Novel wireless-communicating textiles made from multi-material and minimally-invasive fibers

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Abstract — The ability to integrate multiple materials into miniaturized fiber structures enables the realization of novel biomedical textile devices with higher-level functionalities and minimally-invasive attributes. In this work, we present novel textile fabrics integrating unobtrusive multi-material fibers that communicate through 2.4 GHz wireless networks with excellent signal quality. The conductor elements of the textiles are embedded within the fibers themselves, providing electrical and chemical shielding against the environment, while preserving the mechanical and cosmetic properties of the garments. These multi-material fibers combine insulating and conducting materials into a well-defined geometry, and represent a cost-effective and minimally-invasive approach to sensor fabrics and bio-sensing textiles connected in real time to mobile communications infrastructures, suitable for a variety of health and life science applications.

I. Introduction

As the relationship between humans, computers, and machines grows towards an uninterrupted and ever-closer connection, mobile biomedical devices such as bio-sensing textiles will prompt many new ubiquitous mobile applications on a global scale such as 24-hour medical monitoring, medical emergency communications, and patient data recording, to name a few. In fact, clothing and other wearable garments are increasingly set to become platforms for arrays of biomedical sensors, transducers and microprocessors that may continuously monitor health while interacting cost-effectively with the user, service provider, and the cloud.

Multi-material fibers have the potential to address some of the major challenges in developing sensor fabrics and bio-sensing textiles connected in real time to mobile communications infrastructures. Research in co-drawn metal-insulator-semiconductor photo-detecting fiber devices with mesoscopic-scale cross-sectional features has heralded a novel path to acoustic, thermal, and optical detection [1-3]. In such fibers, various functions may be delivered at length scales and in a mechanically flexible form. Multi-material fibers weaved into textiles can be made suitable for a variety of ubiquitous mobile applications pertaining, for example, to 24-hour-per-day connected healthcare and body area networks, which require sensor/processor/power interconnects, and delivery of wireless radio-frequency (RF) signals, as schematized in Fig 1. For instance, several applications in connected healthcare are envisioned for RF integration into textiles, many of which rely on WLAN, cellular networks, or other wireless communication bands to be effective 24 hours per day.

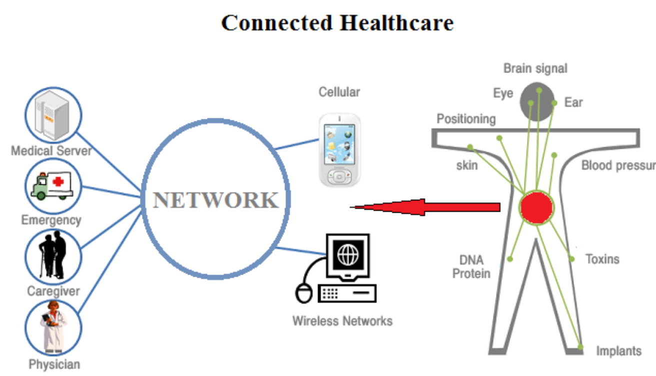

Fig. 1. Multi-material fibers weaved into textiles are suitable for a variety of health and life science applications pertaining to bio-sensing textiles connected through wireless networks.

The current trend of wireless textile communications devices is geared towards obtrusive monolithic patch designs: textile patch antennas made from conducting yarns [4], or patch-like sensors for health-monitoring applications [5]. However, since patch antennas have to be introduced onto a textile surface in a separate post-processing step, this makes fabrication of RF textiles labor intensive and expensive. Thus, multi-material fibers provide a perfect building material for the next generation of biomedical textiles as they can be easily integrated during the weaving process in a cost-effective and minimally-invasive manner while preserving the mechanical and cosmetic properties of the garments.

II. Fiber-based RF-antennas and Interconnects

In this work we propose to implement the core functionalities, i.e. signal delivery and radiative emission at 2.4 GHz frequency, and electrical interconnects, within the sub-millimeter fibers themselves which are weaved into the threads of a fabric.

