Preparation and Transmission Characteristics of Hybrid Structure Yarns with Nylon fiber for Smart Wear

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ABSTRACT
Twisted Copper Filaments (TCF) were made by a yarn covering process in order to transmit signals and power for electronic textiles. The 560 denier polyurethane filaments were covered in the S-twist direction by urethane-coated copper wires. Two TCF's twisted in the Z direction were further covered in the S direction by nylon filaments to make final hybrid structure yarns (HSY).The HSY prepared was proportionally increased in apparent resistance and showed resistivity of 1.6210^{-8}Ω·m. The number of ply was critical in terms of resistance variation, showing a linear increase in resistance with ply number. The twist factor, however, was not as significant. Final filaments were found to be changed in resonance frequency mainly due to the change of di-electricity and thus capacitance caused by the nylon covering. It is concluded that while resonance frequency was primarily determined by filament length and dielectric constant of the covering yarns, resonance frequency S11 and S21 were mainly determined by measurement length and ply number.

INTRODUCTION

Recent years have seen rapid development of intelligent materials applicable in the construction of smart garments [1]. A new field of science known as textronics is concerned with the implementation of electro-conductive materials, various types of modern sensors as well as electronic and computer systems in textiles [2]. In short, this area is a combination of textiles, electronics and informatics. The current state of technological advancement in textronics concerns smart clothing prototypes consisting of conventional electronic components connected by transmission lines in the form of conventional wires [3].

However, great effort is being made to replace conventional transmission lines by ones containing a conductive path often made of textile structures placed directly on a flat textile product [4, 5].. In the case of production of longer series this should reduce significantly the cost and increase the reliability of manufacturing intelligent clothing. Such lines may have a path in the form of conductive fibers or yarns supplying power to electronic components, or transmit digital or analog signals. Therefore they are an important part of any textronic system [6].

Currently, there are many opportunities to implement a transmission line into a textile substrate. Along with the fast growth of metal processing and yarn covering processes, copper fibers less than 100 μm diameter twisted with textile fibers with a relatively low cost compared to conductive polymer coated fibers are now commercially available.

The hybrid fibers provide an efficient way of preparing a cost effective data transmission media without any significant loss of the tactile and flexible characteristics of textile fibers [7]. Special interest should be given to balancing and optimizing mechanical characteristics of components such as the covering and core yarns in order to avoid data transmission delays due to the capacitance component introduced [8]. Safarova studied the effect of number of twists on resistivity using a 500μm diameter poly-propylene fiber covered by 8μm stainless steel staple fiber [9]. Tunde Kirstein analyzed resonance frequency and impedance by comparing two different PET and copper wire twisted yarns of 140 and 200 denier. The results showed that thickness of the yarns had a great effect on the di-electricity [10]. Further, Choi investigated the effect of measurement length and ply number on resonance frequency S11 and S21 by using hybrid yarns with two intertwined PET fibers (2D/24F) covered by Ag wire [11].

This study presents an elastic hybrid yarn with a new structure showing 0.01Ω·m conductivity, and investigates DC resistance, resonance frequency, S11, and S21 in order to examine the feasibility of applying to data transmission yarns for wearable devices.

EXPERIMENTAL METHODS

Preparation of Hybrid Structure Yarn (HSY)

560 Denier PU fibers covered by urethane coated copper fiber were prepared by twisting nylon fibers in order to measure electrical characteristics as data transmission media. Because of higher mechanical strength, copper fibers can be treated without the issues associated with silver fibers. Z twist could be incorporated between PU and copper fibers at speeds as high as 12000 rpm.

