Scattering and Absorption by Thin Metal Wires in Rectangular Waveguide – Chiral Cranks versus Non-Chiral Staples

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Abstract

We investigate the physical validity of the claims about chiral microwave absorbers which have appeared in the engineering literature of the last decade. These assert that the performance of synthetic microwave absorbing materials (RAM) may be significantly enhanced by the addition of chiral inclusions, such as wire helices. We compare the performance of chiral, non-chiral and racemic absorbers by embedding unit cells—which are designed to be geometrically closely related—in an absorbing dielectric. We have found no physical mechanism to support the assertions that chirality is the key to improved microwave absorbers. Instead, in synthetic composites which employ thin metal wires in a lossy dielectric or magnetic host, it is the half-wave resonance of the inclusions—not their geometric shape—which plays the crucial role in absorption.

1. Jagadis Chunder Bose and the First Artificial Chiral Materials

Last year we became aware of the work done more than a century ago, in about 1897, on optical activity by the Indian scientist Jagadis Chunder[1] Bose [1, 2]. Until then we—like many others who have been working on artificial chiral materials during the past decade or so—mistakenly gave Lindman [3, 4] the credit for the first microwave experiments on artificial chiral materials.

Priority, however, belongs by about two decades to Bose whose remarkable experiments were conducted in the centimeter and millimeter regime [2]. A reading of his original paper leaves us in no doubt that Bose fully appreciated the role of chirality in optical activity, and that he built artificial chiral and racemic materials to simulate optical activity. A photograph of one of his jute elements is shown in [2, Figure 12].

2. Chiral Microwave Absorbers—Champions and Skeptics

Bose and Lindman, and subsequently Tinoco and Freeman [5], were interested in that most familiar of chiral phenomena—the rotation of the polarisation plane of linearly polarised waves.

Instead, much of the recent attention of microwave and antenna engineers to synthetic chiral materials was attracted by claims in refereed journals which promised microwave absorbers endowed with significantly improved properties. For example "... the possibility of designing anti-reflection coatings using chiral composites" [6]; "It is concluded that chirality can be used as a sensitive parameter to control EM wave propagation characteristics in dielectric composites" [7]; "... a novel material which reduces target RCS, through electromagnetic chirality, and makes it invisible to radar" [8]; "By incorporating electromagnetic chirality these screens offer unique

[1] Also spelled Chandra in the literature.

advantages, such as increased absorption in thin layers for a relatively wide range of frequencies, over conventional designs" [9]. A number of patents were issued in the same period.

In 1992 Bohren *et al.* challenged these claims about the efficacy of chiral absorbers [10]. After studying the effect of chirality on the reflection coefficient of a chiral slab backed by a conducting surface—the chiral Dällenbach layer—for normal incidence, they conclude that "while chiral inclusions may be advantageous, any absorber performance that can be obtained from a chiral composite may be obtained from its non-chiral counterpart." In 1994 Brewitt-Taylor independently came to a similar conclusion after an optimization study. He found "that the shape of the reflection curve is not much affected by the aspect ratio of the included helices, including the non-chiral extreme cases of a straight wire and a flat loop. Thus by this test the introduction of chirality by wire helices has not yielded any improvement" [11]. In a study, conducted between 1993 and 1997 and which used Kuehl's [12] mass production technique for helical inclusions, Cloete *et al.* find that "tiny copper helices can somewhat enhance the performance of dielectric absorbers about the frequency where the helices are one half-wave resonant, and that a racemic absorber is as effective as its purely chiral counterpart." They also find "that, unlike straight filaments (chaff), the helix makes a conveniently compact resonator." However, like Bohren *et al.* and Brewitt-Taylor they conjecture that chirality does not play an essential role in absorbers [13]. Recent network theoretical studies by Rozanov [14] and Brewitt-Taylor [15] on the fundamental limits of the bandwidth of layered absorbers are also relevant because they imply that chirality can not improve on the performance of an optimally designed dielectric-magnetic absorber.

A round table discussion, with participation from the audience, was held in June 1997 at Bianisotropics'97 in Glasgow to review whether or not chiral absorbers could yield superior performance to conventional dielectric-magnetic absorbing materials. (It is unfortunate that none of the chiral absorbing material protagonists were present[2].) The outcome of this discussion is summarized by Weiglhofer: "There seemed to be general consensus—certainly as far as technological significance is concerned—that chirality has not delivered the superior radar-absorption capabilities that some researchers had promised" [16].

