Metallic Coil-Polymer Braid Composites: II. Material Processing and Characterization

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ABSTRACT

Thin metallic straight wires or thicker wire coils may be incorporated into composite materials to tune their overall electromagnetic (EM) properties, *e.g.,* to render their index of refraction equal to 1, over a range of frequencies. These wire arrays act as scattering elements, providing controlled response to EM radiation such as RF communication signals, radar, or other signals in the infrared range. Integrated into composites, the arrays further contribute to their structural integrity. Braided composites function as ideal hosts for coiled wire arrays due to the helical nature of the braiding process and the periodicity of laminated composites. The coil's pitch and diameter, as primary EM tuning parameters, can be closely controlled in the braiding process to optimize EM properties. Structural fibers are braided with copper wire to form individual elements of the array. Additionally, thermoplastic matrix fibers are commingled into the core and outer portions of the braid to facilitate complete fiber wetting of the composite and ensure structural integrity. These elements are woven, or oriented otherwise, into layers to form arrays with periodic spacing in three dimensions. The composite is then laminated, together with additional thermoplastic matrix material, to yield a fully integrated system with tunable multifunctional properties. Chiral EM properties in the composite, resulting from the helical configuration and periodic arrangement of the wires, can be controlled or completely eliminated by design in the braiding and weaving processes. This paper deals with the processing and characterization of the metallic coil polymer braids and serves as a companion paper to a detailed study of EM properties and chirality effects, entitled "Metallic Coil-Polymer Braid Composites: I. Numerical Modeling and Chirality".

Keywords: Multifunctional materials; braided composites; electromagnetic scattering; chiral media

INTRODUCTION

We seek to integrate other functions into materials that foremost have outstanding structural integrity. Our primary goal is to develop structural composite materials with controlled electromagnetic properties. Those properties include electromagnetic enhancements in the form of a tunable index of refraction and controlled RF absorption, among others. Such properties are the result of integrating periodic metal scattering elements to create an *effective medium* response over desired RF frequency ranges.[1-3] These arrays act as inductive structures with a plasma-like response to control the electric permittivity. As a result, for instance, the index of refraction of the material may be rendered close to or equal to one over a desired frequency range.

In this paper we integrate electromagnetic designs in the form of periodic arrays of conductive coils into composite materials. Such designs are analogous to fiber-reinforced composites having embedded thin, straight wire arrays as reported previously.[4,5] These wires were on the order of 50-100μm in diameter and were processed into host composites by hand-layup. Wires were arranged in a grid pattern of desired spacing and held under tension within layers of pre-impregnated fibers (prepreg) while the polymer matrix was cured at elevated temperature and pressure. The delicate nature of such fine wire posed processing challenges in maintaining the spacing of the array and avoiding breakage of the wire. A special layup jig was designed for this purpose, which along with careful assembly enabled production of numerous panels. However, as an alternative we have tailored the design of the electromagnetic arrays to allow use of thicker, more robust wire, in the form of coils that alleviates processing of delicate wires while it also introduces other functionality into the composite. Additional multifunctional aspects related to this work are detailed in a separate paper entitled "Self-healing Structural Composites with Electromagnetic Functionality", also presented at this conference.

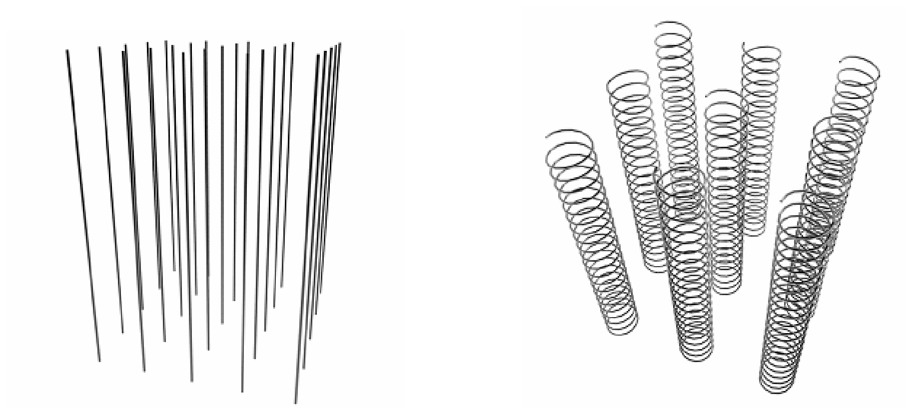


Figure 1. Example artificial plasmon media. [Left] Unidirectional thin wire array. [Right] Unidirectional thick wire coil array. Note opposite sense of adjacent coils.