Research supported by The Natural Sciences and Engineering Research Council of Canada (NSERC), Grant number STPGP 430237-12.
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By combining insulating and conducting materials into a well-defined geometry imbedded in a fiber, many functional electronic devices are achieved, in particular fiber and textile devices that lend themselves to RF-emission adaptable to existing broadband mobile infrastructures. Leaky Coaxial Cables (LCXs) are known for their capability of distributing radio waves in tunnels, mines, underpasses, and many other confined environments, with smooth electrical field coverage [6]. There are very few studies on the use of small-scale LCXs for novel mobile communications systems such as biomedical textiles. Fiber RF-antennas based on LCXs can be achieved through combinations of materials and careful design to impart fiber RF-functionality, while preserving fiber sub-millimeter size and flexibility suitable for integration into textiles.

Theoretical modeling of LCXs has been treated in many publications [6–9]. LCXs generally consist of three parts: an inner conductor, a dielectric material, and an outer conductor that exhibits periodic slits at a prescribed periodic distance *d*. Usually, the theoretical modeling considers an infinitely long coaxial cable that supports a single TEM propagation mode. This allows the use of Bloch-Floquet theory, which greatly eases the analysis of the radiation properties. The geometric parameters of the LCX are generally chosen as to allow only the $m=-1$ fundamental spatial harmonic [6], which radiates at an angle of:

$$\phi_m = \sin^{-1}\left(\sqrt{\varepsilon_r} + m\lambda/d\right)$$

This mode of operation provides a nearly transverse (i.e. broadside) radiation pattern. The frequency range of LCXs is determined by the periodic distance *d* of the slits and the relative permittivity ε_r of the dielectric, defined for the $m=-1$ fundamental spatial harmonic by the inequality:

$$\frac{c}{(\sqrt{\varepsilon_r}-1)d} \leq f \leq \frac{c}{(\sqrt{\varepsilon_r}+1)d}$$

The fiber antenna itself may represent only a few small threads in the textile fabric, thus enabling the use of non-standard textile fiber materials, such as polymer-clad silica fibers, without disrupting the mechanical and cosmetic attributes of the garment. This opens the possibility of leveraging the polymer-clad silica fiber manufacturing capabilities of the fiber optics industry. Such fibers (ε_r ~3.7) provide interval distances *d* in the range from 1 cm to 40 cm, compatible with typical clothing dimensions, for carrier frequencies in the range from 0.8 GHz to 5.0 GHz, respectively. Therefore the LCXs can be designed for textile antenna applications with the WLAN 802.11b/g/n 2.4GHz ISM band in mind, and can be scaled according to any desired carrier frequency of most wireless networks while leveraging the economies of scale of polymer-clad silica fiber industry. A transmission loss of a few dB/m for the coaxial cable is acceptable for textile antenna applications where typical clothing dimensions are below the meter range.

This theory can only be of qualitative use, as the specific properties of the actual design render most approximations invalid. The short length of the fiber prevents the use Bloch-Floquet theory while the thinness of the metallic conductor layers forces to model skin depth effects. These include modification of the propagation modes in the coaxial line as well as radiative coupling that stems from the evanescent fields penetrating the metallic conductor layers. Notwithstanding the theoretical difficulties, LCXs have been simulated via finite-element calculations on ANSYS-HFSS and COMSOL softwares. Here, difficulties have been encountered in reproducing experimental results. Directly meshing the metallic layers turned out to be unfeasible, but replacing them by impedance boundary conditions was successful in approximately reproducing experimental results.

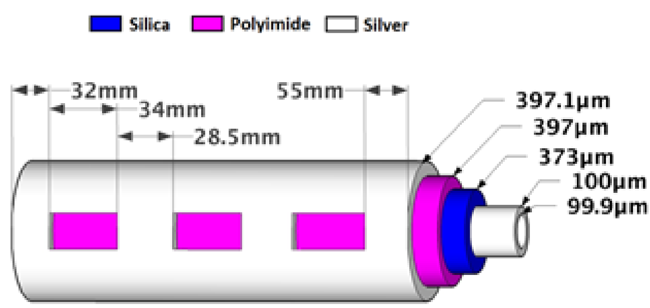

Fig. 2. Schematic and radii of the fabricated 3-slit LCXs using hollow-core polymer-clad silica fibers and operating at 2.4GHz. A 20µm layer of protective acrylic coating was deposited over the fiber except for two 2mm endpoints to allow for electrical connections.

