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Elastomeric composites with tuned electromagnetic characteristics

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Abstract

This paper presents a novel elastomeric composite that exhibits a deformation-induced change in chirality. Previous efforts primarily dealt with a coil array in air without chiral tuning. Here, a composite is created that consists of an array of parallel, metallic helices of the same handedness embedded in a polymer matrix. The chiral response of the composite depends on pitch, coil diameter, wire thickness and coil spacing; however, pitch has the greatest effect on electromagnetic performance. The present study explores this effect by using helical elements to construct a chiral medium that can be mechanically stretched to adjust pitch. This adjustment directly affects the overall chirality of the composite. A prototype sample of the composite, fabricated for operation between 5.5–12.5 GHz, demonstrates repeatable elastic deformation. Using a transmit/receive measurement setup, the composite scattering response is measured over the frequency interval. The results indicate substantial tuning of chirality through deformation. An increase in axial strain of up to 30% yields a $\sim$18% change in axial chirality.

(Some figures may appear in colour only in the online journal)

1. Introduction

Pioneering work on chirality at microwave frequencies was performed by Lindman in the early 1920s when he embedded helices of the same handedness in foam and observed the rotation of the plane of polarization [1]. Ever since, different elements exhibiting chiral characteristics have been proposed [2–4]. This paper investigates chiral, uniaxial, bianisotropic elastomeric composites with mechanically tunable electromagnetic properties whose mechanical attributes have been maintained. Elastomeric composites with robust mechanically tunable EM properties may have application in skins or the flexible multifunctional elements in tensegrity structures.

Mechanically tunable composites have been investigated over the years for a variety of applications. Chiang *et al* [5] applied external stresses to a 2D array of gold nano-particles embedded into polydimethylsiloxane (PDMS) to increase the distance between the particles. In this study, mechanical stress increased the surface plasmon frequency. Schmidt *et al* [6] used an external stimulus to control the stiffness of an electrochemically responsive polymer nano-composite thin film. Blaszkiewicz *et al* [7] applied uniaxial compression to a silicone rubber and piezoelectric ceramic electro-acoustic transducer, which tuned its resonant frequency. Truxal *et al* [8] mechanically strained a PDMS grating in a MEMS device for photo-spectroscopic measurements, varying the wavelength of diffracted light. Tunability can extend to non-EM property control. Kennedy *et al* [9] increased cellular fiber alignment and tuned porosity in a polyurethane scaffold for cardiac tissue by elongating the scaffold after fabrication.

The overall EM properties of composite materials have also sparked the interest of researchers over the years. Of particular interest are materials with plasmon frequencies in the microwave range [10–13]. Pendry *et al* [10] demonstrated that achieving a relatively low plasmon frequency is possible using an array of thin metallic wires. In the microwave range, however, Smith *et al* [11] noted the infeasibility of such an array and instead suggested using loop–wire elements. The loops achieve similar results with thicker wire and smaller unit cells, making the fabrication of such a material more viable.

A practical alternative to the loop–wire is the coiled wire helix [14]. Tuning the plasmon frequency is accomplished by changing the dimensions of the building blocks [12, 13]. The EM performance of an array of coils depends on the coil inner diameter, coil spacing, wire thickness, and pitch. Through a series of EM simulations, Nemat-Nasser *et al* [13] determined pitch to have the greatest effect on performance. Schuil *et al* [14] experimentally examined the effect of pitch on plasmon frequency with an array of coils in air. A 30% increase in pitch corresponded to an increase in plasmon frequency from 6.3 to 7.5 GHz, thus demonstrating the effectiveness of such an array.

The present work seeks to develop a material with a deformation-induced change in chirality. To create such a composite, the metallic helices must be embedded in a matrix capable of supporting the large elastic deformation and shear stresses required to extend the coils and vary the pitch. Ceramics are brittle by nature and metals would reflect incident waves. In this case, the most logical choice is an elastomer, such as low durometer polyurethane. Furthermore, the elastomeric material protects the fragile coils against damage and permanent deformation due to unwanted contact and out-of-plane loads. Polyurethane elastomer has been used in a variety of applications, including biomedical research [15], and the creation of nano-composites [16]. This broad span of utility is largely due to its material properties. A polyurethane chain forms when a polyisocyanate reacts with a polyol. Polyurethanes exhibit high tear resistance, high toughness, and high elongation before break [17], as well as high elasticity and adhesion [18]. These properties make polyurethane an ideal material for use in a mechanically adjustable composite.

