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Soft capacitor fibers for electronic textiles

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A highly flexible, conductive polymer-based fiber with high electric capacitance is reported. The fiber is fabricated using fiber drawing method, where a multimaterial macroscopic preform is drawn into a submillimeter capacitor microstructured fiber. A typical measured capacitance per unit length of our fibers is 60–100 nF/m which is about 3 orders magnitude higher than that of a coaxial cable of a comparable diameter. The fiber has a transverse resistivity of 5 kΩ m. Softness, lightweight, absence of liquid electrolyte, and ease of scalability to large production volumes make the fibers interesting for various smart textile applications. © *2010 American Institute of Physics*. [doi:10.1063/1.3488351]

Smart textiles (or e-textiles) can sense and respond to the environmental stimuli of electrical, mechanical, thermal, and chemical nature. Smart textiles originally emerged as garments for biomedical monitoring[1,2] and wearable computing.[3] Over the years e-textiles have received much attention due to their potential applications in energy harnessing,[4] heat-storage, and thermoregulated clothing,[5] smart cars,[6] apparel with tuneable appearance,[7] etc.

Most of the "smart" functionalities in the currently existing smart apparel are enabled by various point devices attached onto a textile. Majority of such point devices (electronic chipsets, batteries, etc.) are rigid and incompatible with standard weaving techniques. As a consequence, high volume production, wearability, and reliability of such garments are problematic. This stimulated recent effort into the development of flexible electronic components. Ideally, if all the electronic functionalities could be realized in a fiber itself, such fibers would provide a perfect building material for smart apparel. Currently there are only few known examples of electronic fibers. These include, conductive fibers prepared by wet spinning of polyaniline[8] or coating carbon nanotubes on cotton yarns,[9] a piezoelectric microfiber nanogenerator,[10] a stretchable conductive textiles,[11] and organic all-fiber transistors.[12]

In this paper we present a soft, high capacitance electronic fiber fabricated from conductive polymer composites. Prior proposals for a capacitor fiber and its applications include a load bearing avionic textile that was also able to store energy. Such a textile was made of a large number of low capacitance coaxial cables.[13] Another example is a double layer capacitor fiber made of carbon nanotube impregnated threads.[14] Such fibers required soaking in liquid electrolyte for their operation. Possible applications of capacitor fibers are in textile-based energy storage, flexible electronic circuitry for product labeling, distributed sensing of electric and mechanic influence, etc.

The capacitor fibers described in this paper are fabricated using the technique of fiber drawing from a structured multimaterial preform. The technique is analogous to that used for the fabrication of microstructured optical fibers.[15] Fibers with very complex microstructure and nanostructure can be fabricated via largely homologous reduction in the preform macrostructure during drawing.

The soft capacitor fibers presented in this work comprise two conducting layers and two isolating layers. To achieve homologous drawing, materials in the preform should have compatible rheological and thermomechanical properties. Conductive layers are made from carbon black (CB) filled polyethylene (PE) composite film (BPQ series, volume resistivity of 2.2 Ω m) provided by Bystat International Inc. Isolating layers are made of the low density PE (LDPE) film. Cross section of a typical fiber of ~1 mm diameter is presented in Fig. 1. The fiber has cylindrical geometry with two conductive composite electrodes in the form of a spiralling multilayer [see Figs. 1(a) and 1(b)]. A 100 μm copper wire electrode was introduced into the hollow core during drawing. The second electrode was an aluminum foil or a conductive paint placed on the outer surface of the fiber. In the