Nylon fibers (36 filaments and 140 denier) were used for covering those fibers followed by S twisting at 12,000 rpm. The final HSY is shown in *Figure 1.*

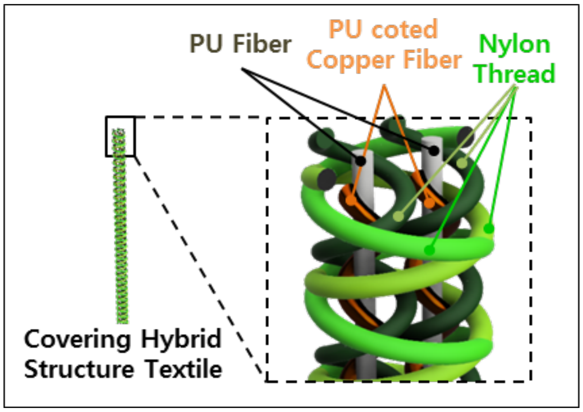

FIGURE 1. Schematics of the Hybrid Structure Textile (HSY).

Various types of samples using HSY have been prepared in order to measure data transmission characteristics. Examples are shown in *Figure 2* and *Figure 3*. *Figure 3(c)* shows in a graphical manner the details of the fibers prepared by the method above.

Geometry of Hybrid Structure Yarn (HSY)

SEM (CX-100S, Semicoxem co.) and optical microscopy (OM) were 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 were separately measured and analyzed for further use. OM was mainly used to examine the twist number, twist angle and contact area the of the copper fibers.

Measurement of Electrical Conductivity

Effect of measurement length on electrical resistance was investigated in order to quantify the transmission characteristics by testing 5, 10, and 20 samples. One and 2 ply yarns of 10 cm length were used in order to compare electrical conductivity.

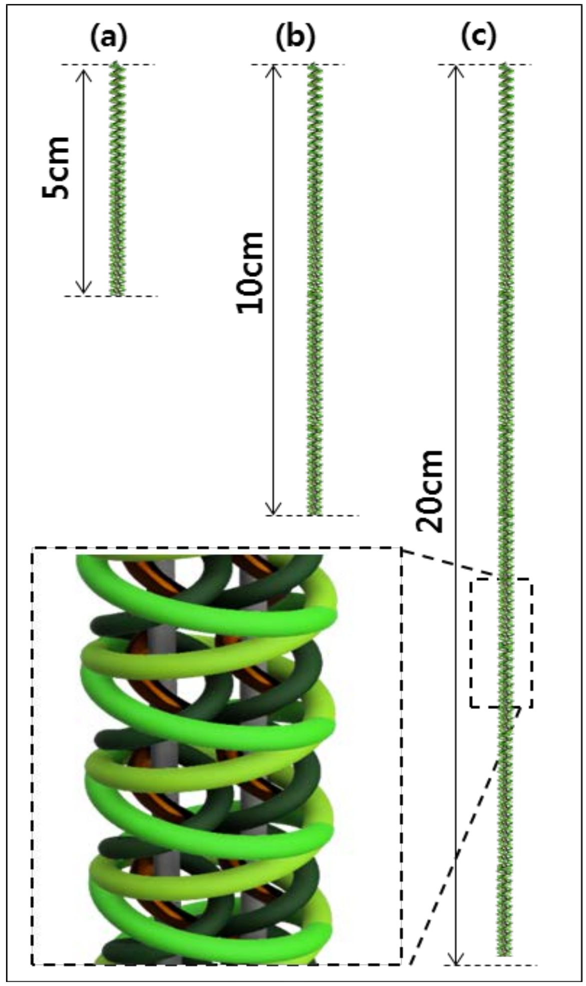

FIGURE 2. Changes in Electrical Conductivity and Signal Transmission Characteristics According to Measurement length ((a) 5cm, (b) 10cm, and (c) 20cm))

Urethane components coated on fiber surfaces were completely removed using DMF in order to ensure electrical contact between fibers and probes. Conductivity measurements were made using the Milliohm Tester (HIOKI 3540 Hi-Tester) shown in *Figure 4.* All samples were treated with silver paste on both ends in order to insure low impedance contacts.

Measurement of Data Transmission Speed

Resonance frequency, S11, and S21 of different lengths were measured using the network analyzer (E5061B, Agilent Co.) shown in *Figure 5* in order to quantify the data transmission characteristics. The effect of number of yarn plies and number of twists was investigated by placing two yarns in parallel on a specially invented fixture as shown in *Figure 6(a).* A Teflon based printed circuit board (PCB) was used after in order to enhance measurement reliability, fixtures with two separate sections for signal and ground were used.