The present paper serves as a companion paper to "Metallic Coil-Polymer Braid Composites: I. Numerical Modeling and Chirality" which describes the electromagnetic characteristics and associated chirality of coiled periodic scattering arrays. As such, the reader is directed to that paper for a detailed description of the electromagnetic theory and calculations. Rather this paper will cover the processing of such EM arrays into composites and their EM characterization.

INTEGRATION INTO COMPOSITE MATERIALS

To integrate such electromagnetic designs into materials, one needs a periodic material that can accommodate the explicit three-dimensional arrangement of the electromagnetic elements. Fiber-reinforced polymer composites facilitate such arrangements due to the natural periodicity of their laminate construction. The arrangement of fibers within each layer provides flexibility in orientation, spacing, and geometry of the electromagnetic elements. Each layer may contain elements with orientation in only one direction, as in a unidirectional laminate, or the elements may be woven such that each layer has bi-directional elements. Variation of the spacing of these elements in the thickness (z) dimension of the material is controlled by the sequence in which laminae are stacked to form the laminate.

Braiding

Using thicker wire with coil geometry facilitates more robust processing of our electromagnetic designs. Therefore we have identified textile braiding as an ideal method to integrate the conductive wires with the reinforcing fibers of the structural composite. The braiding process interlaces two or more yarns to form a unified structure. Our process uses a two-dimensional tubular braiding machine, as shown in Figure 2, that operates in a maypole action, whereby half of the yarn carriers rotate in a clockwise direction, weaving in and out of the remaining counter-rotating carriers. This action results in a two-under two-over braid pattern. Each yarn makes a helical path around the axis of the braid to create a uniform coil. To integrate the wire coil into such a structure we simply replace one of the fiber carriers with a wire carrier. A comprehensive description of the textile braiding process is given by Ko et al.[6,7]

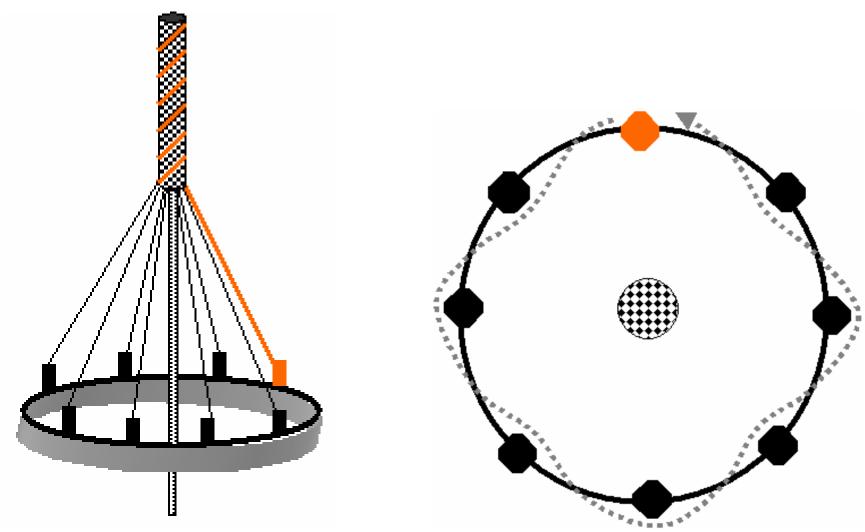


Figure 2. [Left] Schematic of tubular braiding machine. Fibers and wire (indicated in gray) are spooled from carriers that rotate on a circular track. Fibers may be braided around a center mandrel or other fibers in the core of the braid. [Center] Arrow indicates path taken by one yarn carrier in maypole braiding pattern.

