
6 ment in the frequency range  $[0.06, 60]$  THz, and for different values of electrical  
7 permittivity  $\varepsilon_r$  corresponding to the case of (i) vacuum ( $\varepsilon_r = 1$ ), (ii) calcium  
8 ( $\varepsilon_r = 3$ ), and (iii) silicon ( $\varepsilon_r = 12$ ). We observe that low values in  $\xi_{\text{Chir}}$ , *i.e.*  
9  $\xi_{\text{Chir}} = 1$ , contribute to a lower rate of attenuation (*i.e.*,  $< 60 - 80$  dB) in the  
10 lower THz band  $[0.06, 10]$  THz, for observation points laying in the range of mil-  
11 limeters (see Figure 3 (a) and (b)). Graphs are plotted for same different values  
12 in the relative electric permittivity  $\varepsilon_r$ , and can be of some interest for a biological  
13 propagation medium. We also observe that path loss increases for higher values

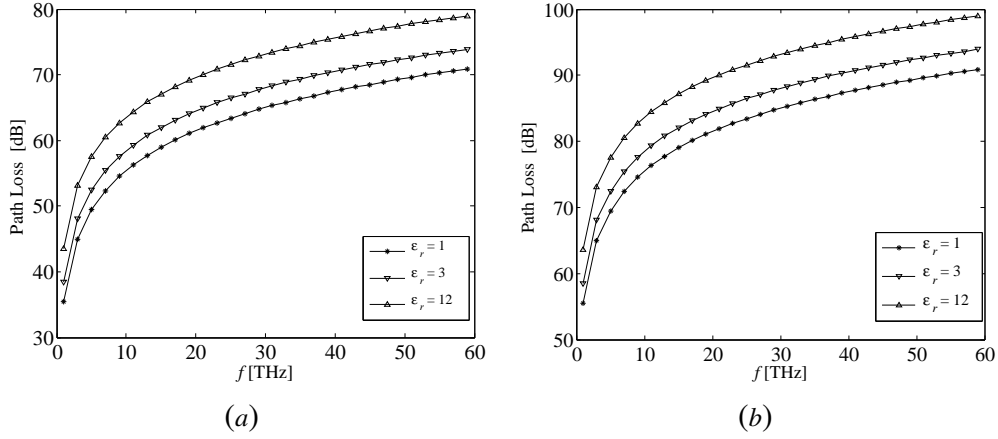


Figure 3: Total path loss for LoS propagation in a biological environment with a chirality-affected channel ( $\xi_{\text{Chir}} = 1$ ), for (a)  $d = 1$  mm, and (b)  $d = 10$  mm.

1 of  $\epsilon_r$ .

2 For LoS propagation effects in an indoor environment, Figure 4 (a) and (b) re-  
 3 ferred to  $\xi_{\text{Chir}} = 1$  and  $d = 1$ , and  $d = 10$  m, respectively, show similar behaviors  
 4 but with different dynamicity in the lower THz band. Specifically, in the range  
 5  $[0.06, 10]$  THz, the attenuation values span from  $[100, 125]$  dB to  $[140, 170]$  dB,  
 6 respectively in Figure 4 (a), and (b).

7 In NLoS propagation case, we have a similar behavior as those observed in  
 8 LoS propagation. Figure 5 regarding the propagation in bio-media shows small  
 9 variations for different values of  $\epsilon_r$ , with levels of attenuation higher than those  
 10 exhibited in the LoS propagation scenario. In fact, in Figure 5 (a) we observe a  
 11 path loss ranging around  $[30, 90]$  dB, while values increase for higher distances as  
 12 depicted in Figure 5 (b) for indoor environment. A similar behavior is observed  
 13 in Figure 6 related to indoor NLoS propagation, where the path loss graphs are  
 14 higher w.r.t. the values in the biological scenario, *i.e.*, they lay in the ranges  $\approx$