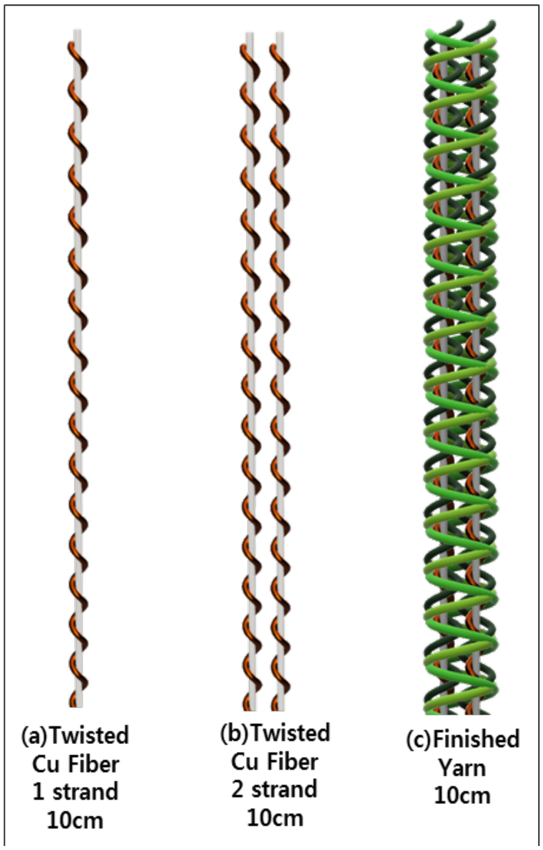

FIGURE 3. Changes in Electrical Conductivity and Signal Transmission Characteristics According to Number of Strands ((a) 1, (b) 2 strands, and (c) Finished Yarn).

FIGURE 4. Conductivity measurement of Conductive Yarns Using a Low Ohm Meter.

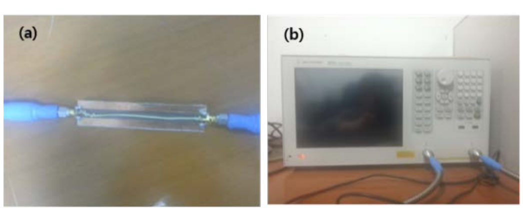

FIGURE 5. Fixture Connection between (a) samples, (b) Network Analyzer

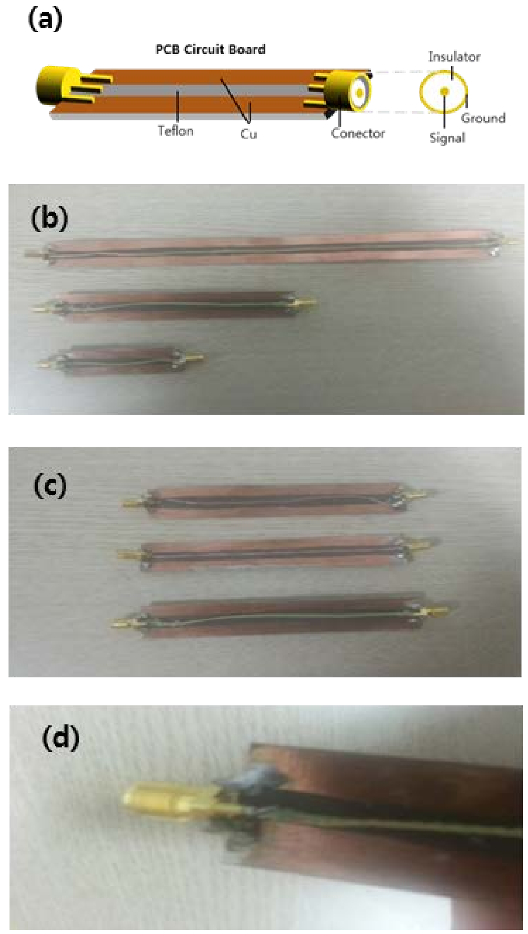

FIGURE 6. Images of (a) Schematics of Fixture, (b) Types of Fixtures, (c) Different Strands, (d) Connection I Details.

