Developing Chiral Media Based on the Inclusion of Metallic Cranks

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Abstract—**A review of the manufacturing techniques for developing chiral media based on the inclusion of cranks is presented. Chirality is usually obtained by a randomdistribution of helices in a host medium. Here the chiral elements are obtained by bending thin metal-wires in three segments. We will show that a random distribution of cranks is able of rotate the polarization angle of the transmitted linearly polarized wave at microwave frequencies. This effect can be enhanced by the precise location of cranks forming a 2D periodic lattice. Several structures are analyzed looking for isotropy, reciprocity and homogeneity.**

Index Terms—**Chiral media, Materials science and technology, Microwave measurements.**

I. INTRODUCTION

ELECTROMAGNETIC activity is the property of some materials to rotate a linearly polarized incident wave. These media are composed by elements with chiral symmetry, and the phenomena occurs at frequencies depending on the size of the elements. In such material the electric and magnetic fields are coupled, which can be macroscopically described through the following constitutive relations [1]:

$$\vec{D} = \epsilon \vec{E} - j\kappa \vec{H}$$
$$\vec{B} = \mu \vec{H} + j\kappa \vec{E}$$

where $\epsilon = \epsilon_0 \epsilon_r$ is the permittivity, $\mu = \mu_0 \mu_r$ is the permeability and κ is the chirality parameter.

For a linearly polarized incident wave, the transmitted wave passing through such medium is rotated and elliptically polarized. This is a consequence of the differences on phase velocities and on absorption for the left -and right- circularly polarized components. These propagation constants can be determined by:

$$k_{\pm} = \omega \sqrt{\mu \epsilon}\,(1 \pm \kappa_r)$$

where $+$ and $-$ subscripts are related with the right- and left circularly polarized waves, respectively, and κ_r is the relative chirality $\kappa_r = (\epsilon_r \mu_r)^{-1/2}$.

For homogeneous and isotropic media, the chirality parameter is a complex number and its real part is related to the rotation angle by:

$$\theta = 2d\omega \sqrt{\epsilon_0 \mu_0}\kappa'$$

therefore the experimental determination of the rotation angle provides information about the real part of the chirality.

Materials with electromagnetic activity at microwave frequencies are usually made by spreading helical inclusions into a host medium. The helices must be randomly oriented with no special direction in order to assure isotropy, otherwise the result is a macroscopically bianisotropic material. We have developed a new kind of materials based on the inclusion of three segment wire hooks, “cranks”.

In a previous paper, we show that a random distribution of cranks produces girotropy, and the rotation angle depends on the frequency following a Condon model, with only one frequency [2]. However, a helix is a much compact structure, and for the same total wire length helix are smaller than cranks, which makes the number density of cranks to be lower than the one using helices and increases the inhomogeneity. Therefore, the material can present both local density variations and accidental alignments of the cranks, which causes fluctuations of the transmitted wave when the sample is rotated or when a different sample area is illuminated by the incident beam. To experimentally determine the rotation angle, we had to measure several samples and a mean value of the rotation angle was carried out.

In order to enhance the isotropic degree, we have searched the chiral behavior by placing the cranks forming 2D periodic structures. We have designed several lattices composed by cranks with different sizes and orientations. In this paper we make a short review of some of our achievements in the development of chiral media based on metallic cranks.

II. DESIGN OF CHIRAL MEDIA

The most widely used fabrication technique consists on distributing, as randomly as possible, helices in a dielectric host medium. Following this procedure, chiral media using cranks instead of helices was manufactured, by first time [2]. Chiral elements were produced from a 0.4 mm diameter and 12.6 mm length copper wire. Wires are bent in three segments by two 90 degrees angles, all with the same handedness. The elements were dispersed in an epoxy resin with a low curing temperature. Special attention was paid to obtaining a random and homogeneous distribution without privileged directions. The samples were 30 cm diameter and 1.5 cm wide disks, with an average inclusion number density around 2 cm^{-3}. The density results much lower than the inclusion number density obtained when helices were used [3] and therefore a higher inhomogeneity degree.

The homogeneity problem can be solved by locating the cranks forming 2D structures. For example, by introducing

This work was supported by the Dirección General de Investigación of the Spanish Ministerio de Educación y Ciencia, under the projects/grants TEC2006-13268-C03-01. TEC2006-13268-C03-02 and TEC2006-13268-C03-03.

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one of the segments into the host medium, a 5 mm width slab of foam with a relative permittivity close to one. The rest of the crank, two segments forming a 90 degrees angle, remains located on the front side of the host medium. Keeping the back side of the medium completely free of metals. This is a quite laborious technique with some problems linked to the manufacturing process, such us the lack precission in the location of the cranks.

In order to increase the fabrication quality and to introduce more parameters for material design, we make use of printed circuit boards, PCB. The three dimensional cranks are produced by using conductive pathways in both sides of the PCB and metalized holes.

