Mechanically-Tunable Composite Filter at Low Frequencies

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ABSTRACT

Previous studies into the possibility of a plasmonic medium of a coiled conductor array in air have shown promise. This work serves to evaluate the possibility of creating a mechanically-tunable composite filter at low frequencies. Copper springs were created with varying starting pitches using a coil winder. These springs were then embedded into a flexible host polymer. The mechanical and electromagnetic properties of each spring design were predicted and tested. Two horn antennas were used to characterize the overall electromagnetic (EM) properties of the composite. The pitch of each spring was increased mechanically through application of force to the entire polymer-metal composite at equal intervals, with an EM test completed at each step. Using an Agilent 8510C Vector Network Analyzer (VNA), the frequency spectrum within the microwave range was scanned. Relative amplitude and phase measurements were taken at equal frequency and pitch steps. With no polymer surrounding the springs, plasmon turn-on frequencies were observed to span the microwave bands as the pitch of the springs were increased. Similar results are expected with the springs embedded in a polymeric matrix. These results suggest a method of creating a mechanically-tunable composite filter for use at low frequencies.

Keywords: electromagnetic waves, plasmon turn-on frequency, mechanically-tunable filter

1. INTRODUCTION

The overall electromagnetic properties of composite materials have sparked the interest of researchers over the years. Of particular interest are materials with plasmon, or turn-on, frequencies in the microwave range, as they can be used as electromagnetic filters. Above the plasmon frequency, electromagnetic waves are transmitted through the material. Below the plasmon frequency, the waves are mostly reflected. Typically, this frequency is in the ultraviolet range for bulk metals[1].

In 1996, Pendry et al.[1] demonstrated that achieving low turn-on frequencies is possible with an array of thin metallic wires. In the microwave range, however, Smith et al.[2] found the required ratio of wire spacing to wire radius yielded the structure physically infeasible and instead suggested using wire loops. The loops achieve similar results with larger wire and smaller unit cells, making the fabrication of such a material more viable.

Varying the plasmon frequency can be accomplished by varying the overall dielectric constant. The pitch between loops, the inner diameter of the loop, the diameter of the wire, and the size of the unit cell affect the overall dielectric constant[3]. The ability to mechanically tune the plasmon frequency allows for greater flexibility in the material properties. Instead of achieving a different turn-on frequency by creating a new material with different parameters, one material can be made and tuned as necessary.

Previous efforts in this area have determined that such a material can be made with an array of wire coils in air[4]. This study seeks to further this idea by embedding the coils in solid elastomeric polyurethane. Based on coil unit cell height and width, coil inner diameter and wire thickness, the turn-on frequency was estimated to be around 6.47 GHz based on numerical calculations[3,5]. Sample sizes and fabrication techniques will be discussed in addition to the details of mechanical and electromagnetic experiments.
2. MATERIALS

2.1 Sample Preparation

VytaFlex 20, polyurethane elastomer of durometer 20A, was obtained from Smooth-On, Inc in two parts. Each part was mixed separately and degassed for one hour. The two were then mixed together under vacuum for three minutes, and injected into a mold with a syringe. Using a coil winder, copper coils were created with an inner diameter of 4 mm. These coils were embedded in the polyurethane between stainless steel dowel pins with a composite unit cell 6 mm wide, 6 mm thick, and 150 mm long. Prior to curing, the samples were degassed 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%. Upon curing, the samples were post-cured in a 65°C oven for 4 hours.

2.2 Sample Dimensions

Tension test sample configurations consisted of 1 unit cell and 8 unit cells arranged in a single layer, with widths measuring 6 mm and 48 mm, respectively. Pure polyurethane samples without springs were created for comparison. For the electromagnetic tests, 24 unit cells were used in the sample also arranged in a single layer, for a total width of 144 mm. A single unit cell is shown in Figure 1 along with a diagram of test sample geometries.

![Sample geometry diagram](image-url)

Figure 1: Sample geometry, \(n = 1, 8, 24\)

3. EXPERIMENTS

3.1 Mechanical Testing

Preliminary tension tests were conducted on unit cell samples to determine the composite strength of each component. These tests were performed using an Instron load frame with a 1 kN Interface model 1500ASK-200 load cell. The samples were installed such that the grips pulled on the dowel pins at a rate of 76.2 mm/min. Figure 2 shows the test setup. Some samples were tested to failure in order to obtain the complete stress-strain behavior of the composite. The remaining tests were stopped at different times to determine the elastic limit of the composite. Larger samples measuring 8 unit cells wide were then tested under similar conditions to determine the feasibility of elastically stretching the composite material.
3.2 Electromagnetic Testing

3.2.1 Test Setup
The sample for the electromagnetic tests was held in a test fixture consisting of a Plexiglas frame and nylon screws. Threaded nylon rods and nuts were used to adjust the height of the cross-head beam. The frame was secured in place with threaded nylon rods. Each test was performed using an Agilent 8510C Vector Network Analyzer (VNA). Two horn antennas were placed on either side of the sample to measure reflected and transmitted signals, as shown in Figure 3.

![Figure 2: a) Front view of test setup, b) side view showing grip position](image)

3.2.2 Experimental Procedure
The pitch of each spring was mechanically increased at equal intervals. At each step, the frequency spectrum in the microwave range was scanned. Scattering parameters and relative magnitude and phase measurements were taken at each frequency and pitch step to find the overall electromagnetic response.

![Figure 3: Electromagnetic test setup with sample in place](image)
4. RESULTS AND DISCUSSION

The results of the tension tests on single units showed the maximum strain at which the material will still behave elastically is around 50%. This yield point provided the upper limit for the distance the springs can be stretched during the electromagnetic tests. The 8-unit-cell samples also behaved elastically up to 50% strain, indicating the feasibility of mechanically tuning such a composite.

In the case of the springs in air, the turn-on frequency increased with increasing pitch\(^4\). At first, the transmitted power is low, as the composite is highly reflective. At the turn-on frequency, the transmitted power increases as the material becomes transparent. Similar results should occur with the polymer-spring composite. However, the initial sample was too small for the low frequency horn antennas to measure accurately. As the length of the sample increased, the width decreased and created air gaps on both sides of the sample. These gaps provided an unimpeded path for the signals, thus affecting the received signal. Due to these gaps and the dielectric nature of the polyurethane, the turn-on frequency occurred outside the range of the horns. Instead of the predicted 6.47 GHz, the actual plasmon frequency was less than 5.5 GHz. Since the horns are rated between 5.5 and 8.5 GHz, the precise turn-on frequency was not recorded.

Data obtained during the tests indicated that stretching the composite affects the transmitted power signal. As the material is stretched, greater transmission occurs. In order to see the effects of pitch on the plasmon frequency, a larger sample is necessary. Slight inconsistencies during sample creation may account for differences in the electromagnetic behavior of the overall material. In addition, better insulation around the test setup could improve the quality of the signals transmitted and received. Further electromagnetic tests with a larger sample are still ongoing and will be discussed at the conference. Nevertheless, this study suggests a pathway towards creating a mechanically-tunable polymer-spring composite filter for use at microwave frequencies.

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