RESULTS AND DISCUSSION

Structure of Hybrid Structure Yarn

Figure 7 shows cross-sectional SEM images of urethane coated copper fibers under different magnifications. Pristine and urethane coated copper fibers have diameters of 90µm and 110µm, respectively. In spite of the irregular boundary between copper urethane coated fibers, the average coating thickness was determined to be about 5µm, and thus cross-sectional area (A_{cu}) was calculated to be $6.358\cdot10^{-9}m^2$ by Eq.(1).

$$A_{cu} = \left({}^{d_{cu}}/_{2}\right)^2 \pi \qquad (1)$$

d_{cu} is the diameter and A_{cu} is the cross sectional area of the copper fiber.

According to OM measurements in *Figure 8*, $3.2\cdot 10^{-4}$m diameter PU fiber (d_{pu}) were covered by urethane coated copper fiber every $5.38\cdot 10^{-4}$m (g_t, gap between twist each) or about 47*TP I*(n_{inch}, number of twist per inch) as calculated by Eq.(2).

$$n_{inch} = {}^{0.0254}\!/_{g_t} \tag{2}$$

The circumference of the PU fiber cross sections (C_{pu}) was calculated to be $2.096\cdot 10^{-3}$m by Eq. (3). Total length of copper fibers per 1m in a single ply TCF (l_T) was calculated to be 3.878m by Eq. (4), thus the two ply TCF (l_H) was 7.756m by Eq. (5).

$$C_{pu} = 2\pi \cdot d_{pu} \tag{3}$$

$$l_T = 39.37 \cdot C_{pu} \cdot n_{inch} \tag{4}$$

$$l_H = 2 \cdot l_T \tag{5}$$

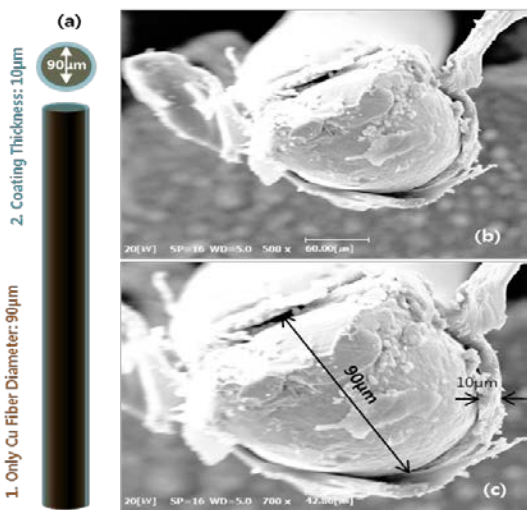

FIGURE 7. SEM Images of PU Coated Copper Fiber, (a) Diagram of Coated Fiber (b) x1k, (c) x500.

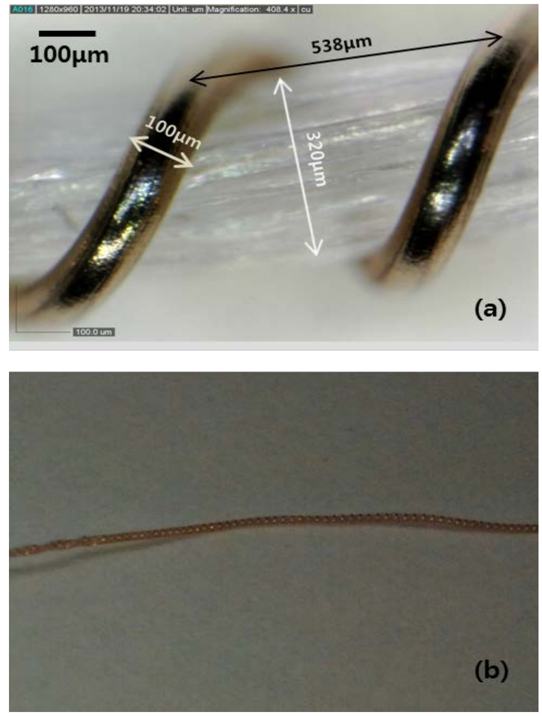

FIGURE 8. Images of (a) Twisted Copper Fiber (x400) and (b) Twisted Copper Fiber (x1).

