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Electrical Characteristics and Signal Transmission Characteristics of Hybrid Structure Yarns for Smart Wearable Devices

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Abstract: Twisted Copper Filaments (TCF) have been made by a yarn covering process in order to transmit signals and powers for electronic textiles. The 560 den. poly urethane filaments were covered in S-twist direction by urethane-coated copper wires. Two TCF twisted in Z direction were further covered in S direction by PET filaments to make final hybrid structure yarns (HSY). The HSY prepared was proportionally increased in apparent resistance along with measurement length, and showed resistivity of 0.00414 Ω·m. The number of ply was critical in terms of resistance variation, showing a linear increase of resistance with ply number. The twist factor, however, was not so significant without a slight decrease for severe twist level. Resonance Frequency, S11 (reflection), S21 (transmission) were measured and compared in order to examine the feasibility of applying to electrical signal transmission for wearable textiles. As expected, amplitude of resonance frequency was significantly decreased mainly due to increase of capacitance caused by length increase. It has been shown that S11 and S21 has been increased and decreased, respectively due to increase of transmission distance. While resonance frequency has been kept along with the ply number, S11 and S21 were decreased and increased, respectively according to decrease of copper fiber. Final filaments were found to be changed in resonance frequency mainly due to the change of di-electricity and thus capacitance caused by PET covered on it. It have been concluded that while resonance frequency was primarily determined by filament length and dielectric constant of covering yarns, S11 and S21 were mainly determined by measurement length and ply number.

Keywords: Hybrid structure yarn, Digital textile, Conducting fibers, Smart clothing, Power loss of conducting fibers, Transmission parameters of conducting fibers

Introduction

Active research on highly flexible data transmission fibers for electronic textiles has been increasing, with strong focus on wearable devices such as smart shirts, shoes, and clothing [1]. Au, Cu metal fibers coated with nonconductive polymers, and polymeric fibers with conductive organic coatings are reportedly practical material options in terms of quality and cost [2]. According to an analysis, polymeric fibers with conductive coating showed more flexibility and elasticity at moderate levels of electrical conductivity [3]. Copper-coated cotton fabrics have been prepared and characterized by Svetlana Vihodceva [4], and Akif kaynak executed the vapor-polymerization of conductive monomers directly onto the surface of nylon and cotton fabrics [5]. In spite of all the advantages mentioned above, polymeric fibers suffer due to low conductivity that lies between 10^{-3} and 10^{-2} Ω·m; hence, they cannot be effectively employed for the specific use of data transmission due to low capacity for information delivery. Presently, the most popularly used transmission fibers are polymer coated copper fibers [6]. In addition to high metal processing and yarn covering speeds, copper fibers of less than 100 μm diameter twisted with textile fibers have relatively lower cost when compared to conductive polymer coated fibers. The hybrid fibers provide an efficient option for preparing cost effective data transmission media without any significant loss to the tactility and flexibility characteristics of textile fibers [7]. Techniques for balancing and optimizing the mechanical characteristics of the two components, coating and core yarns, should be given special consideration to avoid data transmission delay due to the introduced capacitance [8]. Safarova studied the effect of the number of twists on resistivity using a 500-μm diameter polypropylene fiber coated with an 8-μm stainless steel staple fiber [9]. Tunde Kirstein analyzed the resonance frequency and impedance by comparing two different pairs of Polyester (PET) and copper wire twisted yarns, measuring 140 denier and 200 denier. The results showed that thickness of the yarns have great effect on their dielectricity [10]. Furthermore, Choi investigated the effect of measurement length and ply number on the resonance frequency, S11 and S21, by using hybrid yarns along with two intertwined PET fibers (2D/24F) covered by Ag wires [11]. In our study, we propose an elastic hybrid yarn with a new structure showing 0.01 Ω·m conductivity; and report the DC resistance, and resonance frequency, S11 and S21, to examine the feasibility of data transmission in textiles for wearable devices.