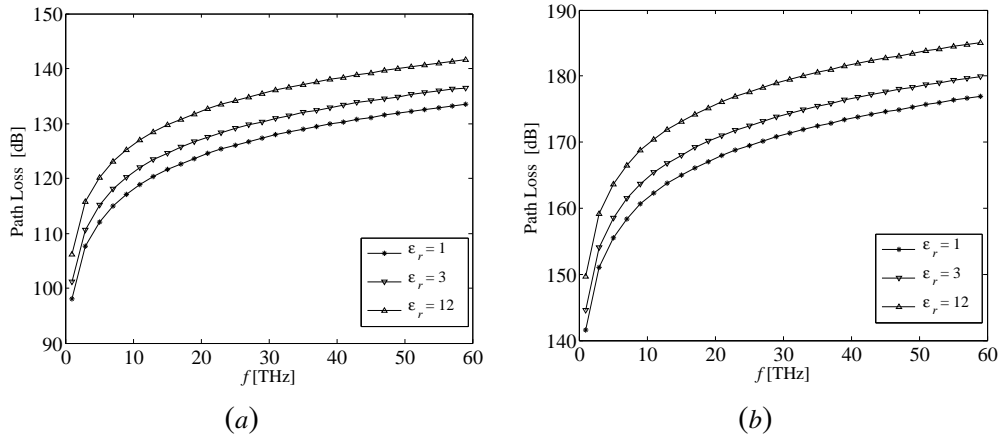


Figure 4: Total path loss for LoS propagation in an indoor environment with a chirality-affected channel ( $\xi_{\text{Chir}} = 1$ ), for (a)  $d = 1$  m, and (b)  $d = 10$  m.

1 [95, 155] dB and  $\approx [160, 225]$  dB for  $d_1 = d_2 = 1$  m, and  $d_1 = d_2 = 10$  m,  
 2 respectively.

3 Finally, we investigate the path loss for LoS and NLoS scenarios in media  
 4 that exhibit high values of  $\xi_{\text{Chir}}$ , that is when the environment where the electro-  
 5 magnetic field is propagating is a chiral unconventional material (Chiral Meta-  
 6 Material). In Figure 7 we observe a reduction of the attenuation in the band  
 7 [0.06, 10] THz w.r.t the remaining (higher) THz band, but with higher levels of  
 8 path loss. Furthermore, it is observed [19, 20, 23, 24] that the GOA produces  
 9 also a growth in the effective values of  $\epsilon_r$  and  $\mu_r$ . This difference in the values of  
 10  $\xi_{\text{Chir}}$  is due to the higher electromagnetic interactions that arise when the doping  
 11 impurities (cross-wire structures) are used in GOA materials.

12 In the case of GOA scenario and indoor LoS propagation (Figure 8), we ob-  
 13 serve again low attenuation levels in [0.06, 10] THz but with a fast dynamicity  
 14  $\approx [130, 150]$  dB for  $d = 1$  m, and [170, 190] dB for  $d = 10$  m. Finally, for NLoS

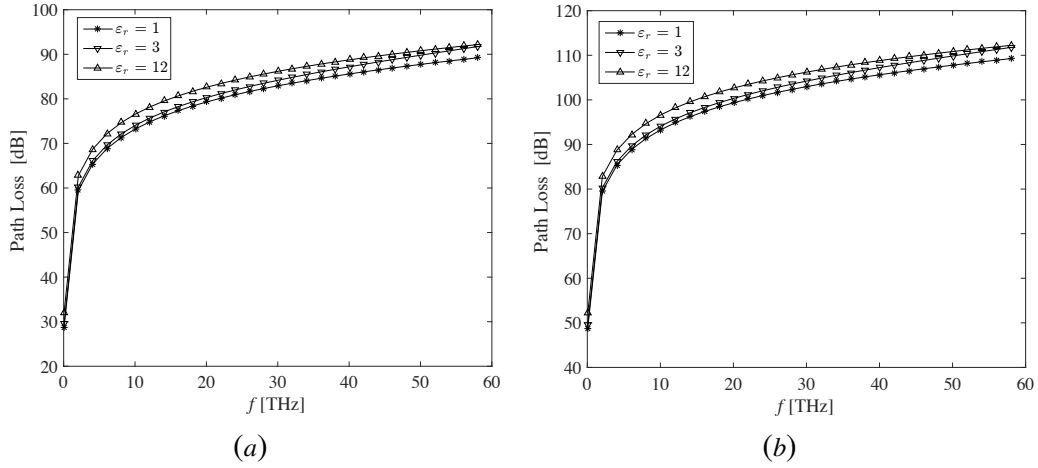


Figure 5: Total path loss for NLoS propagation in a biological environment with a chirality-affected channel ( $\xi_{\text{Chir}} = 1$ ), for (a)  $d_1 = d_2 = 1$  mm, and (b)  $d_1 = d_2 = 10$  mm distance.