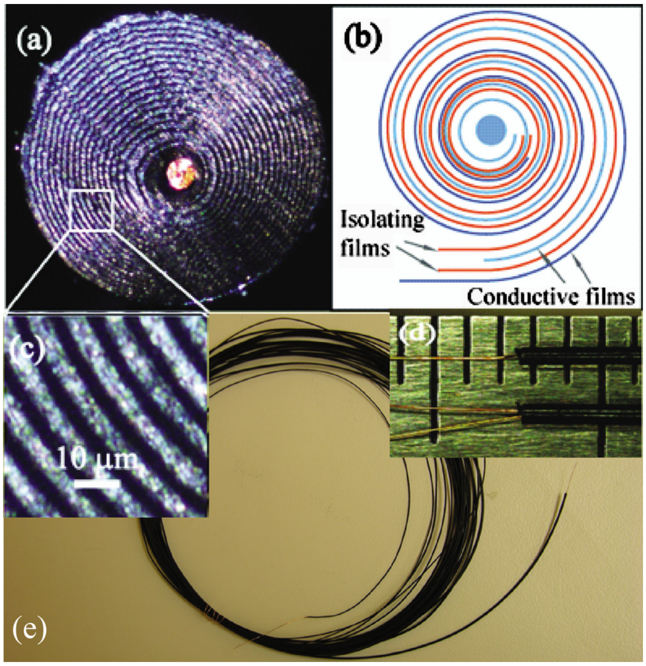

FIG. 1. (Color online) Capacitor fibers fabricated with copper electrodes in the center. (a) and (c) show cross sections of the capacitor fibers. (b) is a schematic of the fiber. (d) is a side view of the fiber with one and two electrodes in the center. (e) Spool of a drawn capacitor fiber.

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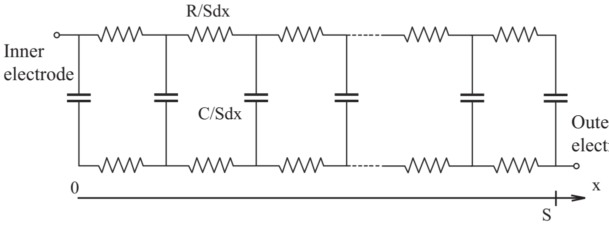

FIG. 2. Ladder network model of the capacitor fiber.

preform, both conductive layers are 75 μm thick, while the two insulating LDPE layers are 86 μm thick.

Capacitor fiber electric properties are described in terms of an ideal capacitor with capacitance C_F connected in series to an ideal resistor with resistance R_F. We used a simple measurement circuit where the fiber capacitor was connected to a function generator through a known reference resistor. Using an oscilloscope we measured the amplitude ratio and phase shift in the voltage drop over the reference resistor as compared to the output voltage of the function generator at various frequencies from 1 Hz to 3 MHz. By fitting the experimental data to the equivalent circuit model, the capacitance and equivalent resistance of the fibers can be deduced. As mentioned earlier, the fiber outer electrical probe is an aluminum foil wrapped around the fiber. Our measurements show that a fully covered fiber always exhibits smaller resistance than a partially covered one. Due to the space constraints, in this paper we only report measurements conducted using fully covered fibers.

Due to high resistivity of conductive composite films the capacitor fiber behaves like a resistor-capacitor (RC) ladder circuit shown in Fig. 2. Here, C is capacitance of the two co-rolled conductive films, while R is transverse resistance of a single conductive film spiralling from the fiber core toward its surface. As thicknesses of the dielectric and conductive layers in the fiber are hundred times smaller than the fiber diameter, fiber capacitance can be well approximated using an expression for the equivalent parallel-plate capacitor, as follows:

$$C \approx 2\varepsilon_0 \varepsilon L S / d_i. \tag{1}$$

Here ε is dielectric constant of the isolating films, ε_0 is permeability of the vacuum, L is fiber length, S and d_i are, respectively, width and thickness of the rolled isolating films. Similarly, conductive film transverse resistance is the following:

$$R \approx \rho_v S/(L d_c), \tag{2}$$

where ρ_v and d_c are the volume resistivity and thickness of the conductive films. Analytical solution of the ladder circuit model gives the following expressions for the effective capacitance and effective series resistance:

$$C_F = -\{\omega R \times \mathrm{Im}[f(B)]\}^{-1} \underset{\omega \to 0}{\to} C,$$

$$R_F = R/2 + R \times \mathrm{Re}[f(B)] \underset{\omega \to 0}{\to} 2/3R, \tag{3}$$