Electrical Resistance

As shown in *Figure 9*, electrical resistance measured using a digital multi-meter increases from 63.6mΩ to 254.8mΩ over a range of 5~20cm in measurement length. Resistivity (ρ, Ω·m), intrinsic resistance is related to apparent resistance (R, Ω) and conductive fiber structures as follows:

$$\mathrm{R} = \rho \cdot {}^{L}\!/_{A} \tag{6}$$

L is the conductive fiber length and A is the conductive fiber cross-sectional area

The HSY resistivity (ρ_H) is estimated to be $1.62\cdot 09^{-8}$Ω·m by multiplying the slope (S, Ω/m) in *Figure 9* and cross-sectional area of two copper fibers included in one thread of HSY as follows Eq. (7).

$$\rho_H = 2A_{cu} \cdot \mathrm{S} \tag{7}$$

Structural characteristics of a typical HSY are shown in *Table I*.

TABLE I. Characteristics of a Hybrid Structure Yarn.

HSY Structure	1) Core yarn: polyurethane 560D 2) Total TCF Diameter: 100µm (Only Cu fiber Diameter: 90µm + Pu coating thickness: 10µm) 3) Only Cu fiber Cross-sectional area: $6.358 \cdot 10^{-9}$ m^2 4) Covering yarn: Nylon 6_140D/36F
Number of Twist per a meter in a TCF	47TPI = 538µm/a twist
Cu fiber length per 1m of TCF length	3.878m (Cu fiber) / 1m(TCF)
Twisting condition	TCF: Z twist, 1st Covering: S twist, 2nd Covering: Each S and Z twist

Electrical resistance was measured for single and double ply copper twisted yarns, and tends to decrease with number of plies. As shown in *Figure 10*, single and double ply fibers show 254.5mΩ and 127.2mΩ, respectively. As expected, the final HSY showed the resistivity of 127.1mΩ, the same as that of double ply yarns.

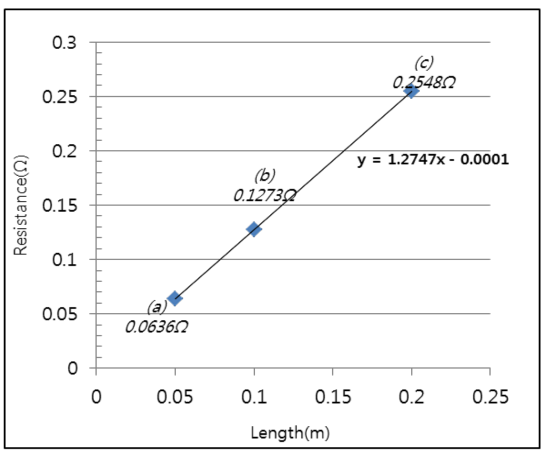

FIGURE 9. Resistance Vs. Measurement Length ((a)5cm, (b)10cm, (c)20cm).

Electrical Properties in Frequency Domain

A network analyzer was to measure electrical properties of samples as a function of frequency. *Figure 11* shows that a 5cm HSY has 2.52GHz resonance frequency, -34.3dB S11, and 2.4dB S21. A 10cm HSY, however, shows multiple resonance frequencies in the vicinity of 1.17~2.42GHz. S11 and S21 show -14.8dB and 3.4dB, respectively at 1.17GHz, first resonance frequency (*f0*). *f0* is defined as the frequency producing resonance phenomena when intrinsic frequency determined from inductance (L), capacitance(C) and applied frequency are the same. f0 is mathematically defined as follows by Eq. (8).