LCXs were fabricated using a hollow-core silica fiber with an inner radius of 100µm and outer radius of 373µm, coated with a 24µm thick polyimide layer, and where the inner and outer surfaces of the hollow-core polyimide-silica fiber were coated with a thin film of silver metal, as schematized in Fig. 2. Silver metal coating was obtained using Tollen's reaction [10], a redox chemical reaction that consists in the precipitation of an aqueous solution composed of a mixture of silver nitrate ($AgNO_3$), potassium hydroxide (KOH), dextrose ($C_6H_{12}O_6$), and ammonium hydroxide (NH_4OH). The aqueous solution was injected into the inner hollow capillary at 500 µL/min rate using a motorized precision syringe, providing a flexible inner silver thin film lining of about 0.1µm thickness with good adhesion to silica glass, as shown in Fig. 3. For the outer polyimide-coated surface of the capillary, Tollen's reaction was preceded by a piranha etching in order to enhance silver adhesion to the polyimide, except where masks were applied to create apertures, or slits, in the outer coaxial conductor. The measured DC electrical resistances of the inner and outer coaxial conductors were generally between 40 and 70 Ohm, thus offering good electrical matching to the standard 50 Ohm impedance of electronics components. Finally, a thin layer of protective acrylic coating was deposited over the entire 250mm-long LCX fiber except for two 2mm endpoints to allow for SMA electrical connections. Since the inner core of the LCX fiber remained hollow, the endpoint male electrical connection was formed by a tin-coated copper wire (ø 127 µm) inserted through the inner hollow core.

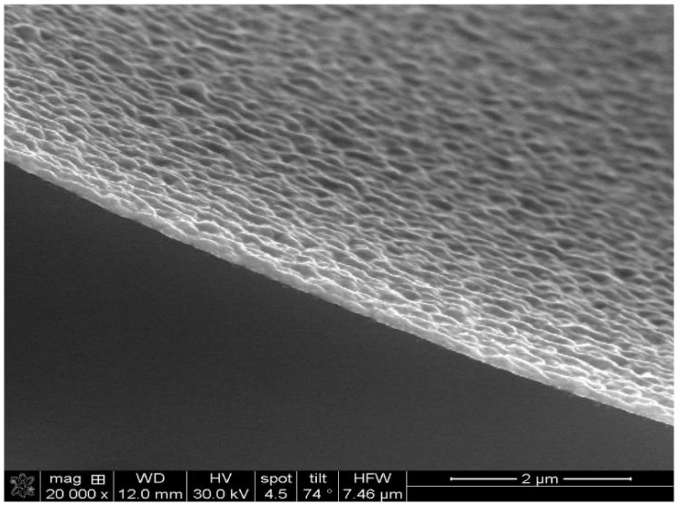

Fig. 3. SEM picture of the LCX inner silver thin film lining.

Silver metal coatings obtained from Tollen's reaction exhibit a low electrical sheet resistance of Rs = 0.25 Ohm/sq that remains stable over time even when the silver film is exposed to oxidation. This provides a suitable conductor element for long electrical interconnects imbedded within the fiber. Multi transmission lines can be fabricated using hollow-core fibers such as the dual-core interconnect depicted in Fig 4. The two 75 µm diameter hollow-cores were coated with a silver lining providing a DC electrical resistance of only 100 Ohm over a length of 1 meter, which is suitable for a variety of applications pertaining to textile bio-sensor interconnects.