1 scenario with GOA effect, we notice low values of path loss for lower frequencies,  
 2 while increasing trends are observed with higher frequency range, both for the bi-  
 3 ological and indoor cases (see Figure 9 and Figure 10, respectively). In the typical  
 4 range of Terahertz nanocommunications *i.e.*,  $[0.06, 10]$  THz, NLoS path loss with  
 5 GOA has low and almost flat values, thus representing an efficient transmission  
 6 scenario. For higher frequencies, the behavior is strongly dependent on the rel-  
 7 ative electrical permittivity, and then on the specific features of the transmission  
 8 material.

9 To summarize, we can conclude that chirality effects act differently on the  
 10 LoS path and on the NLoS path. Specifically, low values affect the LoS attenua-  
 11 tion with a progressive increase for higher frequency range up to 60 THz, and this  
 12 effect is more consistent with the growth in the values of  $\epsilon_r$ . Higher values are  
 13 also experienced for higher distances (indoor scenario). For a better understanding

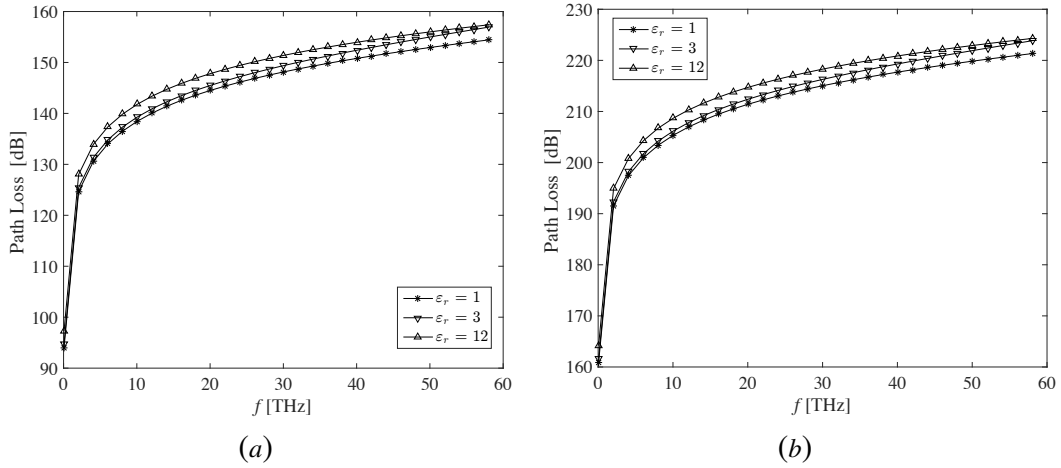


Figure 6: Total path loss for NLoS propagation in an indoor environment with a chirality-affected channel ( $\xi_{\text{Chir}} = 1$ ), for (a)  $d_1 = d_2 = 1$  m, and (b)  $d_1 = d_2 = 10$  m distance.

1 of the obtained results, Table 2 collects the path loss values for different scenar-  
 2 ios in the lower frequency range *i.e.*, [0.06, 10] THz. Different is the situation in  
 3 NLoS scenario. In fact the impact of the chirality factor is well hidden by the  
 4 presence of the scattered rays through the high values associated to the Rayleigh  
 5 roughness factor. This means that a chiral medium is more sensible to an incident  
 6 reflected electromagnetic field than to a scattered one. Finally, in all the scenarios  
 7 with GOA the path loss shows on average higher values w.r.t. the cases with-  
 8 out GOA. However, small variations occur in NLoS at lower THz frequencies  
 9 *i.e.*, [0.06, 10] THz, while very high values are for increasing frequencies. This  
 10 highlights the possibility to use chiral metamaterials with GOA as transmission  
 11 channels in the low THz frequency range.