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Experimental

Preparation of Hybrid Structure Yarn (HSY)

560 Denier PU fibers covered by urethane coated copper fiber have been prepared by twisting PET fibers in order to measure electrical characteristics as data transmission media. Copper fibers have been known to be possibly treated without any significant problems due to mechanical strength larger

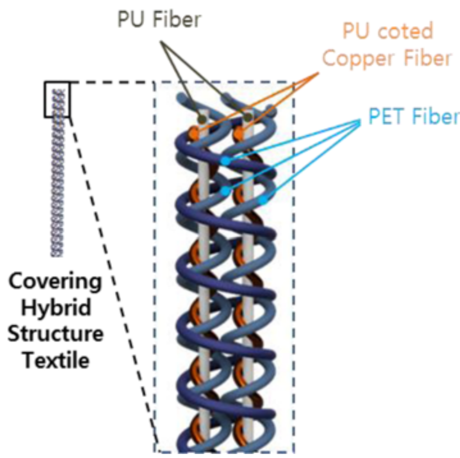

Figure 1. Schematics of the hybrid structure textile (HST).

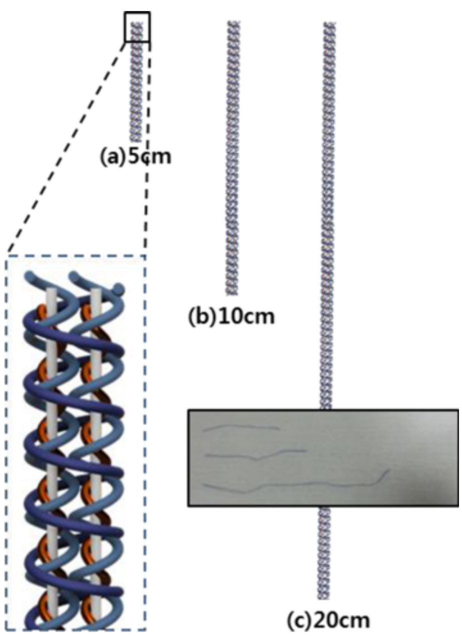

Figure 2. Changes in electrical conductivity and signal transmission characteristics according to measurement length; (a) 5 cm, (b) 10 cm, and (c) 20 cm.

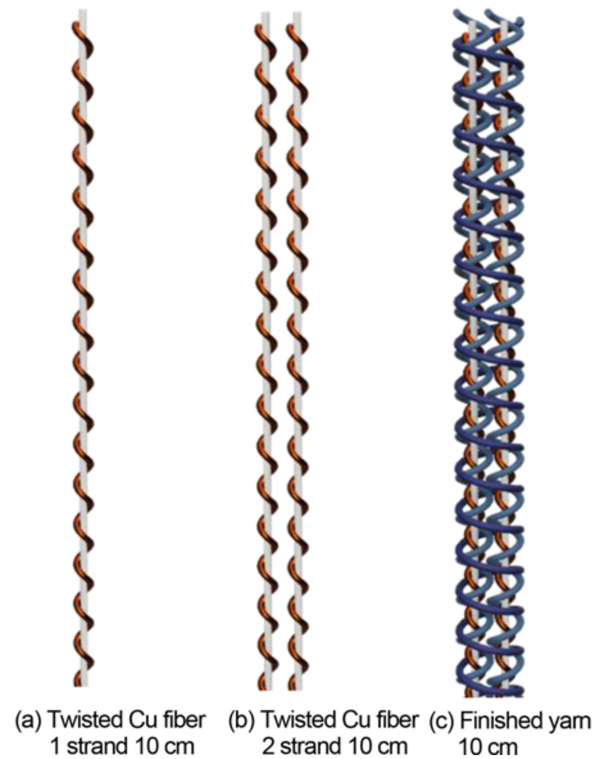

Figure 3. Changes in electrical conductivity and signal transmission characteristics according to number of strands; (a) 1 strand, (b) 2 strands, and (c) finished yarn.

than silver fibers. Quite fast condition, 9,000 rpm, could be applied for incorporating Z twist between 560D PU fiber and copper fiber. Figure 3(c) shows in a graphical manner the details of the fibers prepared by the method above. PET fibers (45 fila. and 150 den.) were used for covering those fibers followed by S twist at 9,000 rpm. The final HST has been shown in Figure 1. Various types of samples using HST have been prepared in order to measure data transmission characteristics in Figure 2 and Figure 3.