We, however, did not consider the matter to be closed after this meeting. Also, to the best of our knowledge, none of the original claims in the refereed literature [6, 7, 8, 9] have been retracted. Fundamental questions remain to be answered—and consensus opinions by panels of scientists and engineers have sometimes turned out to be wrong in the past. Weiglhofer continues: "Yet, at the same time, one must recognize that the number of research groups involved in experimental research on chiral composites is comparatively small, so that many avenues that can lead to the proverbial "pot of gold at the end of the rainbow" still need to be explored" [16].

In this light—despite our negative findings and those of others—we decided in 1996 to embark on a more fundamental theoretical and experimental investigation. Our goal was to find a link—if any—between chirality and enhanced absorption.

The key phrases of Pasteur's scientific thinking are inscribed on the chapel walls of the Pasteur Institute in Paris—among them are the words *dissymétrie moléculaire* [17]. Geometry is the essence of chirality. Both Bohren *et al.* and Brewitt-Taylor had considered the geometry of the individual inclusions as a parameter. Bohren *et al.* compared an array of three-turn helices with an array of non-chiral inclusions made of three coaxial loops, presumably connected by a straight wire. Brewitt-Taylor varied the geometry of a wire parametrically from a straight wire (dipole) to a helix to a broken loop. In previous experimental work the chiral absorbers were invariably composed of randomly oriented helical resonators, which explains the emphasis on helical inclusions in the studies of Bohren *et al.* and Brewitt-Taylor.

[2]Members of the panel were *inter alia* Arne Jacob, Colin Brewitt-Taylor, Udo Unrau, Akhlesh Lakhtakia and Johannes Cloete.

3. Anisotropic Absorbers: Chiral, Racemic and Non-chiral

Instead, in search of deeper physical understanding, we decided to study periodic arrays of thin, bent wires, of resonant length, embedded in a dielectric host [18]. The resulting synthetic anisotropic media are amenable to deterministic numerical analysis, to simple physical realisation, and to microwave experiments. Most important is the clarification of the role of chirality in microwave absorbers which the new "crystalline" systems allow.

The three segment wire hook [20] was chosen as the basic element, instead of the helix, because of the simple geometrical relationship between the chiral enantiomorphs and the non-chiral structures depicted in Figure 1. Rotation of one of the outside segments in steps of $\pi/2$, in the plane normal to the central segment, transforms the non-chiral staple into a chiral crank; then a non-chiral crank; then a chiral crank of opposite hand; and back to the non-chiral staple. An obvious feature of this simple topological relationship between them is that the unwrapped length of the wire remains invariant. This turns out to be an important property because it is known that the unwrapped length of thin wires is a dominant parameter in determining their resonant scattering frequencies. As will be seen, resonance—not chirality—is the key to enhanced absorption in our systems.

Four uniaxial unit cells—one chiral, two non-chiral, and one racemic—were invented and classified according to their point group symmetry [18]. Two of them are shown in Figures 2 and 3. The unit cells were designed to fit into rectangular or square waveguide, with their optic axes parallel to the waveguide axis. This allows accurate measurement of their reflection and transmission coefficients for comparison with numerically simulated data.

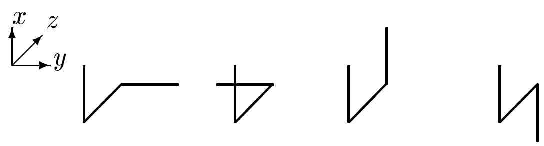

Figure 1: Basic wire structures. Two chiral cranks of opposite handedness (enantiomorphs), a non-chiral staple and a non-chiral crank.

The cells were especially studied around resonance. Because the hooks do not each occupy an electrically small volume in their resonant regime, a constitutive parameter description of the "crystals" cannot be used [21]. This does not matter, because we wished to make a direct physical study of absorption—the phenomenon of interest. This was done by using the measured or computed scattering parameters for a unit cell of the synthetic material, and the law of energy conservation, to determine the absorption spectrum. (The metal walls of the waveguide provide a well-defined and controlled environment for this approach, in contrast to a free space illumination

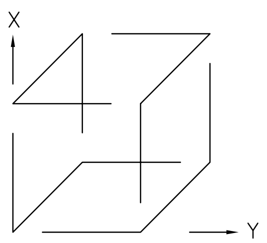

Figure 2: Chiral unit cell of point group 422 symmetry.