Using numerical and experimental tools, we aim to create an electromagnetically transparent polymer–helix composite with enhanced and tunable chirality, operating between 5.5 and 12.5 GHz frequencies. Electromagnetic simulations are used to identify important design parameters for the elastomeric helix composite. A prototype sample of the helix composite is fabricated and characterized. To evaluate the tuning performance, the sample is stretched up to 30% and the chirality is measured as a function of helix length using the procedure described in Bayatpur *et al* [19].

2. Electromagnetic simulations

Chirality quantifies the level of coupling between the components of an EM wave while traveling through a material [1]. A chiral material, in general, is represented by four constitutive parameters in tensorial form [20]:

$$\bar{D} = \bar{\bar{\epsilon}}\bar{E} + \bar{\bar{\xi}} \tag{1}$$

$$\bar{B} = \bar{\bar{\mu}}\bar{H} + \bar{\bar{\zeta}}\bar{E}, \tag{2}$$

where permittivity $\bar{\bar{\epsilon}}$, electric polarization $\bar{\bar{\xi}}$, permeability $\bar{\bar{\mu}}$ and magnetic polarization $\bar{\bar{\zeta}}$ are 3×3 complex-valued matrices. A chiral medium couples the electric and magnetic components of the wave, thus rotating the wave polarization. As a result, the strength of chirality depends on the amount of polarization rotation (cross-polarized transmission response): the higher the cross-polarized transmission, the larger the chirality.

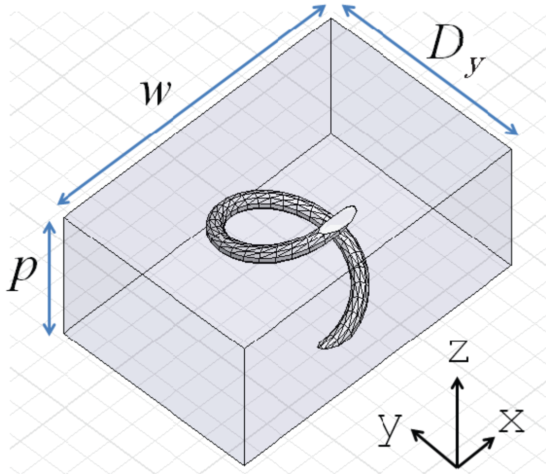

Figure 1. The polymer–helix composite unit cell consisting of one turn of one helix embedded in polyurethane. The array is periodic along $\hat{y}$ and $\hat{z}$.

Table 1. Helix composite design parameters: Nominal values (mm).

D_y	p	d	t	w
4	2.7	2	0.29	6

The dielectric properties of the polyurethane are considered in designing the helices to achieve the desired EM frequency behavior. This is done through a full-wave simulation using Ansoft HFSS finite element solver. The simulation considers the polymer–helix as a periodic array of parallel, infinitely long helices embedded in a polyurethane matrix. The helix handedness remains constant throughout the array. Given its periodic structure, this composite can be simulated using the periodic boundary condition setup in HFSS. The model unit cell is shown in figure 1. This unit cell represents an array of helices that are periodic along $\hat{y}$, and their axes are parallel with $\hat{z}$.

A sensitivity analysis on the helices' pitch, diameter, spacing and wire thickness was performed as a guide for fabrication. Through full-wave simulation, this analysis seeks enhanced cross-polarized transmission through the composite over the band of operation while keeping the total transmissivity high. In these simulations, the incident wave propagates in the $\hat{x}$ direction and is linearly polarized parallel to a single layer of composite with periodicity in the $\hat{y}$ and $\hat{z}$ directions. The nominal values for the unit cell dimensions, adopted from an earlier work [14], are provided in table 1. In this table, D_y is the spacing of the helices in the array, p is the helix pitch size, d is the helix inner diameter, t is the wire thickness, and w is the overall composite thickness.