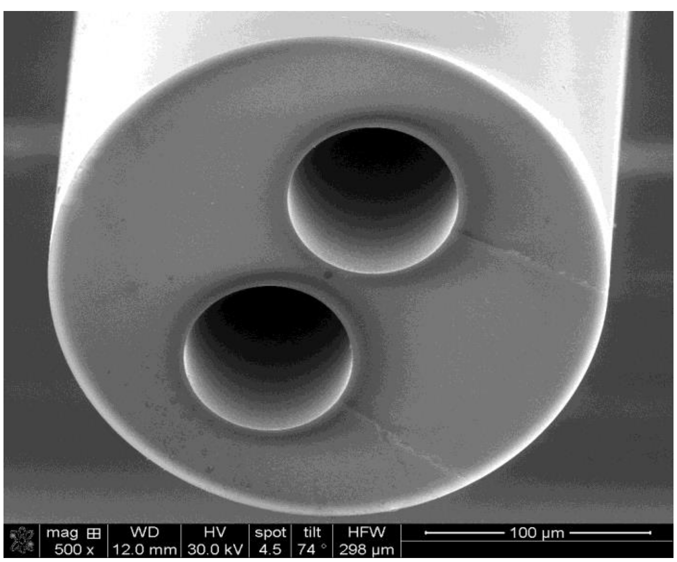

Fig. 4. SEM picture of a 75 µm dual-core fiber interconnect.

III. 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 a standard weaving process allowing the design and production of complex textile patterns. The LCXs themselves represent only a few small threads in the textile fabric, as shown in Fig 5. The LCXs appeared to be flexible and unobtrusive enough to be essentially indistinguishable from the textile host, thus providing a minimally-invasive attribute to the textile integration. Also, the LCX fibers withstood conventional weaving process and textile manipulation without damage.

Since fibers are inherently congenial to textile manufacturing, the process for mass producing traditional textiles is not disrupted significantly by the use of sub-millimeter-size multi-material fibers, which can have the same mechanical flexibility as traditional textile threads. This represents a cost-effective and minimally-invasive approach to fabricating bio-sensing textiles. Two significant cost benefits can be obtained from multi-material fibers: 1) these fibers are congenial to the textile industry and can be adapted directly to traditional industrial looms, and 2) they benefit from the economies of scale of the fiber optics manufacturing industry. In addition, by using chemically stable, mechanically strong, and thermally robust fiber cladding materials (such as silica glass and high-Tg polymers of Fig. 1), the imbedded elements within the fibers can be shielded from water, detergent, and chemical exposure, physical stress, and extreme temperatures, while preserving the cosmetic appeal and mechanical properties of traditional textile threads.

Fig. 5. LCXs (arrowed) weaved into the threads of a textile fabric.

IV. TEXTILE ANTENNA CHARACTERIZATION

The radiation pattern measurements of the 3-slit LCXs were obtained in an anechoic chamber using a wide-band Log periodic directional antenna HyperLOG-7060 from 700MHz to 6GHz along with a tunable signal generator on the transmission side, while the LCXs acted as the far-field receiver. The LCX fibers were carefully positioned with the slits facing the transmitting antenna at 0° position. Radiation pattern measurements along the E-plane (parallel) and H-plane (perpendicular) polarizations are presented in Fig. 6. In agreement with theoretical predictions, the LCXs exhibited an omnidirectional radiation pattern in the H-plane, while the E-plane presented several radiation lobes due to spatial harmonics of the 3-slit LCX structure. Peak directivities in the E-plane were calculated at 3.3 dB for the LCX operating at 2.4 GHz. Slight asymmetries in the radiation pattern of the LCX fiber may be attributed to roughness, thickness and electrical conduction non-uniformities in the silver thin film lining of the LCXs. The sub-millimeter attribute of the coaxial design, the thinness of the conducting layers, and the inherent process variations of Tollen's silver nitrate reduction, render the LCX device sensitive to skin depth effects.