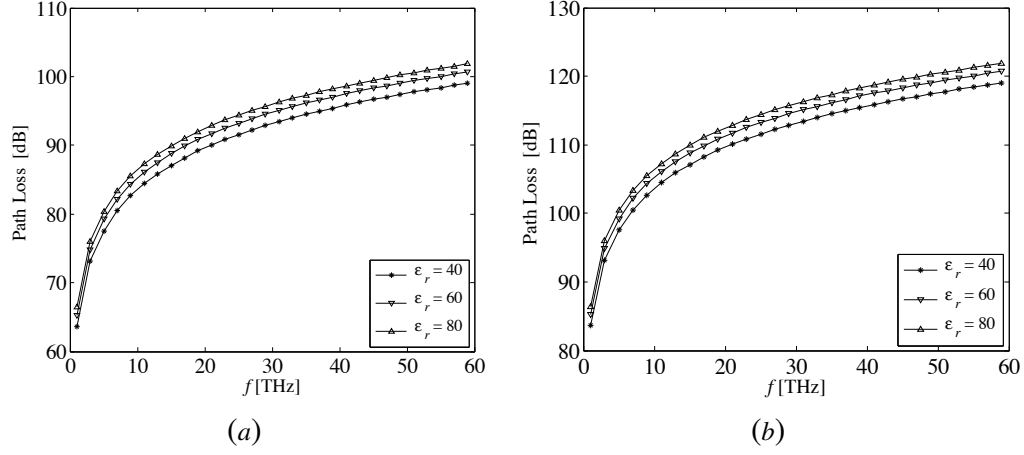


Figure 7: Total path loss for LoS propagation in a biological environment with GOA effect ( $\xi_{\text{Chir}} = 10$ ), for (a)  $d = 1$  mm, and (b)  $d = 10$  mm.  $\epsilon_r$  and  $\mu_r$  effective values have been chosen in accordance with [19]- [24].

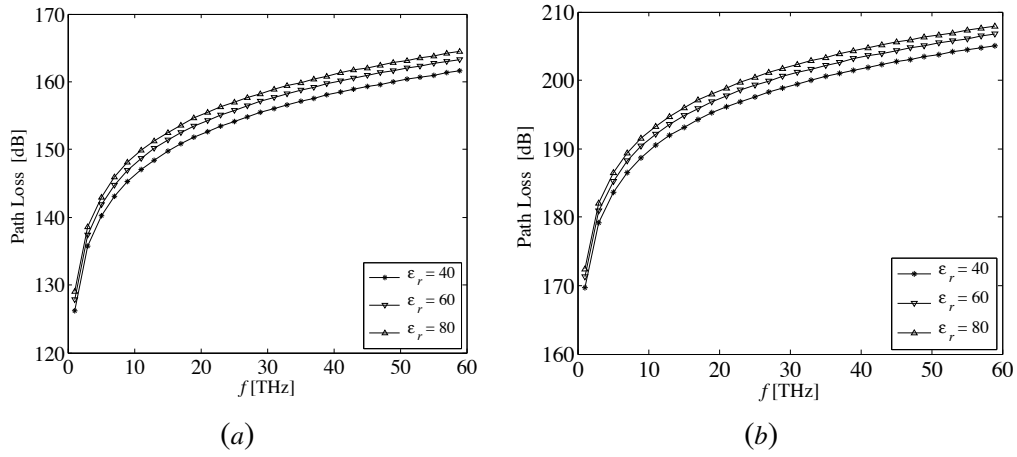


Figure 8: Total path loss for LoS propagation in an indoor environment with GOA effect ( $\xi_{\text{Chir}} = 10$ ), for (a)  $d = 1$  m, and (b)  $d = 10$  m.  $\epsilon_r$  and  $\mu_r$  effective values have been chosen in accordance with [19]- [24].