$$f0 = {}^{1}/_{2\pi\sqrt{L \cdot C}} \tag{8}$$

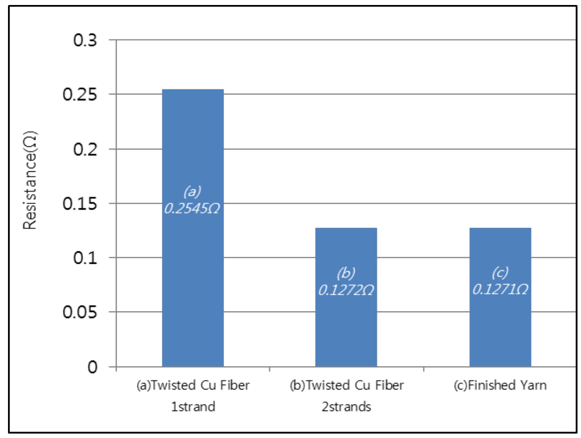

FIGURE 10. Resistance Vs. Number of Strands (a) 1, (b) 2 strands, (c) Finished Yarn.

For 20 cm HSY, five different resonance frequencies were found at 0.49GHz, 1.08GHz, 1.60GHz, 2.21GHz, and 2.73GHz. In the vicinity of 0.52GHz (f0), S11 and S21 were -8.34dB and -4.06dB. There is a strong increase in S11 and decrease in S21 over the range of 5~15cm measurement length. A slight decrease in resonance frequency (f0) was found as a function of measurement length.

According to general capacitor theory, PU fiber of TCF is considered to be a type of dielectric. Thus, the length of TCF as electrode area (A_{el}) acts as a conductor. Capacitance will be increased with an increase in the length of TCF (L_H) and resonance frequency can be calculated using Eq. (9), where d_{el} is the distance between two electrodes and g_{cu} is the gap between the two copper fibers twisted within the HSY and ε is permittivity.

$$C = {}^{\varepsilon \cdot A_{el}}/_{d_{el}} = {}^{\varepsilon \cdot L_H}/_{g_{cu}} \tag{9}$$

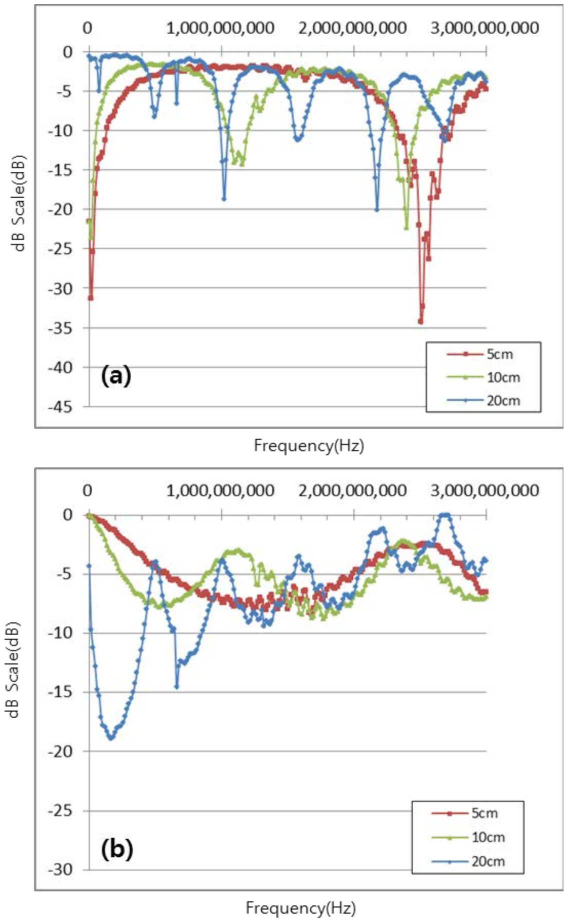

FIGURE 11. Values of (a) S11 (b) S21 According to Frequency and Measurement Length for Finished Yarn.