Geometry of Hybrid Structure Yarn (HSY)

SEM (CX-100S, Semicoxem Co.) and optical microscopy (OM) have been employed in order to measure diameter and twist numbers for a variety of samples. Since the cross-sectional area of copper fibers has a great effect on their electrical resistance, copper fiber diameter and outer coating thickness have been separately measured and analyzed for further use. OM has been mainly used in order to examine the twist features of copper fibers such as twist number, twist angle and contact area.

Measurement of the Electrical Conductivity

Effect of measurement length on electrical resistance has been investigated in order to quantify the transmission characteristics by using 5, 10, and 20 samples. 1 and 2 ply yarns of 10 cm length have been employed in order to compare electrical conductivity. Urethane components coated on fiber surface have been completely removed by DMF in order to ensure electrical contact between fibers and probes. The conductivity measurement has been implemented by Milliohm Tester (HIOKI 3540 Hi-Tester) in Figure 4. All the samples have been treated with silver paste on their both ends in order to ensure low impedance contacts.

Measurement of Data Transmission Speed

Resonance frequency, S11, and S21 of different lengths have been measured and compared by using network analyzer

Figure 4. Conductivity measurement of conductive yarns using a low ohm meter.

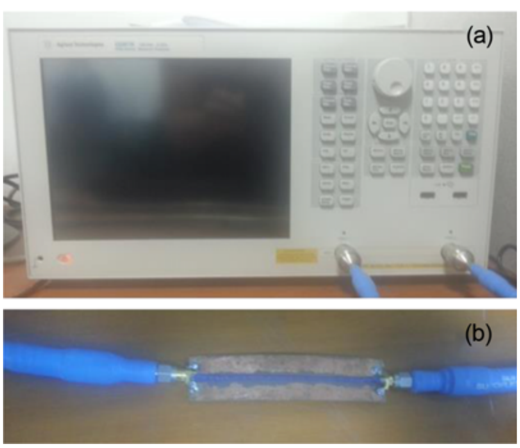

Figure 5. Fixture connection between (a) network analyzer and (b) a sample.

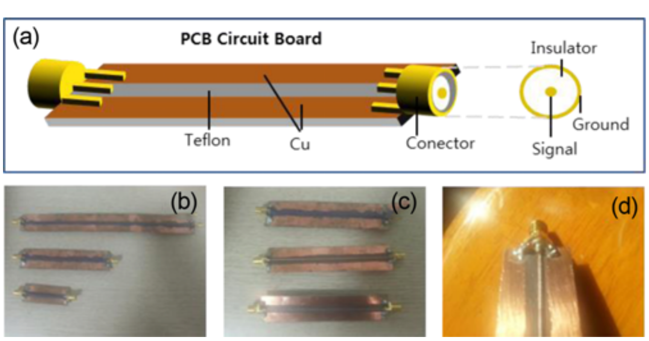

Figure 6. Images of (a) schematics of fixture, (b) types of fixtures, (c) different strands, and (d) connection I details.

(E5061B, Agilent Co.) in order to quantify the data transmission characteristics. Effect of ply numbers has been investigated by placing two yarns in parallel on the specially invented fixture. Those yarns have been further used in order to study the effect of twist numbers by incorporating varying twist levels. Teflon based PCB has been used after etching in order to enhance measurement reliability, and showed fixtures with two separate sections for signal and ground in Figure 5 and Figure 6.

