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Novel Multi-material Fibers for Wireless Communication Textile Devices

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***Abstract*—Miniaturized, multi-material fibers represent a novel promising approach to integration of higher-level functionalities into textile mediums. In this work, we present novel 'smart textile' fabrics featuring multi-material fiber antennas compatible with existing 2.4GHz wireless communication networks. A sub-millimeter leaky coaxial cable fiber antenna is shown to be fully compatible with a textile weaving process, and exhibits an isotropic radiation pattern in the H-plane and multiple radiation lobes in the E-plane, in accordance with theory and simulations.**

Keywords - wearable antennas, multi-material fibers

I. Introduction

Conventional designs for wearable antennas range from planar metal-insulator-semiconductor configurations to the patterned embroidery of conductive yarn [1], [2]. As advanced technology is being integrated into everyday clothing and wearable garments, the need for unobtrusive, highly integrated, and efficient wearable antennas increases. Multi-material fibers have the potential to address some of these major challenges in developing textiles connected in real time to wireless communications infrastructures. This allows the on-body processing and transmission of data in a mechanically flexible form for applications such as 24 hour monitoring for healthcare or biometric athletic performance assessment [3]–[7].

Most of the current designs for wearable antennas have to be integrated in a post-processing manufacturing step and can be invasive for the user [8], [9]. Inversely, sub-millimeter-size multi-material fibers are inherently compatible with textile manufacturing, and present the same mechanical strength and chemical durability as traditional textile fibers. Furthermore, the fabrication process is suitable for large-scale production and uses low-cost chemical products [10]. Multi-material fibers thus provide an excellent building platform for the next generation of textiles as they can be easily integrated during the weaving process and can be produced in large scale at low costs.

II. Fabrication of RF fiber antennas

In this paper, multi-material fibers were designed to form Leaky Coaxial Cable (LCX) antennas. The fabrication of a fiber-based LCX was achieved through the assembly of chemically-compatible dielectric materials and metallic layers. The geometry was carefully designed to impart the fiber with RF functionality, while preserving sub-millimeter size footprint and flexibility suitable for integration into textiles.

LCXs generally consist of three parts: an inner conductor, a dielectric material, and an outer conductor that exhibits apertures at a prescribed periodic distance d [11]–[14]:

$$\frac{\lambda_0}{n+1} \leq d \leq \frac{\lambda_0}{n-1} \tag{1}$$

Where λ_0 is the free-space wavelength and n the mode propagation index. An effective index of $n = \sqrt{\epsilon_r}$ is expected for the dominant quasi-TEM mode of propagation in LCXs. For textile antenna applications in the 2.4 GHz ISM band, the design consisted of windows equally spaced with a period $d = \lambda_0/n = 63\,\text{mm}$ and an aperture $h = \frac{\lambda_0}{2n} = 31\,\text{mm}$ to maximize wave leakage.

To equate the need for mechanical resistance, chemical durability and known dielectric properties, synthetic fused silica capillaries with polyimide claddings were purchased from Polymicro Technologies. The outer and inner diameters of the capillary fibers were chosen to obtain the necessary flexibility for the weaving process and to facilitate the soldering of both of the ends of the fibers with SMA connectors. A schematic with nominal dimensions is shown in Fig. 1

Inner and outer conductive layers were deposited using a combination of surface activations, liquid-phase silver electroless deposition and copper electroplating techniques. The inner silica surface was activated by circulating a solution of 0.024M tetraethyl orthosilicate (TEOS) and 0.86M methanol, regulated at a pH of 2 using concentrated HCl into the capillary for 30 minutes using a syringe pump. The polyimide cladding was then oxidized by dipping the capillary in a bath of piranha acid composed of H_2SO_4 and H_2O_2 in a 2:1 ratio. These processes are well known and permit stronger bonds to be formed between the dielectric substrate and the plated metal [15].

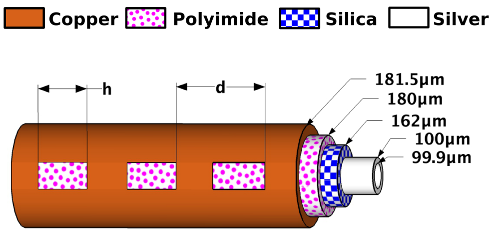

Fig. 1. Schematic showing the windows sizes and radii of the fabricated LCX fiber. Two end-point, SMA-compatible, soldered connexions were exposed for fiber interconnections.