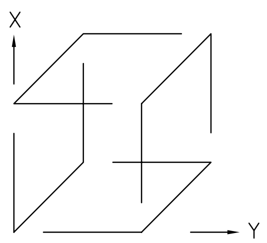

Figure 3: Non-chiral unit cell of point group 4/m symmetry.

system where out-of-beam scattering may occur.)

A finite-difference time-domain (FDTD) code was developed for the full-Maxwellian numerical analysis of thin-wire structures—with finite conductivity—embedded in an absorbing dielectric host in a rectangular or square waveguide [18]. The code was validated against physical experiments in the S-band (2–4 GHz). Figure 4 shows the results for the chiral (422 point group) unit cell of Figure 2. The measured data were obtained with an HP 8510C automatic network analyzer [18]. Agreement between the measured and simulated data for wires, made of both copper and steel, is sufficiently accurate for our purpose.

Further numerical experiments were then confidently performed in a square waveguide on the chiral, non-chiral, and racemic wire unit cells to study their absorption properties. Square waveguide was chosen so as to impose no constraints on the propagation of the cross-polarised TE_{01} mode.

4. Resonant Copper Wire Unit Cells Embedded in a Microwave Absorber

Synthetic chiral microwave absorbers usually consist of a conventional microwave absorber which contains suitable macroscopic chiral objects, such as our hooks or the more fashionable wire helix.

During the experiments to validate the FDTD code it was found that copper hooks embedded in a microwave absorber are just as effective as steel hooks[3] [18]. Therefore only the interaction between copper wire unit cells and the microwave absorbing host was studied in the square waveguide by means of the FDTD code. The microwave absorber had material parameters $\epsilon_r = 1.67$ and $\sigma = 0.04$ S/m, and an effective thickness of 18 mm. Each hook had a total length of $L = 48$ mm $= 3 \times 16$ mm ($f_0 \approx 2.4$ GHz for a deeply embedded, isolated hook), and the centre legs of the hooks were separated by 24 mm in a unit cell. The wire conductivity was 5.7×10^7 S/m.

The absorption spectra of the four uniaxial unit cells are compared in Figure 5. The microwave absorber, without any wire inclusions, absorbs on average about 25 % of the power across the band. The absorption is strikingly enhanced by the inclusion of *resonant* wire structures in the microwave absorber. This is observed whether the inclusions are chiral, non-chiral or racemic. Half-wave resonance of the wires, in the case of the chiral cell, is associated with the Cotton effect—circular dichroism—as also observed by Lindman, and Tinoco and Freeman [3, 5]. Maximum circular dichroism usually coincides with peak absorption [19], but nevertheless absorption at the Cotton frequencies of our chiral unit cell is not superior to absorption at the half-wave resonance of the non-chiral (cranks) or racemic unit cells. Evidently the unit cell of non-chiral cranks couples the incident field to the loss mechanisms of the host as effectively as the chiral and racemic unit cells.

5. Chirality is not a Geometrical Requirement for Absorption

Our experiments show that absorption by a lossy host is significantly enhanced by the inclusion of *resonant* metal-wire structures—whether the inclusions are chiral or non-chiral. Although there were differences in the enhancement of absorption by the four unit cells, the important insight is that the unit cell of non-chiral cranks couples the incident field to the loss mechanisms of the host just as effectively as does the unit cell of chiral hooks and the racemic unit cell of enantiomorphous hooks.

The essence of the claims about chiral absorbers is that the chirality of the inclusions affords an additional degree of freedom for the design of composite materials with enhanced microwave absorption. The implication is that chirality somehow provides the key to improved absorbers.

[3]There is however a marked and important difference when the hooks are embedded in a low loss host. The steel hooks, as expected, make much more efficient absorbers than the copper hooks.

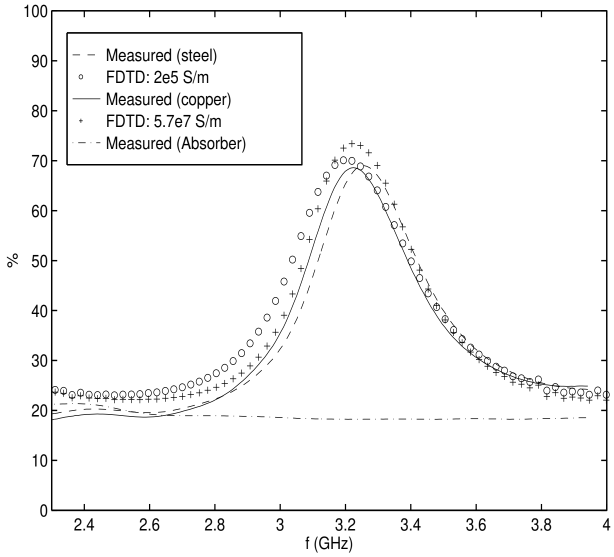

Figure 4: Point group 422 chiral unit cell in an absorber, in rectangular waveguide. Comparison of the percentage power absorbed by a copper and a steel unit cell, measured and predicted.