Results and Discussion

Structure of Hybrid Structure Yarn

Figure 7 shows cross-sectional SEM images of urethane coated copper fibers under different magnifications. It has been revealed that pristine and urethane coated copper fibers have 70 μm and 80 μm, respectively. In spite of irregular boundary between copper fiber and urethane coated, average coating thickness has been determined to about 5 μm, and thus cross-sectional area (A) was calculated to be 3.846×10^{-9}m^2 by equation (1).

$$d_{Cu}\ \text{(Diameter of Cu fiber)} = 7 \times 10^{-5}\ \text{(m)} \tag{1}$$

$$\text{A (Area of Cu fiber cross section)} = (d_{Cu}/2)^2\pi = 3.846 \times 10^{-9}\ (\text{m}^2) \tag{2}$$

According to OM measurement in Figure 8, 320 μm diameter PU fiber were covered by urethane coated copper fiber in every 421 μm, meaning 60 tpi (turns per inch). Total length of copper fibers was calculated to be 4.771 m in a single ply, thus doubled (9.542 m) for two ply TCF.

$$\text{D (Distance of twist by twist)} = 421\times 10^{-6}\left(\frac{m}{1\ Twist}\right) = 2375\left(\frac{Twist}{m}\right) = 60\ \text{tpi (twist per inch)} \tag{3}$$

$$d_{pu}\ \text{(Diameter of PU fiber)} = 320\ (\mu\text{m}) = 3.2\times 10^{-4}\ \text{(m)} \tag{4}$$

$$C_{pu}\ \text{(Circumference of PU fiber Cross section)} = 2\pi\cdot d_{pu} = 2.009\times 10^{-3}\left(\frac{m}{Twist}\right) \tag{5}$$

$$l_T\ \text{(Cu fiber length per TCF length 1 m)} = C_{pu}\left(\frac{m}{Twist}\right)\times D\left(\frac{Twist}{m}\right) = 4.771\left(\frac{m}{m(TCF)}\right) \tag{6}$$

$$l_H\ \text{(Cu fiber length per HST length 1 m)} = 9.542\left(\frac{m}{m(TCF)}\right) \tag{7}$$

Structural characteristics such as have been shown in Table 1.

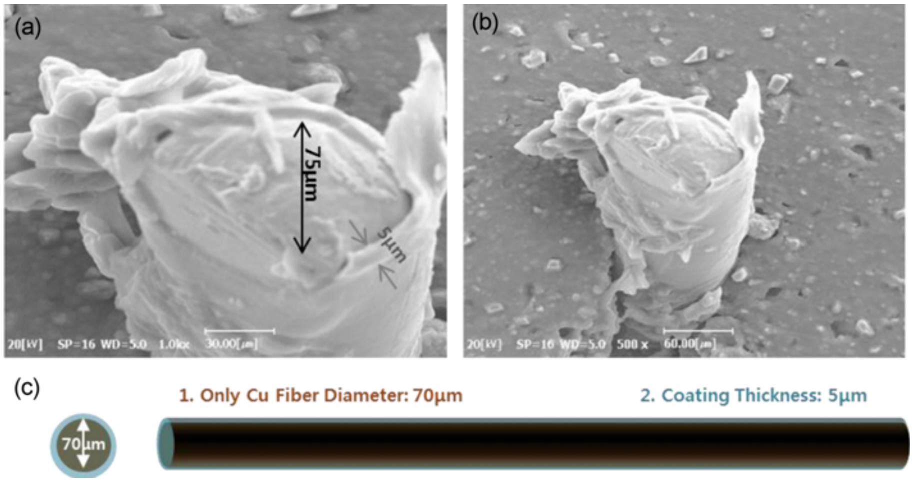

Figure 7. SEM images of PU coated copper fiber, (a) ×1k, (b) ×500, and (c) diagram of coated fiber.

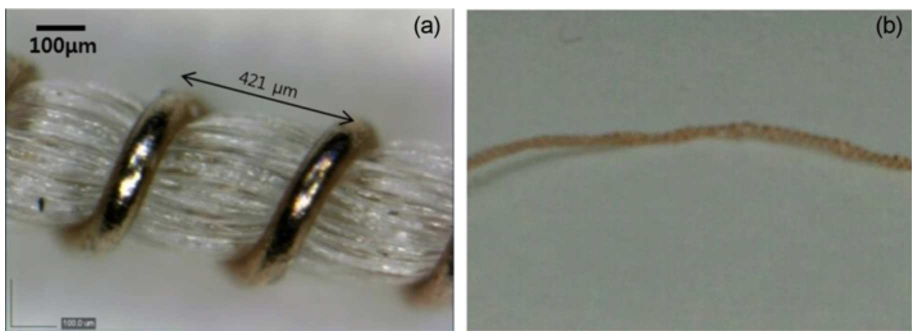

Figure 8. Images of (a) twisted copper fiber (×400) and (b) twisted copper fiber (x1).