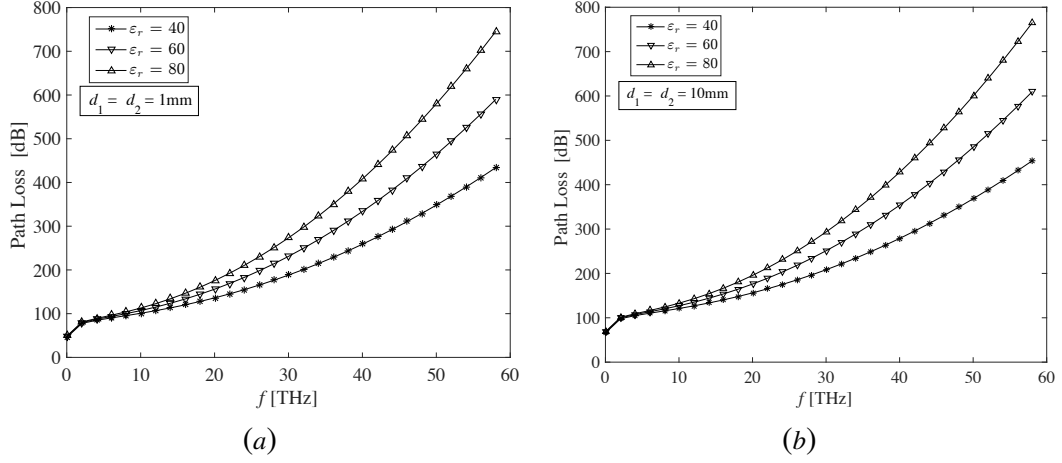


Figure 9: Total path loss for NLoS propagation in a biologic environment with GOA effect ( $\xi_{\text{Chir}} = 10$ ), for (a)  $d_1 = d_2 = 1\text{ mm}$ , and (b)  $d_1 = d_2 = 10\text{ mm}$ .  $\epsilon_r$  and  $\mu_r$  effective values have been chosen in accordance with [19]- [24].

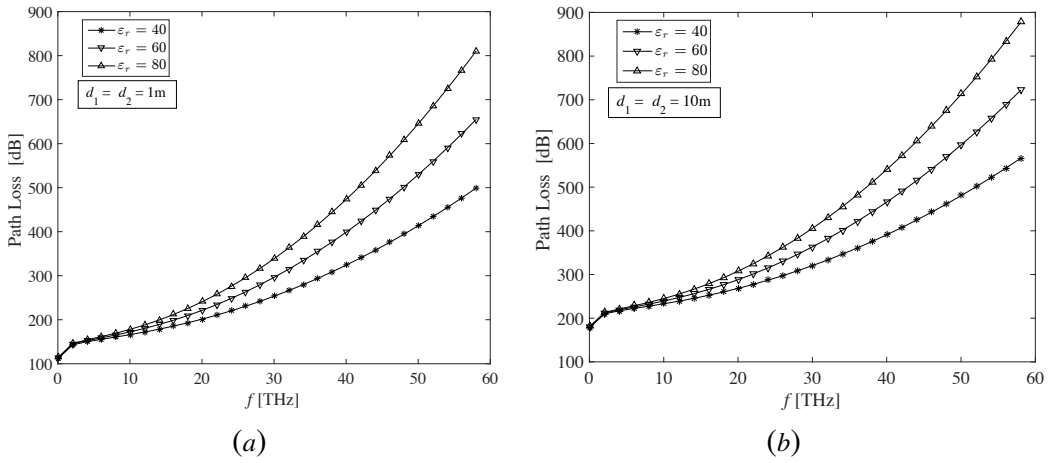


Figure 10: Total path loss for NLoS propagation in an indoor environment with GOA effect ( $\xi_{\text{Chir}} = 10$ ), for (a)  $d_1 = d_2 = 1\text{ m}$ , and (b)  $d_1 = d_2 = 10\text{ m}$ .  $\epsilon_r$  and  $\mu_r$  effective values have been chosen in accordance with [19]- [24].