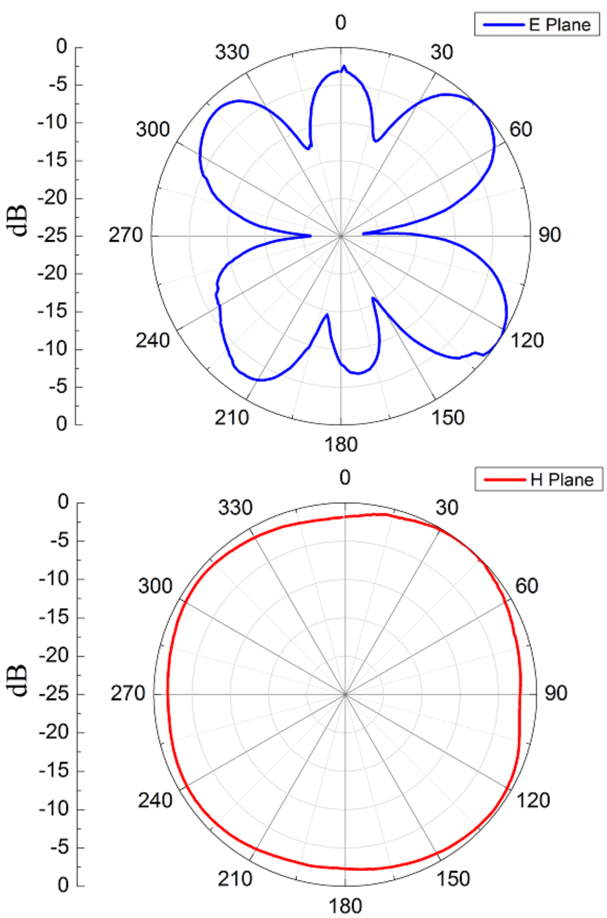

Fig. 6. Radiation pattern measurements along the E-plane (parallel) and H-plane (perpendicular) polarizations of the 3-slit LCX textile fiber operating at 2.4 GHz frequency.

V. Conclusion

In this work, we have demonstrated novel textile fabrics integrating unobtrusive multi-material fibers that communicate through 2.4 GHz wireless networks with excellent signal quality. 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 well-defined geometry, and represent a cost-effective and minimally-invasive approach to sensor fabrics and bio-sensing textiles connected in real time to mobile communications infrastructures, suitable for a variety of health and life science applications.

Acknowledgement

We gratefully acknowledge the fruitful design contributions of Mr. Joey Dumont and Ms. Rim Baklouti of Laval University. This research was supported by The Natural Sciences and Engineering Research Council of Canada (NSERC), Grant number STPGP 430237-12.

References

[1] M. Bayindir, F. Sorin, A. F. Abouraddy, J. Viens, S. D. Hart, J. D. Joannopoulos, and Y. Fink, "Metal-insulator-semiconductor optoelectronic fibres," *Nature,* vol. 431, pp. 826-829, 2004.

[2] M. Bayindir, A. F. Abouraddy, O. Shapira, J. Viens, D. Saygin-Hinczewski, F. Sorin, J. Arnold, J. D. Joannopoulos, and Y. Fink, "Kilometer-Long Ordered Nanophotonic Devices by Preform-to-Fiber Fabrication," *Selected Topics in Quantum Electronics, IEEE Journal of,* vol. 12, pp. 1202-1213, 2006.

[3] F.Sorin, A.F.Abouraddy, N.Orf, O.Shapira, J.Viens, J.Arnold, J.D.Joannopoulos, Y.Fink, "Multimaterial Photodetecting Fibers: a Geometric and Structural Study", *Adv. Mater.* 2007, *19*, 3872–3877.

[4] M. I. Jais, et al., "A novel beam steering of hybrid switchable beam textile antenna," Microw. Opt. Technol. Lett., vol. 55, no. 8, pp.1893−1897 (2013).

[5] M. Catrysse, et al., "Towards the integration of textile sensors in a wireless monitoring suit," Sensors and Actuators A, vol. 114, pp. 302–311 (2004).

[6] J. H. Wang and K. K. Mei, "Theory and Analysis of Leaky Coaxial Cables With Periodic Slits," IEEE Trans. Antennas. Propag., vol. 49, no. 12, pp.1723–1732 (2001).

[7] P. P. Delogne and A. A. Laloux, "Theory of the Slotted Coaxial Cable," IEEE Trans. Microw. Theory Tech., vol. 28, no. 10, pp.1102–1107 (1980).

[8] D. H. Kim and H. J. Eom, "Radiation of a Leaky Coaxial Cable With Narrow Transverse Slots," IEEE Trans. Antennas Propag., vol. 55, no. 1, pp. 107–110 (2007).

[9] G. Addamo, R. Orta, and R. Tascone, "Bloch wave analysis of long leaky coaxial cables," IEEE Trans. Antennas Propag., vol.56, no. 6, pp. 1548–1554 (2008).

[10] W. E. Benet, "The mechanism of the reaction of the Tollen reagent", J. Chemical Research, Vol 35, No 12, pp. 675-677 (2011).