Table 1. Details of a hybrid structure yarn

Type	Conducting fiber
Structure	TCF (twisted copper fiber) 1) Core yarn: polyurethane 560D 2) Total TCF diameter: 75 μm (Only Cu fiber Diameter: 70 μm + Pu coating thickness: 5 μm) 3) Only Cu fiber cross-sectional area: 15386×10^{-12} m^2 4) Covering yarn: polyester 150D/45F
Number of twist (TPI)	60TPI = 424×10^{-6} μm/one twist
Cu fiber length per TCF length 1 m	4.738 m/m (TCF)
Twisting condition	TCF: S twist, 1st Covering: Z twist, 2nd Covering: S twist

	5cm	10cm	20cm
Resistance(Ω)	215.1mΩ	430.6mΩ	860.6mΩ

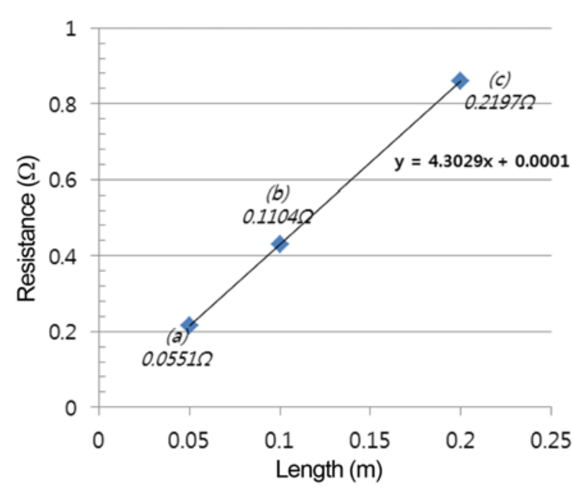

Figure 9. Resistance vs. measurement length; (a) 5 cm, (b) 10 cm, and (c) 20 cm.

Electrical Resistance

As shown in Figure 9, electrical resistances increase from 215.1 mΩ to 860.6 mΩ within 5-20 cm measurement length by using a digital multi-meter. Resistivity (ρ, Ω·m), intrinsic resistance, is related to apparent resistance (Ω) and fiber

	Twisted Cu Fiber 1strand	Twisted Cu Fiber 2strand	Finished Yarn
Resistance(Ω)	861.2mΩ	430.3mΩ	430.6mΩ

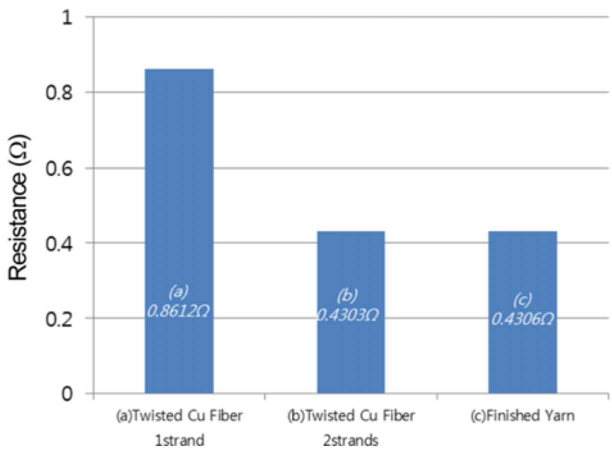

Figure 10. Resistance vs. number of strands; (a) 1 strand, (b) 2 strands, and (c) finished yarn.

structures as follows:

$$R \text{ (Resistance)} = \rho \text{ (Resistivity)} \times \frac{l\ (Fiber\ length)}{A\ (Cross\ section\ area)},\ \frac{R}{l} = \frac{\rho}{A} \tag{8}$$