A periodic lattice of cranks presents some adventages compared with the random distribution of helices. New parameters for material design, such as the relative length of segments and lattice characteristic lengths are now available. However, it present also some disadventajes related with the alignments of the cranks, which produces anisotropic materials. We will prove that unwanted effects can be overcome by using different crank orientations.

Fig. 1 shows pictures of three samples produced by following the manufacturing techniques before described: random distribution of cranks in an epoxy matrix, cross distribution of cranks in foam forming a 2D periodic structure, and a PCB based periodic structure, which are labelled as “RND”, “CROSS” and “PCB”, respectively.

III. Experimental Results

The electromagnetic activity has been measured by making use of an experimental set-up for X-band previously reported [3]. It is based on a free-wave system, initially designed for permittivity and permeability measurements, and adapted to measure the rotation angle of a linearly polarized wave. An incident beam is focused by an ellipsoidal concave mirror so that diffraction problems are minimized, even with relatively small samples. The transmitting antenna is placed at one of the mirror foci and the sample at the other one. The receiving antenna can rotate about the longitudinal axis, which allows the measurement of the scattering parameters (S parameters) corresponding to any polar transmission.

Fig. 2 shows the angle of rotation for RND sample, the error bars show the standard deviation of the mean for 10 measurements at different sample regions [2]. The solid line is the expected value of the rotaion angle obtained by fitting a one frequency Condon model [5] to the experimental data. We observe that the rotation angle depends on the frequency following the typical chiral behavior, with a resonance frequency at around 8.5 GHz. A similar frequency dependence was also observed on composites formed by randomly oriented helix [6], [7] and [3].

When 2D periodic structures of cranks are analyzed, we have found, in most of cases, that the rotation angle depends on the relative orientation between the cranks and the incident wave [4]. Fig. 3 shows an example of the rotation angle for two different orientations between cranks and incident wave. Clearly, the observed girotropy is a non-chiral effect. We have

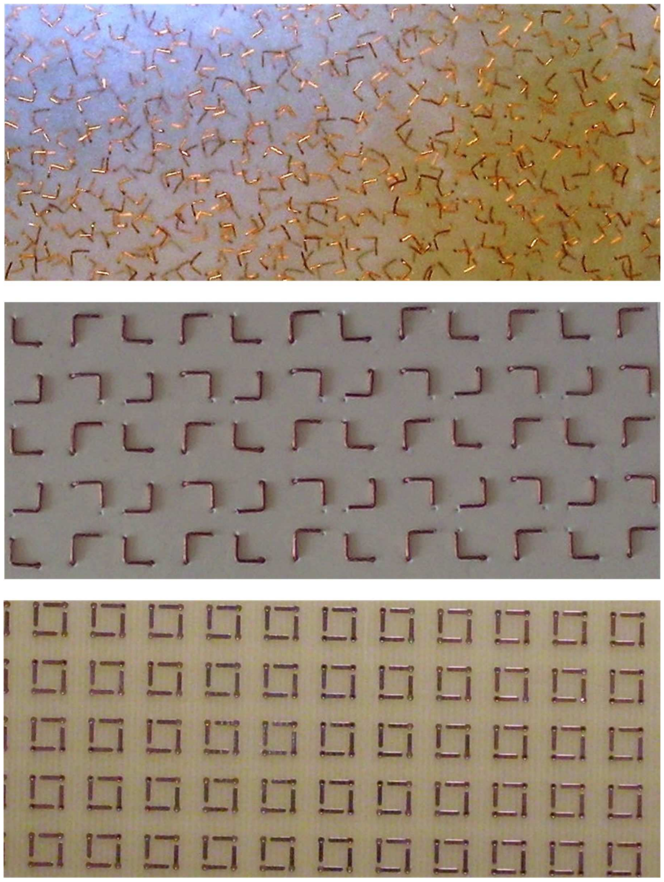

Fig. 1. Detailled image of the samples: a) Random distribution of cranks (RND), b) Cross distribution of cranks forming a 2D periodic structure (CROSS). c) PCB based periodic structure (PCB).

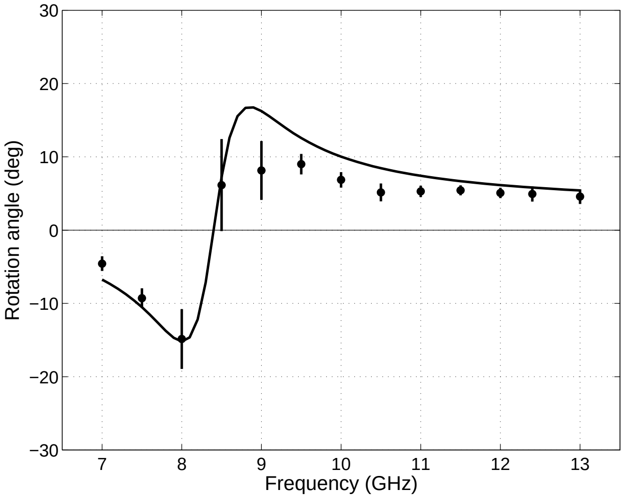

Fig. 2. Rotation angle produced by the sample shown in Fig. 1a. Dots and bars are, respectively, the mean value and standart deviation for 10 measurements of different sample regions. Solid line is calculated by fitting a Condon model to the experimental data. Reproduced from *IEEE-MCWL 19*, 278-280, 2009 [2].

also verified the sample is not reciprocal. Therefore the rotation due to chirality, if any, is hidden by other electromagnetic effects.