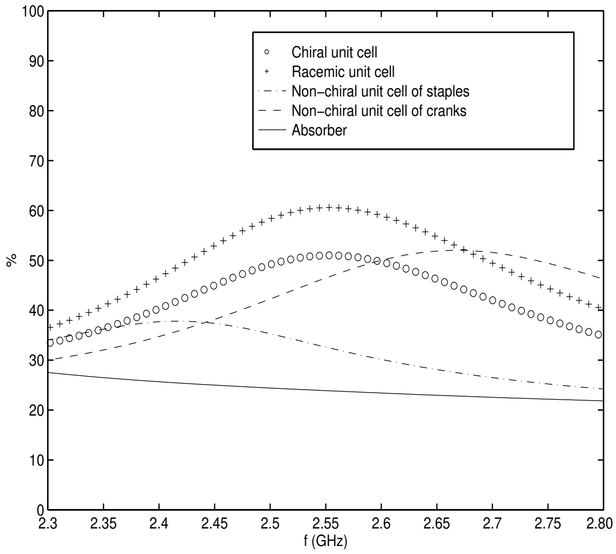

Figure 5: Theoretical absorption spectra of the four uniaxial copper wire unit cells embedded in a microwave absorber, in a square waveguide.

We have found no evidence in support of this. Although—as is well known—chirality is a geometrical requirement for optical activity, we assert that chirality is not a relevant geometrical requirement for absorption.

Instead we propose that in synthetic absorbers, which employ thin metal wires in a lossy dielectric or magnetic host, it is the half-wave resonance of the inclusions, not their shape, which plays the crucial role in absorption. The inclusion of conducting wire structures, whether chiral or not, in a microwave absorber serves only to couple the incident field to the local ohmic, dielectric and magnetic loss mechanisms of the host [13]. Unlike straight chaff-like filaments, the helix makes a conveniently compact resonator, but its chirality does not play a fundamental role in absorption. This contention is supported by the work of Brewitt-Taylor [11], which also provides evidence of enhanced absorption in the region of half-wave resonance for helices.

We recognize that our comparative study of chiral, non-chiral and racemic unit cells is thorough but not exhaustive. However, if a chiral absorber can significantly outperform an equivalent non-chiral counterpart we think that our experiments would reveal this. We are also unaware of any convincing experimental evidence from other researchers that chiral inclusions can markedly improve the performance of an *a priori* well-designed physical absorber using non-chiral conductive, dielectric and magnetic ingredients. Significantly, despite the patent applications made between September 1988 and June 1992, chiral microwave absorbers are apparently not yet available from commercial manufacturers.

Acknowledgement
The written version of this paper is an adapted version of [22]. In the oral presentation we will also draw on results which were presented in [23]. We thank Professor Afonso Barbosa for the kind invitation to present this material at Bianisotropics 2000.

References

[1] J. C. Bose, "On the rotation of plane of polarisation of electric waves by a twisted structure," *Proc. Roy. Soc.*, vol. 63, pp. 146–152, 1898.

[2] D. T. Emerson, "The work of Jagadis Chandra Bose: 100 years of millimeter-wave research," *IEEE Trans. Microwave Theory and Techniques*, vol. 45, no. 12, December 1997, pp. 2267–2273.

[3] K. F. Lindman, "Über eine durch ein isotropes System von spiralförmigen Resonatoren erzeugte Rotationspolarisation der elektromagnetischen Wellen," *Annalen der Physik*, vol. 63, no. 4, pp. 621–644, 1920.

[4] I. V. Lindell, A. H. Sihvola, and J. Kurkijärvi, "Karl F. Lindman—the last Hertzian and a harbinger of electromagnetic chirality," *The Radioscientist*, vol. 3, no. 2, pp. 38, 44–48, 52–53, June 1992.

[5] I. Tinoco, Jr. and M. P. Freeman, "The optical activity of oriented copper helices. I. Experimental," *J Physical Chemistry*, vol. 61, pp. 1196–1200, Sept. 1957.

