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Fabrication Effects on the Resonance Bandwidth of Chiral Materials

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Abstract

A comparison between measured and simulated characteristics of helix loaded media reveals a good agreement for the resonance frequency but significant differences with respect to the resonance bandwidth. This phenomenon is related to the geometrical variations of the commercially available helices due to tolerances. This is confirmed by two models developed to describe these effects.

1. Introduction

A good prediction of the effective constitutive parameters of artificial chiral materials is of basic importance for the development of applications. Because of the great number of inclusions involved this is, in principle, quite a demanding task. The tools developed so far model a large quantity of helices and/or use appropriate averaging procedures [1, 2]. In these studies, however, helices of a given type are always assumed to be identical. As could be observed in various experiments this allows to predict the resonance frequency but leads to significant discrepancies between the simulated and the measured resonant bandwidth. In the following, the causes of this phenomenon will be discussed and modeled.

2. Measurements and Simulations

The chiral material used in this study consists of commercially available 5-turn metal helices embedded in PU-foam spheres. It was fabricated by means of the foam injection procedure presented in [3]. The helices have a nominal radius $r = 0.92$ mm and pitch $p = 0.37$ mm.

The three complex effective constitutive parameters ε_r, μ_r and κ (according to the Lindell-Sihvola notation [4]) were extracted using the circular waveguide setup described in [5]. With three waveguides of different diameter it was possible to cover the frequency range from 2.75 to 5.70 GHz that includes the chiral resonance at 4.2 GHz. As an example Fig. 1 displays the measured complex permittivity ε_r.

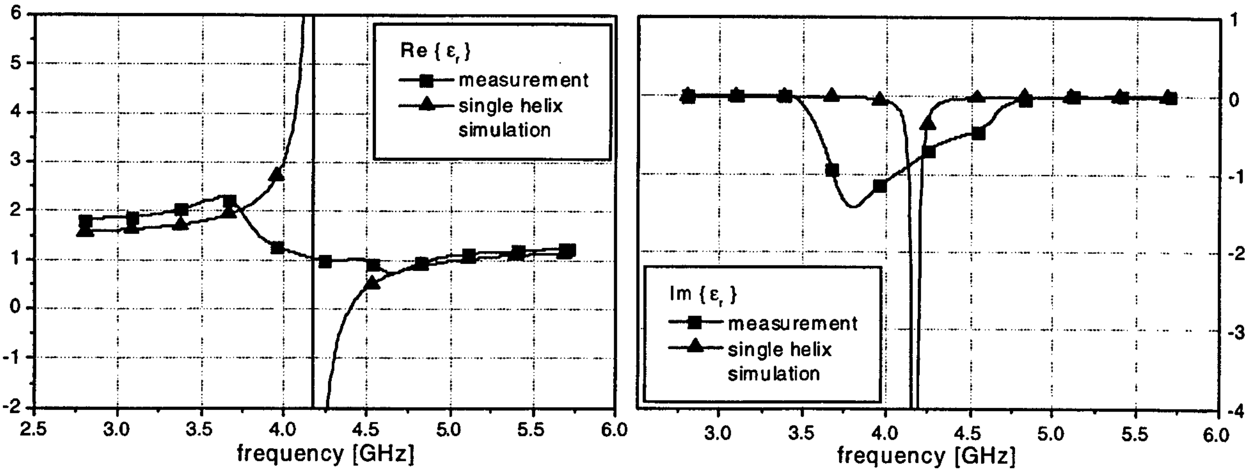

Fig. 1 Measured and simulated permittivity of the chiral material. The simulation assumes identical helices.

In addition, the average polarizabilities of a helix with nominal dimensions were calculated [2]. The constitutive parameters were computed using Maxwell-Garnett mixing rules [4]. As in the experiment the volume fraction of the chiral inclusions was set to 0.45. As can be seen from Fig. 1 predicted and measured resonance frequencies are in good agreement while the resonance width and the magnitude differ significantly.