Table 2: Approximated path loss results obtained for LoS, NLoS, and GOA cases in the frequency range  $[0.06, 10]$  THz and for different distances.

<b>Scenario</b>	<b>Biological</b>	<b>Indoor</b>
LoS	[35, 60] dB, for $d = 1$ mm [55, 85] dB, for $d = 10$ mm	[100, 125] dB, for $d = 1$ m [140, 170] dB, for $d = 10$ m
NLoS	[30, 75] dB, for $d_1 = d_2 = 1$ mm [50, 95] dB, for $d_1 = d_2 = 10$ mm	[95, 140] dB, for $d_1 = d_2 = 1$ m [160, 210] dB, for $d_1 = d_2 = 10$ m
GOA, LoS	[65, 85] dB, for $d = 1$ mm [85, 105] dB, for $d = 10$ mm	[130, 150] dB, for $d = 1$ m [170, 190] dB, for $d = 10$ m
GOA, NLoS	[50, 102] dB, for $d_1 = d_2 = 1$ mm [80, 105] dB, for $d_1 = d_2 = 10$ mm	[100, 190] dB, for $d_1 = d_2 = 1$ m [198, 230] dB, for $d_1 = d_2 = 10$ m



## 1     **5. Conclusions**

2           In this paper, we have presented a theoretical approach to evaluate the chirality  
3 effects on the electromagnetic propagation in a real complex medium. A full-wave  
4 model has been considered and the electromagnetic field has been studied in the  
5 THz frequency band with particular emphasis on the determination of the  $W^{\text{LoS}}$   
6 and  $W^{\text{NLoS}}$  power terms.

7           Chirality has been shown to be responsible of low attenuation in LoS propaga-  
8 tion, while it increases for NLoS scenario due to the the presence of the reflected  
9 rays in two types of environment considered (*i.e.*, biological and indoor applica-  
10 tions). Finally, in the case of GOA both in LoS and NLoS, the path loss has a flat  
11 behavior for lower frequencies (*i.e.*,  $< 10$  THz).

12

## 13     **Appendix**

14           The Maxwell's equations for the harmonic non-conventional medium defined  
15 under the hypothesis of plane wave become:

$$16 \quad \begin{cases} \mathbf{k} \times \mathbf{E}_0 = \omega\xi\mathbf{E}_0 + \omega\mu\mathbf{H}_0 \\ \mathbf{k} \times \mathbf{H}_0 = -\omega\varepsilon\mathbf{E}_0 - \omega\zeta\mathbf{H}_0 \end{cases} \quad (41)$$

17

18           By posing the magnetic field as

$$19 \quad \mathbf{H}_0 = \frac{1}{\omega\mu}\mathbf{k} \times \mathbf{E}_0 - \frac{\xi}{\mu}\mathbf{E}_0, \quad (42)$$

1 we obtain

$$2 \quad \mathbf{k} \mathbf{k} \cdot \mathbf{E}_0 - \omega (\xi - \zeta) \mathbf{k} \times \mathbf{E}_0 + \omega^2 (\mu \varepsilon - \xi \zeta - \mathbf{k} \cdot \mathbf{k}) \mathbf{E}_0 = 0, \quad (43)$$

3 with  $\mathbf{k} \cdot \mathbf{k} = k^2$ , where  $k$  is the complex amplitude of the propagation vector  $\mathbf{k}$ .

4 In order to find the dispersion relation, we need to compute  $\mathbf{k} \cdot \mathbf{E}_0$ , and then  
5 we have to consider the divergence equations for both the electrical and magnetic  
6 displacement  $\mathbf{D}_0$  and  $\mathbf{B}_0$ , respectively. Those equations arise to the following  
7 linear homogeneous system of two equations for the unknown quantities  $\mathbf{k} \cdot \mathbf{E}_0$ ,  
8 and  $\mathbf{k} \cdot \mathbf{H}_0$ :

$$9 \quad \begin{cases} \mathbf{k} \cdot \mathbf{B}_0 = \xi \mathbf{k} \cdot \mathbf{E}_0 + \mu \mathbf{k} \cdot \mathbf{H}_0 = 0 \\ \mathbf{k} \cdot \mathbf{D}_0 = \varepsilon \mathbf{k} \cdot \mathbf{E}_0 + \zeta \mathbf{k} \cdot \mathbf{H}_0 = 0 \end{cases} \quad (44)$$