Braiding the wire with the reinforcing fibers results in an electromagnetic element with uniform geometry that maintains its shape under considerable handling and other processing conditions. The braid itself is a tough structure that protects elements woven into the outer sheath, as well as other elements in the core. Thus functional elements (wires and/or sensors) are truly integrated into the fibers of the host composite, rather than acting as distinct inclusions in the matrix phase. Furthermore, braiding allows fine control of the pitch and diameter of the wire coil such that the electromagnetic properties may be tuned for desired performance. The sense of the coil, as left-handed or right-handed, may also be varied in this process to address issues of chirality. As detailed in “Part I. Numerical Modeling and Chirality”, we can eliminate chiral effects that come from using coil geometries by creating arrays made up of left-handed coils placed adjacent to right-handed coils. The chiral effects of one coil are effectively negated by those of its neighbor coils. The braiding process allows production of coils of both sense by switching the direction of rotation of the wire carrier in the maypole rotation. Two alternative methods to eliminate chirality require that double coils be created. For instance, a coil of one sense may be positioned in the middle of a coil with opposite sense. Braiding may accommodate this arrangement as well by simply overbraiding a left-handed braid on top of a right-handed braid. Otherwise, by including another wire carrier rotating in the opposite direction, a double coil braid consisting of two coils in the same plane may be created if insulated wire is used, such that when the wires cross they do not cause an electrical short at each intersection.

Composites Processing

As an example, we have braided coil elements with para-aramid (DuPont Kevlar®) reinforcing fiber and polyamide (DuPont nylon 6,6) thermoplastic fiber. The outer braid consists of a single 30 gauge (0.254 mm diameter) copper wire, four ends of 200 denier Kevlar fiber, and three ends of 210 denier nylon fiber. The core of the braid consists of one end of 1000 denier Kevlar fiber and three ends of 420 denier nylon fiber. An illustration is provided in Figure 3 showing the constituents of the braid architecture. Nylon is included in the braiding process since it will serve as the polymer matrix of the final composite. Complete fiber wet-out can be a difficult processing challenge in braided composite materials, due to the inherent tight packing of fibers in the braiding process. We have initially addressed this issue by developing a commingled braid composite, which integrates the eventual matrix phase as a thermoplastic fiber that is braided along with the structural fibers. Overall, the composite is designed to have a Kevlar fiber volume fraction of about 50%. Selection of the diameter of the core allows control of the diameter of the coil that is braided around it. The core may be composed of various other elements, including other electromagnetic elements, or perhaps sensors, though in this initial design we incorporate only reinforcing fibers. The pitch of the braids is determined by the take-up and rotation speed of the carriers. The pitch of these coils was maintained at 60° from the axis of the braid.

The braided elements take the form of a laminate by weaving with other reinforcing fibers to form a cohesive fabric. The braids may be oriented in a single direction in each layer or may be woven together bi-directionally. Due to the inherent stiffness of the dry braid, tight weaving patterns in a bi-directional weave, such as plain weave and satin weave, may be restricted since the braid cannot be woven over small intervals without kinking, which compromises the braid structure. This factor is dependent on the braid and wire diameter, where smaller diameters are not subject to such limitations. This limitation is avoided when braids are woven unidirectionally since the fill yarns (weft direction) are able to accommodate such undulation while allowing the braid elements (warp direction) to remain straight. To achieve the desired spacing of the coil array, while maintaining a uniform composite fabric, dummy braids may be woven into the layer or inserted between layers. The dummy braid is identical to the electromagnetic element braid, however the copper wire is replaced with an end of reinforcing fiber. Additionally, as mentioned above, chiral effects of the coil geometry can be eliminated by alternate placement of a left-handed coil next to a right-handed coil. Such an arrangements can be easily achieved in the braiding and weaving processes. Woven layers are stacked in accord with the electromagnetic design and processed with additional thermoplastic matrix at elevated temperature and pressure to form the consolidated composite.