$$f(B) = [1 + \cosh(B)]/[B \times \sinh(B)]; \quad B = \sqrt{2 i \omega R C}.$$

We first study dependence of the fiber capacitance and resistivity as a function of the fiber length at low frequencies (<1 kHz). Two fiber samples were drawn from the same preform but to the different outside diameters of ~950 and ~740 μm. For all the measured fibers the capacitance per unit length, C_F/L, is a constant ~69 nF/m [Fig. 3(a)], and it is close to the value measured for the fiber preform. This is easy to rationalize from Eqs. (1) and (3). Due to homologous drawing, S/d_i is a constant, hence, C_F/L should be the same for any fiber produced from the same preform, regardless of the fiber diameter. The reason why our fibers have large capacitance is because the value of S/d_i is much larger than that of a coaxial cable with only one electrode layer.

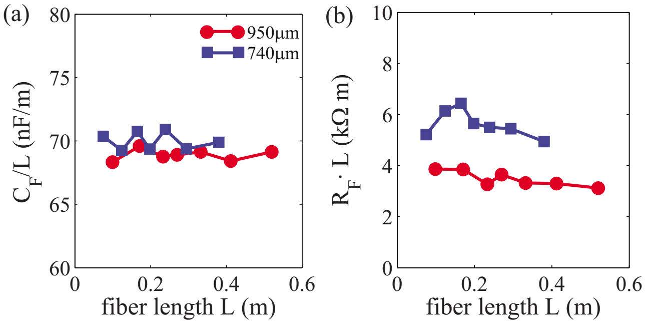

FIG. 3. (Color online) Dependence of the capacitor fiber electric properties on fiber length at low frequencies. (a) C_F/L vs L and (b) $R_F \times L$ vs L.

From Eqs. (2) and (3) and Fig. 3(b) it also follows that at low frequencies fiber resistance decreases inversely proportional to the fiber length. In fact, the product $R_F \times L$ should be constant not only for the fibers of different length, but also for the fibers of different diameters. This is because for homologous drawing, the ratio S/d_c is constant. Experimentally, however, we observe that smaller diameter fibers consistently exhibit higher resistivities. This is related to the fact that volume resistivity of CB/polymer composites increases exponentially fast for larger elongation ratios as the film is stretched.[16] As stretching is unavoidable during drawing we, thus, expect higher volume resistivities of the drawn conductive films, and, hence, higher resistance of the smaller diameter fibers.

To study electrical behavior of our fibers at high frequencies, we have first determined that complex impedance of the measuring circuit (mainly oscilloscope) becomes important only at frequencies higher than 100 kHz. We then studied frequency response of a conductive film from which all the preforms were made. Although it has been reported[17] that near the percolation threshold the resistivity of CB/polymer films decrease with increasing frequency, our measurements showed that resistivity of our films is frequency independent below 100 kHz. In Fig. 4 we present frequency dependence of the effective capacitance and resistance of a 14 cm long

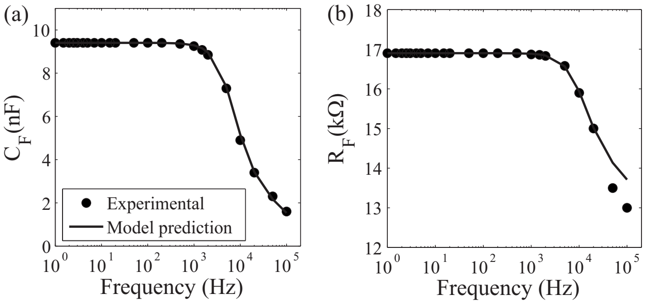

FIG. 4. Frequency dependence of the capacitor fiber effective electric properties. (a) C_F vs ν and (b) R_F vs ν.