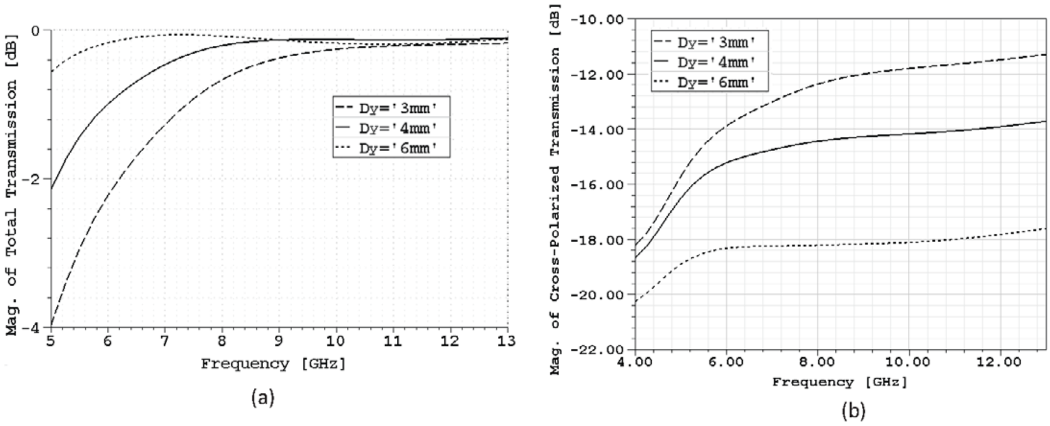

Figure 2. Reducing the spacing between the coils, D_y, reduces the total transmission at the lower end of the frequency range (a) while increasing cross-polarization transmission at all frequencies (b). The incident wave is polarized parallel to the helix.

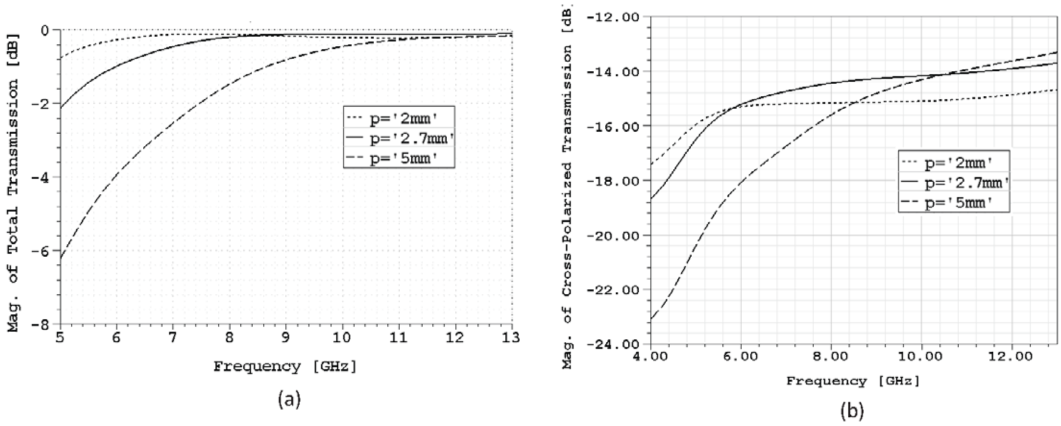

Figure 3. An increase in pitch, p, reduces the total transmission at the lower end of the frequency range (a) while causing an increase in the cross-polarization transmission at higher frequencies (b). The incident wave is polarized parallel to the helix.

Figure 2 shows the effect of spacing D_y on the transmission response. Increasing the spacing increases the total transmission, while the chirality decreases as the cross-polarization level goes down. This shows that the two desired EM properties are inversely correlated based on spacing. Thus a mid-range choice of spacing would be ideal. Pitch is expected to have a major influence on the chirality, which will be larger for a smaller pitch size. This analysis shows that decreasing pitch indeed increases the cross-polarization level, but only up to a limit. This limit, shown in figure 3, decreases by changing the pitch from 2.7 to 2 mm. A smaller pitch yields greater transmission. This full-wave analysis also includes other helix parameters; increasing the diameter enhances the total transmission, as shown in figure 4. The choice of the diameter, however, is dependent on the spacing. Wire thickness has a lesser effect on transmission and chirality.

The analysis shows that spacing and pitch have a more pronounced effect on the EM properties than wire and composite thicknesses. The final design values, however, are chosen after testing the mechanical performance of the design discussed in the next section.