[6] V. K. Varadan, V. V. Varadan, and A. Lakhtakia, "On the possibility of designing anti-reflection coatings using chiral composites," *J Wave-Material Interaction*, vol. 2, no. 1, pp. 71–81, 1987.

[7] T. Guire, V. V. Varadan, and V. K. Varadan, "Influence of chirality on the reflection of EM waves by planar dielectric slabs," *IEEE Trans. Electromagnetic Compatibility*, vol. 32, no. 4, pp. 300–303, 1990.

[8] D. L. Jaggard and N. Engheta, "CHIROSORB^{TM} as an invisible medium," *Electronics Letters*, vol. 25, no. 3, pp. 173–174, 1989.

[9] D. L. Jaggard, N. Engheta, and J. Liu, "Chiroshield: a Salisbury/Dallenbach shield alternative," *Electronics Letters*, vol. 26, no. 17, pp. 1332–1334, 1990. Correction: *ibid.* vol. 27, no. 6, p. 547, 1991.

[10] C. F. Bohren, R. Luebbers, H. S. Langdon, and F. P. Hunsberger, "Microwave-absorbing chiral composites: Is chirality essential or accidental?," *Applied Optics*, vol. 31, pp. 6403–6407, 20 Oct. 1992.

[11] C. R. Brewitt-Taylor, "Modeling of helix-loaded chiral radar-absorbing materials," in A. Priou (Ed.), *Progress in Electromagnetic Research, PIER 9: Bianisotropic and Bi-isotropic Media and Applications*, EMW Publishing, Cambridge, Massachusetts, USA, 1994, pp. 289–310.

[12] S. A. Kuehl, S. S. Grové, E. Kuehl, M. Bingle, and J. H. Cloete, "Manufacture of microwave chiral materials and their electromagnetic properties," in A. Priou *et al.* (Ed.), *Advances in Complex Electromagnetic Materials*, Kluwer, Dordrecht, 1996, pp. 317-332.

[13] J. H. Cloete, S. A. Kuehl, and M. Bingle, "The absorption of electromagnetic waves at microwave frequencies by synthetic chiral and racemic materials," *Int. J Applied Electromagnetics Mechanics*, vol. 9, pp. 103–114, 1998.

[14] K. N. Rozanov and S. N. Starostenko, "Ultimate thickness to bandwidth ratio of single-layer and multi-layer dielectric radar absorbers," in *Proceedings International Conference on Electromagnetics in Advanced Applications* (ICEEA99), Torino, Italy, 13–17 September 1999, pp. 167–170.

[15] C. R. Brewitt-Taylor, "Fundamental limit on the performance of radar absorbing material," in *Digest of the IEEE Antenna and Propagation Symposium*, Orlando, Florida, July 1999, pp. 1938–1941.

[16] W. S. Weiglhofer, "A report on Bianisotropics'97," *IEEE Antennas and Propagation Magazine*, vol. 39, no. 4, pp. 74–75, August 1997.

[17] J. Applequist, "Optical activity: Biot's bequest," *American Scientist*, vol. 75, pp. 59–67, Jan./Feb. 1987.

[18] M. Bingle, *The Role of Chirality in Synthetic Microwave Absorbers.* PhD thesis, Stellenbosch University, Stellenbosch, 1998.

[19] L. D. Barron, *Molecular Light Scattering and Optical Activity*, Cambridge University Press, 1982.

[20] I. P. Theron and J. H. Cloete, "The electric quadrupole contribution to the circular birefringence of nonmagnetic anisotropic chiral media: A circular waveguide experiment," *IEEE Trans. Microwave Theory and Techniques*, vol. 44, no. 8, pp. 1451–1459, 1996.

[21] R. E. Raab and J. H. Cloete, "An eigenvalue theory of circular birefringence and dichroism in a non-magnetic chiral medium," *J Electromagnetic Waves and Applications*, vol. 8, no. 8, pp. 1073–1089, 1994.

[22] J. H. Cloete, M. Bingle, and D. B. Davidson, "The role of chirality in synthetic microwave absorbers," in *Proceedings International Conference on Electromagnetics in Advanced Applications* (ICEEA99), Torino, Italy, 13–17 September 1999, pp. 55–58.

[23] M. Bingle, D. B. Davidson, and J. H. Cloete, "FDTD simulation of scattering by conducting wires in rectangular waveguide," in *Abstracts Millenium Conference on Antennas & Propagation*, AP2000, Davos, Switzerland, 9–14 April 2000, Volume 1, p. 92. (Full paper on CD-ROM SP-444.)