Thin silver layers were plated on the silica and polyimide using a solution prepared with 20 parts of 0.07M $AgNO_3$ solution, 1 part concentrated NH_4OH and 10 parts 0.4M KOH solution, forming the $[Ag(NH_3)^+]$ complex also known as Tollen's reagent [16]. 10 parts of 0.25M dextrose solution was then added as a reducer, making the reduced silver adhere to the dielectric substrate. The inner metallic layer was plated by circulating the plating solution inside the fiber with a syringe pump. The polyimide cladding was then masked with chemically-resistant tape at the prescribed interval d over the prescribed aperture lengths h and dipped in a bath of the solution, forming a windowed external silver layer. Using the outer silver layer as a cathode, a thick layer of copper was deposited using an acidic copper bath composed of 0.56M $CuSO_4{\cdot}5H_2O$ maintained at pH = 3 using concentrated H_2SO_4. Sheet thicknesses were estimated at 150 nm and 20 µm for the inner and outer layers, respectively, using scanning electron microscopy (SEM) images shown in Fig. 2.

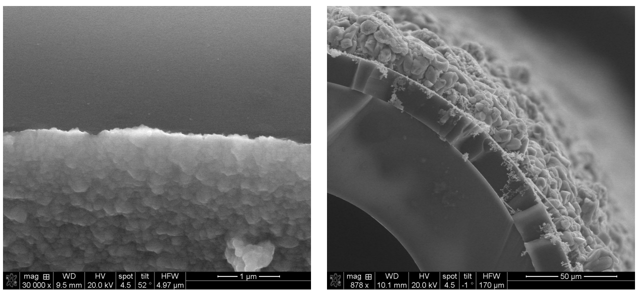

Fig. 2. SEM images of the inner silver layer (top) and of the outer copper layer (bottom)

III. Fiber-based RF Antenna

Two-conductor transmission lines have a dominant quasi-TEM mode of propagation. With a cutoff frequency at DC, antennas such as LCXs based on two-conductor transmission lines impose no size restriction on its operating frequencies, thus offering a competitive edge for miniaturization of RF functionalities. The quasi-TEM assumption is generally valid for structures made with low-loss dielectrics and near-perfect conductors [17], [18]. We note that the latter condition is not strictly enforced by our thin-film conductors. Finite element calculations were carried out to verify that a quasi-TEM mode structure would propagate despite the small silver thickness using COMSOL Multiphysics software. Effective mode indices of $n = 1.94 - 0.17i$ and $n = 1.90 - 0.16i$ were found for the window-less and the windowed portions of the LCX, respectively. The electric field structure and intensities shown in Fig. 3 displaying quasi-TEM mode attributes and the indices nearing the expected value of $n = 1.94$ are strong indicators of quasi-TEM mode propagation.

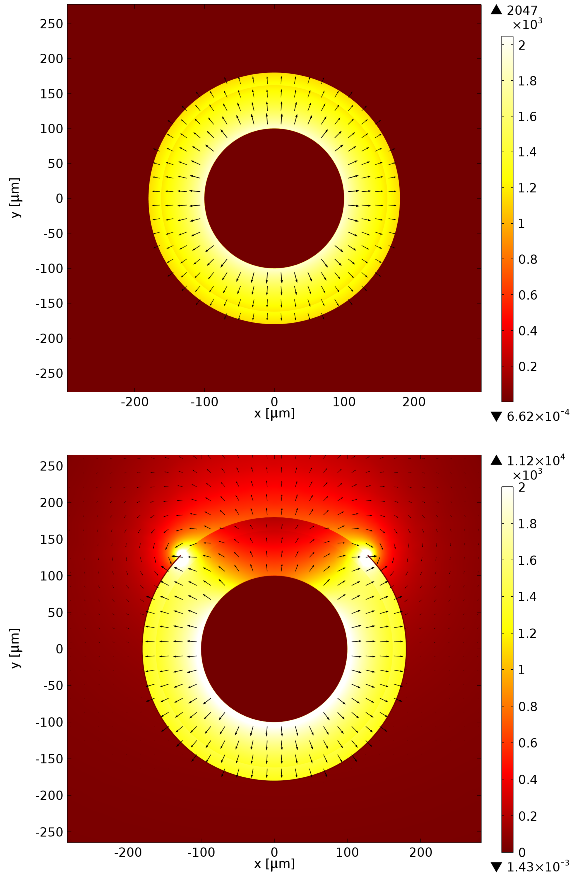

Fig. 3. The quasi-TEM modes of propagation in a windowless (top) and windowed (bottom) portion of LCX with thin metallic layers.