Figure 12 compares S parameters for the 1 and 2 strand yarns and finished yarns at 5, 10 and 20 cm measurement length, respectively. For 1 strand yarn, the resonance frequency (f0) lies in the vicinity of 0.91 and 2.11GHz with S11 of -8.9dB and S21 of -4.1dB, respectively at 0.91GHz. The 2 strand yarn shows a resonance frequency in the vicinity of 0.91 and 2.11GHz. The S11 value was decreased to -14.6dB at 0.94GHz(f0); however, theS21 increased to -3.2dB. Based on these results, the S parameters were affected by the electrical resistance of single strands, as well as that of multiple strands. For 10 cm finished yarn, the resonance frequency was shifted to 1.15 with S11 of -14.8dB and S21 of -3.44dB.

It is interesting that the resonance frequency shifts to a different f0 for nylon covered finished yarns. This result could be possibly caused by a slight change in di-electricity and thus capacitance for these yarn structures. As the nylon fiber is covered, the permittivity changes. This causes a change in the capacitance and resonance frequency. In the absence of nylon, the dielectric substance between the TCF strands is PU and air. With a nylon covering, the dielectric substance between the TCF strands is a combination of nylon, PU and air. The signal is divided between the two copper strands in the TCF. This affects the phase of the transmitted signal as the capacitances between the copper layers have been changed by the addition of the nylon dielectric. Another interesting feature is the fact that S11 and S21 were similar to 2 strand yarn and resonance frequency was only slightly changed without any significant change in the S11 and S21 parameters.

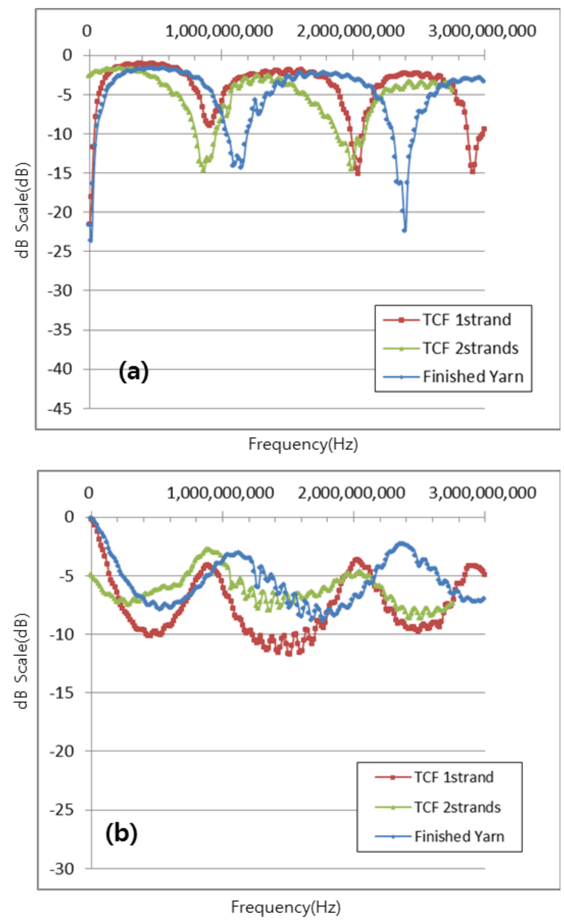

FIGURE 12. . Values of (a) S11 (b) S21 According to Frequency and Number of Strands at 10cm measurement length.

CONCLUSION

HSY for signal transmission was made by combining conductive threads with a covering process. The structural characteristics, electrical resistance, resonance frequency and S parameter were measured in order to study data transmission performances.

Resonance frequency shifts and lower data transmission rate were found with increasing length of HSY. This is caused by an "area increase" in capacitor structure. Since improvement in the transmission rate with number of strands is a result of decreasing electrical resistance, the S11 and S21 parameters will change as a function of the number of strands. The covering process may affect the resonance frequency range through a change in dielectricity. Length and structure of HSY are important variables for tailoring the signal transmission characteristics.

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