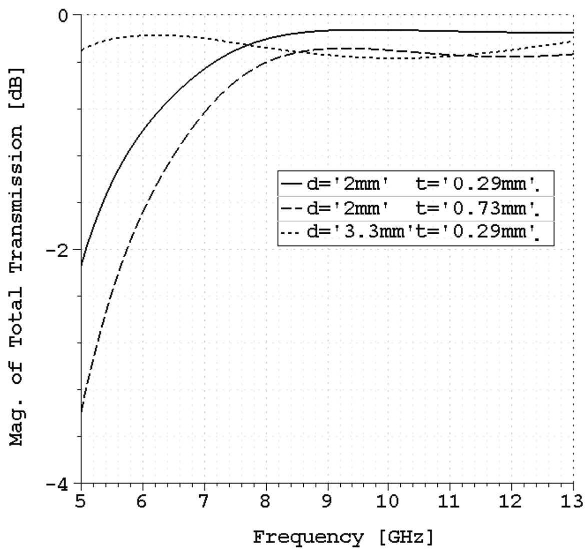

Figure 4. A larger helix inner diameter, d, increases the total transmission at lower frequencies while reducing it at higher frequencies. An increase in t reduces the total transmission. The incident wave is polarized parallel to the helix.

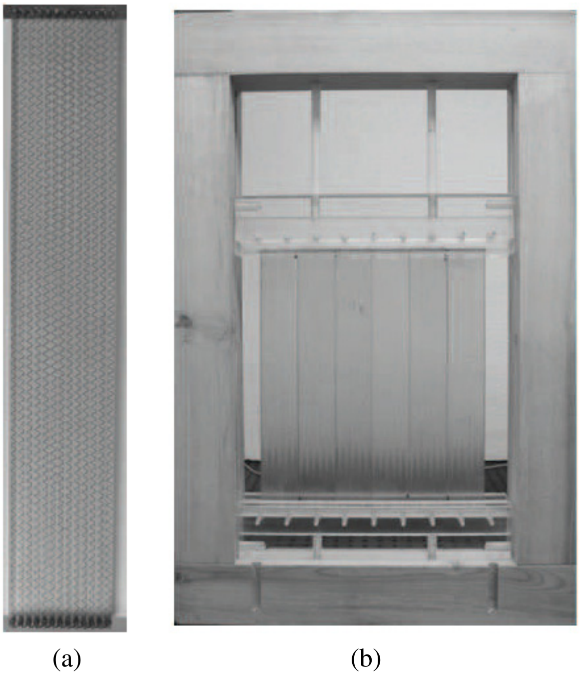

Figure 5. Sample used in the mechanical and EM tests. (a) One unit consists of 13 coils. (b) 6 units in the test frame for a total area of 310 mm × 310 mm.

Table 2. Helix composite design parameters: Finalized values (mm).

D_y	p	d	t	w	L
4	4	2.4	0.29	6	310

3. Fabrication

3.1. Sample preparation

Each coil was wound using the parameters in table 2 with a length, L, along the z-axis. These values were chosen based on the results of the EM simulations.

Polyurethane was used as the host medium for the helices. Smooth-On Inc. VytaFlex 20, a polyurethane elastomer of durometer 20 A, was prepared from two components which have been separately stirred and degassed for one hour. The components were combined and hand mixed for three minutes and mixed under vacuum for another five minutes.

The coils were embedded in the polyurethane. A thin layer of polyurethane was first injected into the Teflon mold with a syringe. Next the coils were linearly positioned and held by wooden dowel pins. The remaining polyurethane was then added. This ensured the coils were near the center of the polymer thickness. Prior to curing, the samples were degassed for 15–20 min to eliminate air pockets and to improve the adhesion between the springs and the polymer. The samples were then cured overnight in an environmental chamber with the relative humidity maintained at 10%. The next day, the samples were post-cured in a 65 °C oven for 4 h. Figure 5(a) shows a completed unit cell: one layer of 13 helices.

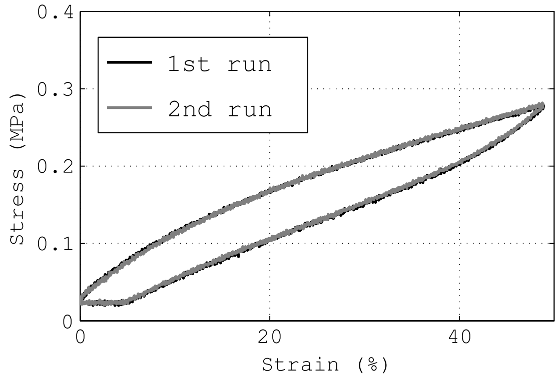

Figure 6. Axial stress–strain curve showing repeatability for one, 13-coil unit.