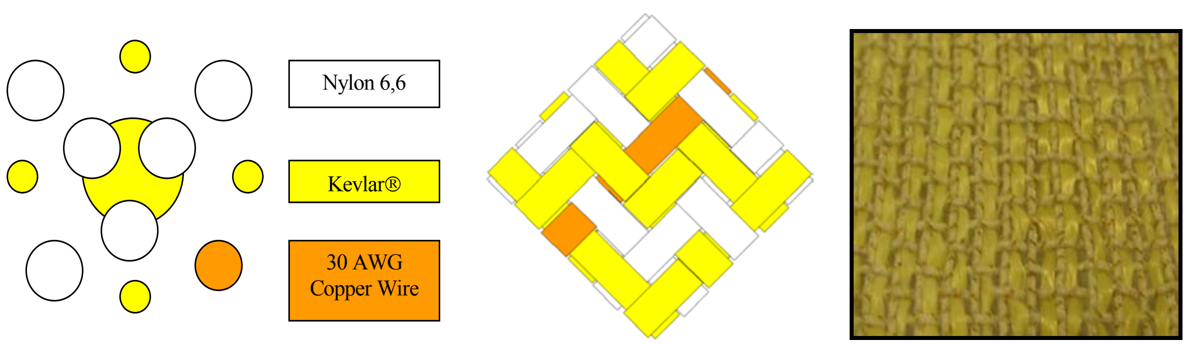
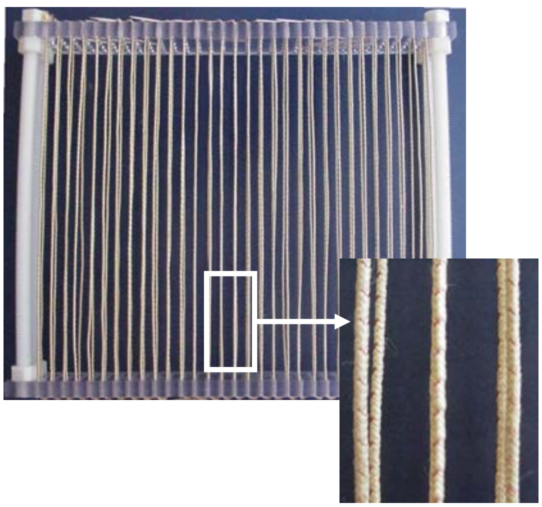


Figure 3. [Left] Schematic of cross-section of tubular braid architecture, consisting of Kevlar, nylon, and copper wire. [Center] Schematic of outer braided architecture with 2 up 2 down braid pattern. [Right] Photograph of braids bi-directionally woven into fabric with additional Kevlar fibers. Coils with opposite sense are woven adjacent to one another.

BRAIDED COIL CHARACTERIZATION

We have tested the implementation of braiding wires and fibers to create coil elements with tunable electromagnetic properties. The braided elements had the following specifications: pitch of 65° to the axis, braid diameter of 0.061", and wire diameter of 0.01". The braided elements were spaced at a distance of 0.39" in two directions. The plasma frequency, or frequency at which the dielectric constant passes through zero, of this sample was predicted at f_p = 6GHz using frequency domain finite element simulations. The geometry of the test arrangement is pictured below in Figure 4.

One may see in Figure 4 that the experimental results showed excellent agreement with our simulations. The dielectric constant of the structure is measured as a function of frequency from 3-12 GHz, whereupon at 6 GHz the dielectric constant passes through zero. This dispersion relation follows the characteristic trend of the thin straight wire arrays studied previously. Between the plasma frequency and the upper limit of our frequency sweep the dielectric constant of the composite array approaches unity. Since the index of refraction of the material is the square of the dielectric constant, we may also conclude that the index approaches unity.



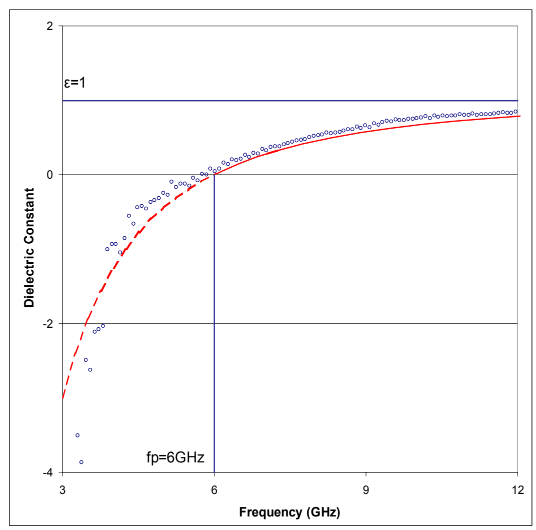


Figure 4. [Left] Test frame containing Kevlar braided with copper wire. Braids are arranged such that adjacent braid elements contain wire coils with opposite sense (inset). [Right] Simulated (dashed line) and experimental (circles) characterization of the braided elements.

SUMMARY

We have presented details on the processing and characterization of structural composites with integrated artificial plasmon media. Arrays of thick wire in coiled geometry were integrated into fiber-reinforced composites by braiding and weaving and subsequently laminated to form a structural composite. We have characterized the electromagnetic response of a freestanding array of such braided elements. Results matched our predictions and were similar to thin straight wire arrays studied previously. Future research in this area will characterize the electromagnetic and mechanical properties of the composite panels, which may show improved toughness and other mechanical attributes due to the novel braided/woven laminate construction.

Acknowledgements

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