However, it is possible to cancel the non-chiral effects by an adequate distribution of cranks and to build chiral media with homogeneous, isotropic and reciprocal behavior at microwave range for normal incidence. Fig. 4 show the rotation angle produced by CROSS sample (dots) and the experimental uncertainty on the angle determination (vertical bars). We have verified that the rotation angle does not depends on the orientation of the sample. It seems that the cross distribution of cranks cancells the non-chiral effects.

The dependence with frequency of the rotation angle is similar to the one obtained by using a random distribution of cranks, Fig. 2. It also follows a Condon model with one resonance frequency at around 10 GHz. We also observe the same dependence for waves incident both from the front side and from the back side, i.e. the media is also reciprocal. We have also experimentally confirmed the fact that a sample formed by elements with different handedness produce a change in the sign of the rotation angle, with the same resonance frequency.

Finally, the typical chiral behavior can be also produced by PCB based materials. Fig. 5 shows the rotation angle produced by "PCB", which does not depend on the relative orientation of the incident wave nor on the incident plane. Here the resonance frequency looks to be outside our measurement range, and it couldnot be determined.

IV. CONCLUSIONS

Here the state of the art for developing chiral media based on conductive cranks is reviewed. We present it is possible to produce a rotation in the polarization angle for a linearly polarized wave at microwave frequencies by using different structures of cranks randomly dispersed or periodically localized in a host medium.

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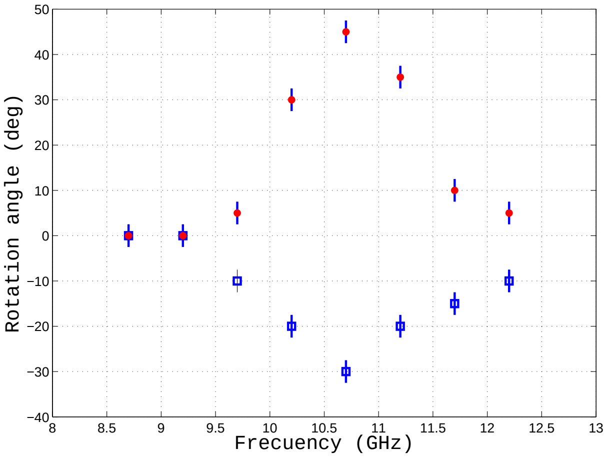

Fig. 3. Girotropy produced by a 2D structure for two different orientations between cranks and incident wave.

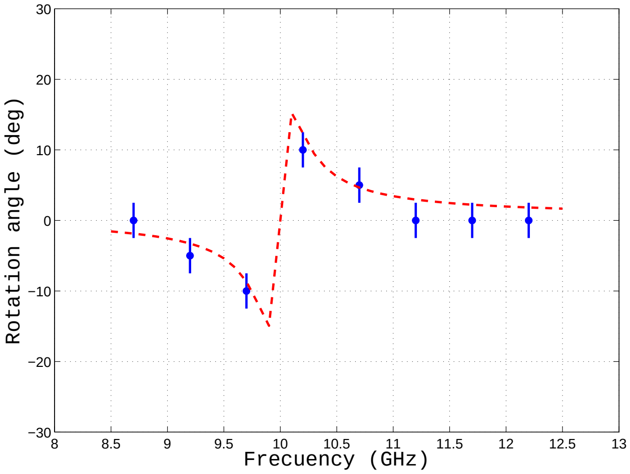

Fig. 4. Rotation angle produced by "CROSS" sample. Dots and bars are, respectively, the experimental value and the experimental uncertainty. Solid line is calculated by fitting a Condon model to the experimental data.

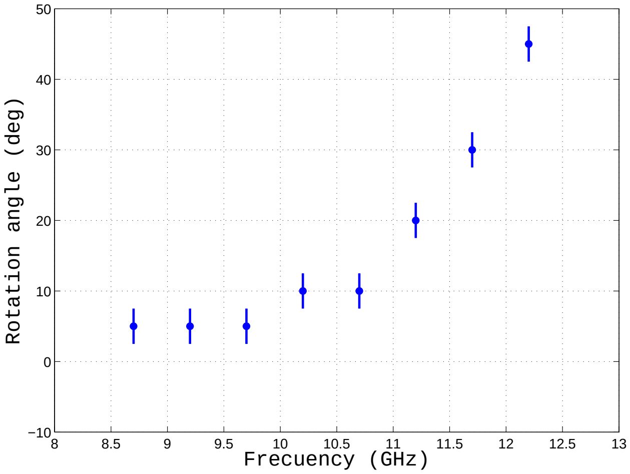

Fig. 5. Rotation angle produced by "PCB" sample.