10

11 We notice that the system in (44) provides (i)  $\infty^1$  autosolutions for  $\mathbf{k} \cdot \mathbf{E}_0 \neq 0$ ,  
12  $\mathbf{k} \cdot \mathbf{H}_0 \neq 0$ , if and only if

$$13 \quad \mu \varepsilon - \xi \zeta = 0, \quad (45)$$

14 and (ii) trivial solutions  $\mathbf{k} \cdot \mathbf{E}_0 = 0$ ,  $\mathbf{k} \cdot \mathbf{H}_0 = 0$ , if and only if

$$15 \quad \mu \varepsilon - \xi \zeta \neq 0. \quad (46)$$

16

17 It is evident that only trivial solutions are acceptable. Indeed, Eq. (46) is never

1 verified since

$$2 \quad \left\{ \begin{array}{l} \xi = \xi_0 \xi_r \\ \mu = \mu_0 \mu_r \\ \varepsilon = \varepsilon_0 \varepsilon_r \\ \zeta = \zeta_0 \zeta_r \end{array} \right. \quad (47)$$

3 and by assuming a reciprocal material *i.e.*,

$$4 \quad \xi = \zeta \Rightarrow j\xi_0 \xi_r = j\zeta_0 \zeta_r, \quad (48)$$

5 we get  $\xi_r > 0$ , and  $\zeta_r > 0$ . So, we can deduce that (46) becomes

$$6 \quad \mu\varepsilon - \xi\zeta = 0 \Rightarrow \mu_0\mu_r\varepsilon_0\varepsilon_r - j\xi_0\xi_r j\zeta_0\zeta_r = 0 \Rightarrow \mu_0\mu_r\varepsilon_0\varepsilon_r + \xi_0^2 \zeta_r^2, \quad (49)$$

7 and this is never null except for Single NeGative (SNG) materials, which are not  
8 considered in this paper.

9 By assuming a reciprocal material, (46) is not verified, and only the trivial  
10 solutions are acceptable. It follows that  $\mathbf{k} \cdot \mathbf{E}_0 = 0$ ,  $\mathbf{k} \cdot \mathbf{H}_0 = 0$  and then, based  
11 on previous hypothesis, the dispersion relation becomes:

$$12 \quad \mathbf{k}\mathbf{k} \cdot \mathbf{E}_0 - \omega(\xi - \zeta) \mathbf{k} \times \mathbf{E}_0 + \omega^2(\mu\varepsilon - \xi\zeta - k^2) \mathbf{E}_0 = 0 \Rightarrow \omega^2(\mu\varepsilon - \xi\zeta - k^2) = 0, \quad (50)$$

13 The values of  $k$  derive from (50) as:

$$14 \quad \mu\varepsilon - \xi\zeta - k^2 = 0, \quad (51)$$

1 that is

$$k = \pm \sqrt{\mu_0 \mu_r \varepsilon_0 \varepsilon_r + \xi_0^2 \xi_r^2} = \pm \sqrt{\mu_0 \varepsilon_0 (\varepsilon_r \mu_r + \xi_r^2)} = \pm \sqrt{\mu_0 \varepsilon_0} \sqrt{\varepsilon_r \mu_r + \xi_r^2},$$

2 (52)

3 being  $\xi_0 = \sqrt{\mu_0 \varepsilon_0}$ . It follows that the propagation vector will be:

$$\mathbf{k} = \pm \sqrt{\mu_0 \varepsilon_0} \sqrt{\varepsilon_r \mu_r + \xi_r^2} \hat{\mathbf{k}}.$$

4 (53)

5 Finally, the amount  $\nu_{\text{Chir}}$  is the relative refractive index for a reciprocal material  
6 (except SNG), whose expression is:

$$\nu_{\text{Chir}} = \sqrt{\varepsilon_r \mu_r + \xi_r^2}.$$

7 (54)

8

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