Resistivity (ρ, Ω·m) could be estimated by multiplying slope (resistance, Ω/m) and cross-sectional area of fibers in Figure 9.

$$\frac{R}{l} = 4.3029\ [\Omega/\text{m}],\ A = 3.846 \times 10^{-9}\ (\text{m}^2) \tag{9}$$

$$\rho = \frac{R}{l} \times A = 1.654 \times 10^{-8}\ [\Omega \cdot \text{m}] \tag{10}$$

Electrical resistances have been measured for single and double ply copper twisted yarns, and tend to be decreased along with number of ply. As shown in Figure 10, single and double ply fibers show 861.2 mΩ and 430.3 mΩ, respectively. As expected, the final HSY showed the resistivity of 430.6 mΩ as same as that of double ply yarns.

Electrical Properties in Frequency Domain

Network Analyzer has been employed in order to analyze electrical properties of samples in frequency domain. Figure 11 shows that 5 cm HSY has 2.51 GHz resonance frequency, -31.2 dB S11, and -10.0 dB S21. 10 cm HSY, however, shows multiple resonance frequencies in the vicinity of 1.17-2.38 GHz. S11 and S21 show -27.6 dB and -13.6 dB, respectively at 1.17 GHz, first resonance frequency (f0). Resonance frequency (f0) is defines as the frequency producing resonance phenomena when intrinsic frequency

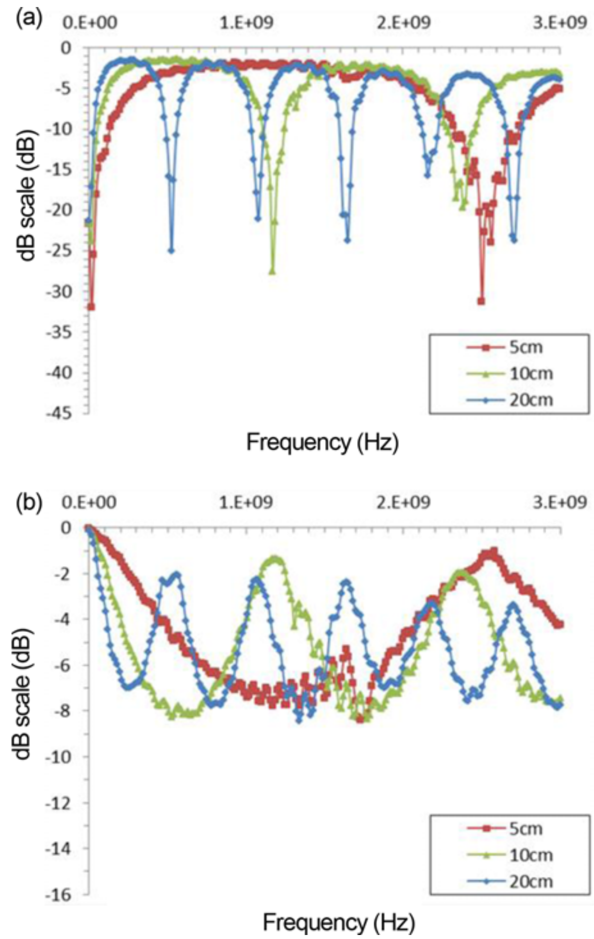

Figure 11. Values of (a) S11, (b) S21 according to frequency and measurement length for finished yarn.

determined by inductance (L), capacitance (C) and applied frequency are same. Resonance frequency (f0) is mathematically defined as follows:

$$\text{f0 (First resonance frequency)} = \frac{1}{2\pi\sqrt{L \cdot C}} \tag{11}$$

For 15 cm, five different resonance frequencies have been found in 0.52 GHz, 1.06 GHz, 1.63 GHz, 2.19 GHz, and 2.70 GHz. In vicinity of 0.52 GHz (f0), S11 and S21 were -25.0 dB and -20.5 dB. There has been found a strong trend of increase in S11 and decrease of S21 in a range of 5-15 cm measurement length. Slight decrease of resonance frequency (f0) was also found along with measurement length.