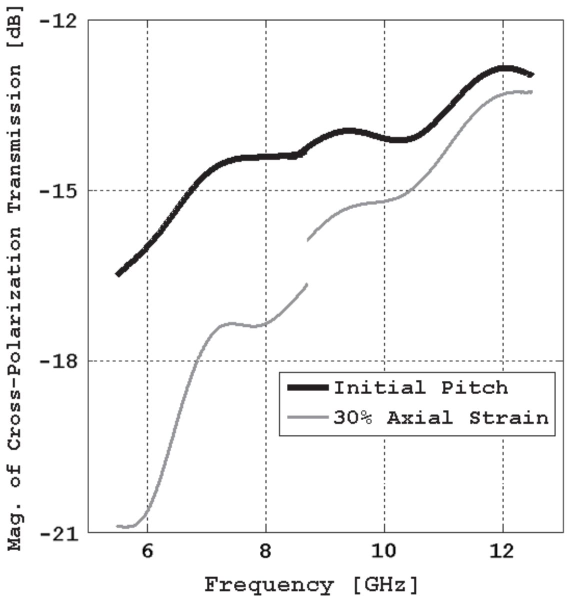

Figure 7. Cross-polarization transmission for initial and stretched composite tests. Note: discontinuity at 8 GHz due to two separate test setups.

3.2. Mechanical repeatability

After performing several tension tests, we determined that coils made with thin wire would allow for elastic deformation more reliably than thicker wire coils. The thick wire springs exert greater force on the polyurethane matrix prior to axial break due to its higher stiffness. This force translates to high shear stress at the interface between the wire and the matrix. As a result, delamination occurs much earlier than with the thin wire coils.

To demonstrate the repeatability of the composite, one sample was tested several times. The results of two tests, shown in figure 6, demonstrate that the sample recovers its initial configuration even after being deformed near the elastic limit of 50% axial strain, thus enabling mechanical tuning of the structure and its EM behavior.

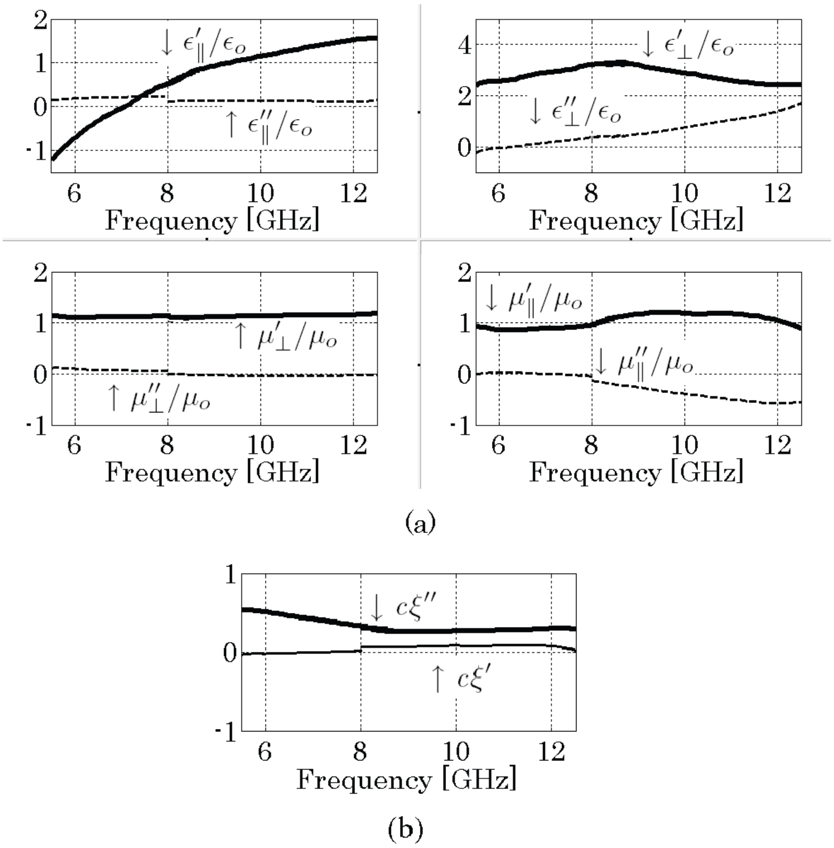

Figure 8. The constitutive parameters of the polymer–helix composite at zero strain. (a) Axial and transverse permittivity ($\epsilon_{\|} = \epsilon'_{\|} - j\epsilon''_{\|}$, $\epsilon_{\perp} = \epsilon'_{\perp} - j\epsilon''_{\perp}$) and permeability ($\mu_{\|} = \mu'_{\|} - j\mu''_{\|}$, $\mu_{\perp} = \mu'_{\perp} - j\mu''_{\perp}$). (b) The axial chirality ($\xi = \xi' - j\xi''$), which is normalized to the speed of light in air, *c*.