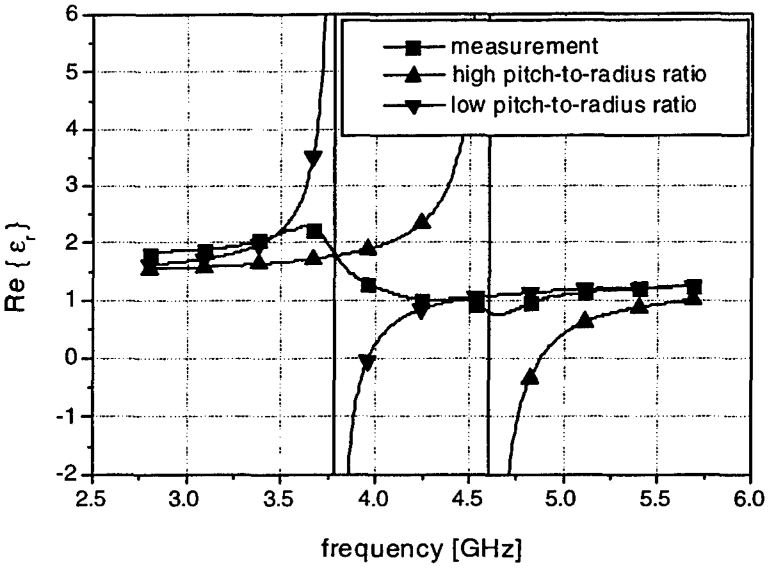

Fig. 2 Measured resonance bandwidth of a chiral material and resonance shift of a single helix due to geometrical tolerances

This phenomenon is possibly caused by the tolerances of the helix dimensions: According to the manufacturer's data sheet the tolerances of helix radius and pitch are approximately ±2.5% and ±10%, respectively. To check this assumption, the material parameters were calculated for different radius and pitch values within these limits. The computed resonance frequencies cover the measured resonance bandwidth. The highest (lowest) resonance frequency corresponds to the largest (smallest) pitch-to-radius ratio (Fig. 2).

To substantiate the above hypothesis further investigations were necessary. A direct experimental check of the material simulation would call for a medium made of identical helices. As this is not available single helices were investigated, instead. To this end individual helices were placed in both a coaxial and a circular waveguide and fixed in a Rohacell™ plug. From the measured scattering parameters S_{11} and S_{21} the quantity $\alpha=|S_{11}|^2+|S_{21}|^2$ was calculated. This is a measure of the energy dissipated in the chiral object. It provides information on the resonance frequency and the resonance bandwidth.

A single helix is only a small disturbance; therefore the measured reflection is generally small while the transmission is close to unity. Further, the scattering parameters are highly sensitive to the helix orientation. Still, the achievable measurement accuracy is satisfactory. For a further discussion, see [6]. Fig. 3 shows, as a representative example, α for a single helix. For comparison, the response obtained with a representative sample of bulk chiral material in the same waveguide is also included. For the latter the absorption bandwidth and the resonance bandwidth of the material parameters (Fig. 1) are in close agreement. The absorption bandwidth of the single helix fits the resonance bandwidth predicted for a material made of geometrically identical helices (Fig. 1). Measurements on different helices show that all resonance frequencies lie within the absorption bandwidth of the bulk material.

The above findings support the hypothesis concerning the tolerances. Still, a model is needed that allows to predict the resonance behavior of the bulk material. This is the scope of the following section which deals with the calculation of the effective constitutive parameters.

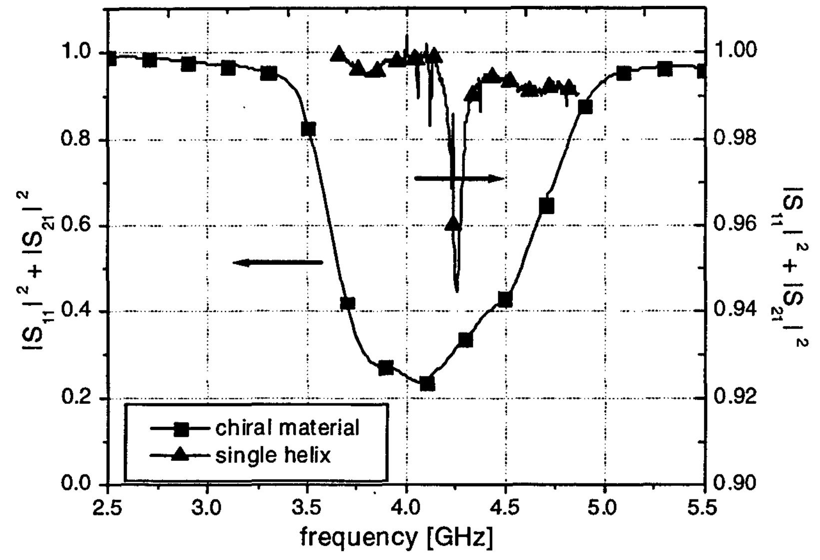

Fig. 3 Coaxial measurements: resonance bandwidth of a single helix and the chiral material