Analogous to general capacitor theory, PU fiber of TCF would be considered as a sort of dielectrics thus, the length of TCF as A (area) of conductor as well. Capacitance will be increased with increase of the length of TCF, thus resonance frequency will be as follows:

$$C = \frac{\varepsilon \cdot A}{d} = \frac{\varepsilon \cdot l}{d} \tag{12}$$

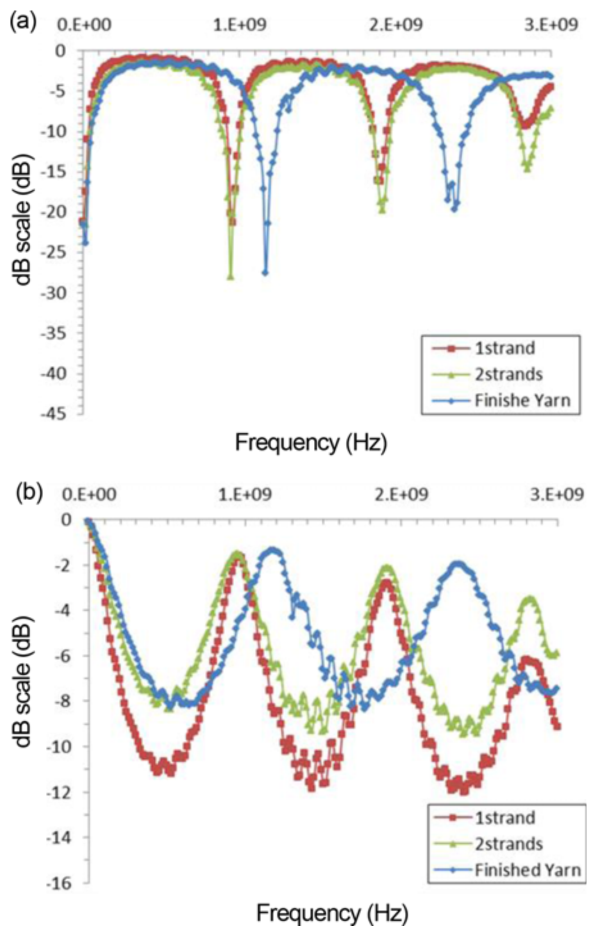

Figure 12. Values of (a) S11, (b) S21 according to frequency and number of strands at 10 cm measurement length.

Figure 12 compares S parameters for 1, 2 strands and finished yarns at 10 cm measurement length, respectively. For 1 strand yarn, resonance frequency (f0) was found in vicinity of 0.94 and 1.91 GHz with S11 of -21.2 dB and S21 of -16.2 dB, respectively. As same as 1 strand yarn, 2 strands yarn revealed Resonance Frequency in vicinity of 0.94 and 1.91 GHz, the S11 value was decreased to -28.0 dB at 0.94 GHz (f0), however, the S21 increased to -15.1 dB. Based on the results, S parameters were affected by electrical resistances of single strand, and number of strands as well. For finished yarn (10 cm), the resonance frequency was shift to 1.17 with S11 of -23.1 dB and S21 of -13.3 dB. It is interesting that the resonance frequency shift to different f0 by PET covered finished yarns. The result could be possibly caused by a slight change of di-electricity thus capacitance for yarn structures. Another interesting feature can be found in the fact that S11 and S21 were similar to 2 strands yarn with only resonance frequency were slightly changed without any significant change of S11 and S21 parameters.

Conclusion

HST for signal transmission was made by combining conductive threads and covering process so that structural characteristics, electrical resistance, resonance frequency and S Parameter were measured in order to study data transmission performances. Resonance frequency shift and worse data transmission rate were found with increase of HST, which is caused by like “area increase” of capacitor structure. Since improvement of transmission rate with number of strands is caused by electrical resistance, S11 and S21 parameters will be resultantly changed according to number of strands. It has been also found that covering process may affect the resonance frequency range through a change of di-electricity. Length and structures of HST may be considered as one of major variables for tailoring the signal transmission characteristics.

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