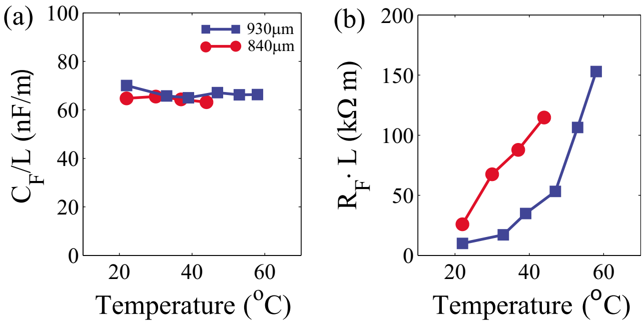

FIG. 5. (Color online) Effect of the operation temperature on the capacitor fiber electrical properties. (a) C_F/L vs T and (b) $R_F \times L$ vs T.

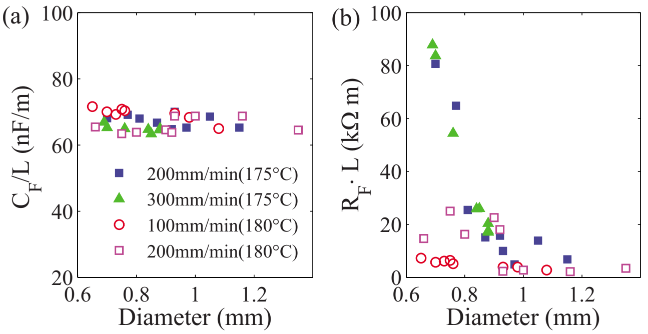

FIG. 6. (Color online) Dependence of the capacitor fiber electric properties on fiber drawing parameters. (a) Capacitance per unit length C_F/L vs fiber diameter. (b) Resistivity parameter $R_F \times L$ vs fiber diameter.

fiber of 0.93 mm diameter. Experimental data can be very well fitted with Eqs. (3) assuming C=9.4 nF, R=26 kΩ. At low frequencies both C_F and R_F are constants but they decrease at frequencies higher than 1 kHz. This behavior is similar to that of a standard electrolytic capacitor and is well explained by the RC ladder network model with a characteristic response frequency of $1/(RC) \sim 5$ kHz.

The operation temperature also has a significant effect on the fiber properties. Our measurements show that at low frequencies while capacitance per unit length remains almost constant with temperature, resistivity parameter $R_F \times L$ increases dramatically as temperature rises (see Fig. 5). This result is in good correspondence with the recent reports on positive temperature coefficient[18] for the resistivity of the CB/LDPE composites. The effect of thermal expansion and a consequent increase in the average distance between CB particles are thought to be the main reasons for the positive temperature coefficient of such composites. This property opens applications of capacitor fibers in self-limiting textiles for intelligent heating. Thus, at cooler temperatures fiber resistivity will decrease, thus driving higher currents, and as a consequence, releasing more heat.

Capacitor fibers presented in this work can be drawn at temperatures in the range 170–185 °C with drawing speeds ranging from 100 to 300 mm/min. We observed that the fiber capacitance C_F/L is largely independent of the fiber drawing parameters, while fiber resistivity parameter $R_F \times L$ is significantly affected by the drawing history. Although Eq. (2) predicts that the resistivity parameter $R_F \times L$ should not depend on the fiber diameter (S/d_c is constant due to homologous drawing), from Figs. 6(b) and 3(b) we find that this expectation does not hold. As mention earlier, this is because bulk resistivity ρ_v of the CB/polymer composite in a drawn fiber depends significantly on the mechanical and thermal history, particularly, on the amount of "cold" stretching during drawing. Consistently, from Fig. 6 we find that fibers with the lowest resistivity are drawn at higher temperatures and lower drawing speeds, processing conditions that both work against increase in the inter-particle separation between CB particles and facilitate the formation of conductive networks during drawing.

In conclusion, soft capacitor fibers made of conductive polymer composites were demonstrated. Such fibers feature relatively high capacitance which is ~3 orders of magnitude higher than that of a coaxial cable of a comparable diameter. The fiber capacitance per unit of length is found to be a very stable parameter independent of the fiber diameter, operational temperature, and drawing history. In contrast, fiber resistivity parameter has a very strong positive temperature coefficient, and it is influenced by the drawing conditions. Our capacitor fibers are well suited for the e-textile applications as they are soft, small diameter, lightweight, and do not use liquid electrolytes.

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