IV. Textile Integration

A computerized loom from AVL Looms Inc. was used to integrate the LCXs into a textile fabric, featuring 16 inch weaving width, 8 harnesses, and an automated weaving process allowing the design and production of complex textile patterns. The integration of LCXs into the threads of a textile fabric is shown in Fig 4. The LCXs appeared to be sufficiently flexible and unobtrusive to be essentially indistinguishable from the textile host, thus providing a minimally-invasive attribute to the textile integration. The properties of the LCX remained unchanged after the weaving process.

Fig. 4. Multi-material LCX fibers (arrowed) weaved into the threads of a textile fabric.

V. Textile Antenna Characterization

Radiation pattern of the LCXs were measured in an anechoic chamber using a wide-band Log periodic directional antenna HyperLOG-7060 operating from 700MHz to 6GHz. A tunable RF signal generator was connected to this reference antenna, forming the transmitting setup. The LCX was placed at the same height, at a distance of 2 m, using an all-dielectric holder, and connected to an external signal analyzer, forming the receiving setup. A diagram of this setup is shown in Fig 5. Co-polarization radiation pattern measurements along the E-plane (along the windows) and H-plane (perpendicular to the windows) are presented in Fig. 6. In agreement with simulations, the LCXs exhibited an omni-directional radiation pattern in the H-plane, while the E-plane presented several radiation lobes that are inherent to finite-length LCXs. The directivity of the LCX was calculated to be 6.8 dBi. The difference between the simulations and the experimental results may be attributed to roughness, thickness and electrical conduction non-uniformities in the silver thin film lining of the LCXs.

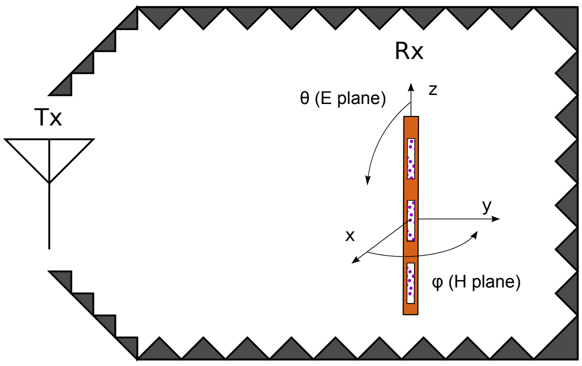

Fig. 5. Diagram of the experimental setup for the radiation pattern measurements with the E and H plane identified.

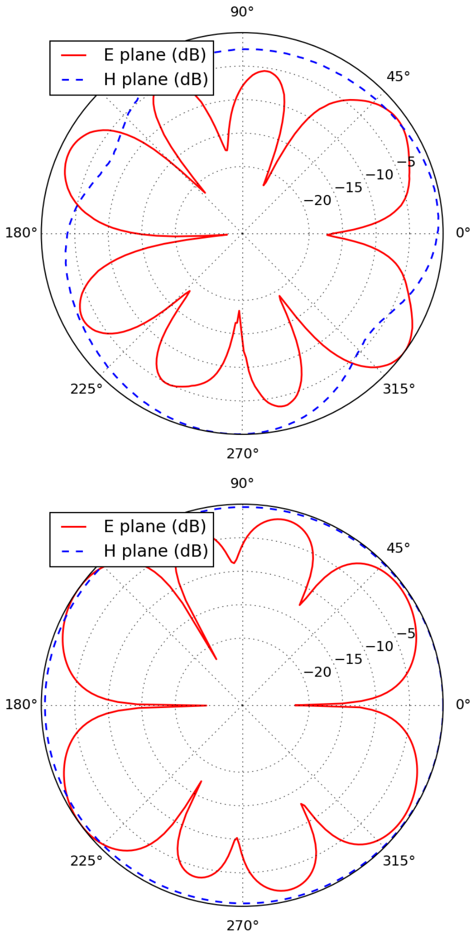

Fig. 6. Measured (top) and simulated (bottom) radiation patterns along the E-plane and H-plane polarizations of the LCX textile fiber operating at 2.4 GHz frequency.

VI. Conclusion

In this work, we have demonstrated novel textile fabrics integrating unobtrusive multi-material fibers compatible with 2.4 GHz wireless networks. The conductor elements of the textiles are embedded within the fibers themselves, providing electrical and chemical shielding against the environment, as well as electrical impedance matching to standard RF devices and systems, while preserving the mechanical and cosmetic properties of the garments. These multi-material fibers combine insulating and conducting materials into a single mechanically-robust and sub-millimiter-size structure. The proposed conductive fibers constitute an enabling platform for cost-effective and minimally-invasive smart textiles connected in real time to wireless communications infrastructures, and suitable for a variety of health and life science applications.

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