4. Chiral helix–polymer composite: measured performance

Through a standard transmit/receive (TR) measurement setup, the EM properties of the finalized sample were measured. This setup includes two horn antennas connected to an Agilent 8510C vector network analyzer. The antennas use microwave lenses located at their apertures to keep the radiating energy focused on the sample. The sample's overall dimensions must be large enough to enclose the beam emanating from the antennas. With the sample placed equidistant between them at their focal point, the antennas collect the scattering parameters of the sample under test. Given the lens–antenna specifications, the beam area may be calculated quantitatively. For our TR setup this minimum area is nearly 1000 cm about 30 cm from the antenna. The size of the assembled sample is big enough to cover this area; it consists of 6 units, each having 13 helices, covering a square area of 310 × 310 mm (see figure 5(b)).

The magnitude of the cross-polarization transmission is given in figure 7 for the unstretched setup and at 30% axial strain. Two separate antenna configurations (5.5–8.7 GHz, 8.7–12.5 GHz) were used to collect data. The discontinuity between the two ranges is small given this change in test setup and represents the reliability and repeatability of our experimental protocol. The experimental results (figure 7) must be compared with the results of the simulation (figure 2(b)). They both represent the significant changes in chirality due to change in axial strain or pitch, shown in terms of raw cross-polarization transmission.

Given its scattering response, the uniaxially chiral slab material presented here is fully characterized for its constitutive parameters. These parameters are carefully retrieved using a process provided in an earlier work [19]. The extracted results for the sample at rest (without any strain) are shown in figures 8(a) and (b), demonstrating an appreciable normalized chirality factor, $c\xi''$. The retrieved permeability for both directions, parallel and perpendicular to the helices ($\mu'_{\|}$, $\mu'_{\perp}$), is ∼1 (lower graphs in figure 8(a)). The permittivity, however, well reflects the uniaxial behavior of the composite; the perpendicular permittivity ($\epsilon'_{\perp}$) is ∼3 on average in the band, while the axial response ($\epsilon'_{\|}$) shows a turn-on frequency of ∼7.1 GHz (see the top-left graph in figure 8(a)).

In another test, the sample was axially stretched, and the EM measurement was performed for this length of the sample. The chirality variation over frequency generated as a result of the induced strain is provided in figure 9. Up to ∼18% tuning is achieved experimentally by a 30% increase in length and, thus, pitch. Based on previous work with achiral samples [14], it is expected that the constitutive parameters continuously change with pitch, within the range established here. The

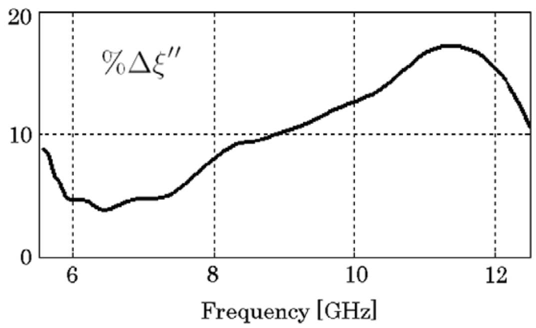

Figure 9. Percentage decrease in chirality (ξ'') due to 30% axial strain as compared to the unstretched results shown in figure 8.

measured results well demonstrate the tuning capability of the polymer–helix composite.

5. Conclusions

A polymer–helix composite with mechanically adjustable chirality was presented. The initial geometry of the sample was selected using an EM sensitivity analysis. Samples were fabricated and mechanically tested to confirm a consistent recoverable strain limit of ~50%. EM tests performed on a larger sample confirm the qualitative results of the simulations. The chiral behavior can be tuned by about 18% through axial strain and frequency variation. This study suggests a method of creating mechanically tunable polymer–helix chiral composite filters for use at microwave frequencies.

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