3. Modeling the Effective Chiral Material

As was shown in the previous section a chiral material is a mixture of helices with slightly differing geometry which leads to a noticeable shift of their resonance frequencies. The effective constitutive parameters follow from a superposition of the individual helix properties. Two approaches were developed to predict the material parameters. In the first one, a discrete set of helices with radius and pitch being equally distributed within the tolerance range was assumed. The average polarizabilities of each helix type were computed next. Finally, multi-phase mixing rules were applied to obtain the constitutive parameters [4]. The second method calculates the average polarizabilities for the helix of nominal dimensions, only. The results are then shifted along the frequency axis within the required resonance bandwidth. The latter can be determined either by measurements (provided the chiral material has already been realized) or by two additional calculations using the helices with smallest and largest pitch-to-radius ratio (see above). As long as the broadening of the resonance frequency is not too large both approaches yield almost identical results. Because the second method is much faster and easier to implement it was preferred in the following.

Fig. 4 shows the computed and measured permittivity of the chiral material mentioned above. The resonance frequencies were assumed to be equally distributed. It can be seen that the model predicts well the measured response. The good fit of the resonance bandwidth is of course inherent to the model. But it is interesting to note how well the model renders the dispersion characteristic of the permittivity. Also the quantitative agreement is satisfactory. This holds for all other constitutive parameters as well. Still, some differences can be observed. For instance, the peak modeled at the low frequency end is not confirmed by the measurements. It may be due to several effects. First, the assumption that the resonances are equally distributed is probably unrealistic. A Gaussian distribution together with a finer discretization is likely to give a better fit, here. Second, the electromagnetic model of the chiral inclusion is based on (the usual) simplifications. Third, the mixing formulas are only approximate. And finally, also errors of the measurement procedure have to be taken into account. Indeed, because at resonance the material is quite lossy, only thin slabs could be characterized in the waveguide setup. As, then, the number of helices was too small to yield statistically meaningful results the material was virtually homogenized and randomized by averaging

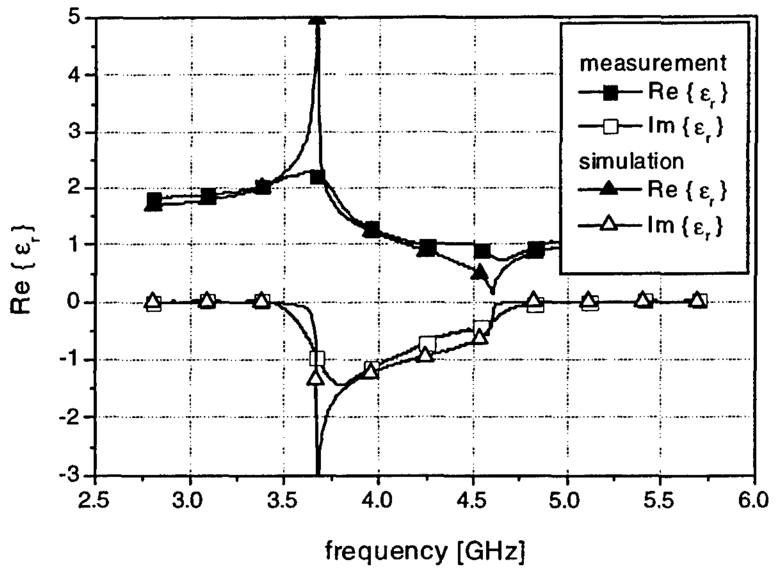

Fig. 4 Measured and simulated effective complex permittivity

the measured responses of several samples with different chiral inclusions, as was suggested in [5].

4. Conclusion

In this contribution fabrication effects on the resonance bandwidth of chiral materials were investigated. The calculated constitutive parameters of a chiral material consisting of helices with nominal pitch and radius were compared to the data extracted from circular waveguide measurements. It was observed that although the resonance frequency can be well predicted significant differences occur regarding the resonance bandwidth. It was shown that this discrepancy is related to tolerance effects of the pitch and the radius of the helices. Two models were developed that allow to accurately predict the constitutive parameters of a realistic chiral material.

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