Embroidered Wearable Multiresonant Folded Dipole Antenna for FM Reception

Jung-Sim Roh, Yong-Seung Chi, Jae-Hee Lee, Youndo Tak, Sangwook Nam, *Member, IEEE*, and Tae Jin Kang

***Abstract*—A wearable textile antenna with multiple resonance frequencies is proposed for the reception of FM signals using conductive embroidery of metal composite embroidery yarn (MCEY) on a polyester woven substrate. This embroidered FM antenna comprises five individual folded dipoles connected in parallel so that the bandwidth can be broadened *via* multiple resonances. The MCEY embroidered multiresonant folded dipole (MRFD) antenna is attached to a jacket, stretched from the left forearm, over the shoulder, and to the right forearm. The proposed antenna provides a wide operating band of 80.5 MHz to over 130 MHz at 5 dB return loss regardless of the arm movements, satisfying the FM broadcast band (87.5–108 MHz). The gain of this body-worn antenna is in the range of −7.08 to −15.79 dBd in the FM broadcast band regardless of the arm movements.**

***Index Terms*—Embroidered antenna, FM antenna, metal composite embroidery yarn (MCEY), multiresonant folded dipole (MRFD) antenna, wearable textile antenna.**

I. INTRODUCTION

WEARABLE textile antennas, combined with the rapid progress of the fabrication technologies of conductive fibrous materials in recent years, have shown enormous potential in creating new flexible and conformable smart structures. Because textile antennas ensure wearing comfort thanks to their flexibility, conformability, and alleviated weight load despite inhomogeneity of the substrate, research on smart interactive textile systems has focused on wearable textile antennas. The potential applications of textile antennas are diverse, ranging from medical applications to protective, military, and space applications. A variety of microstrip patch antennas [1]–[5] that are composed of a conductive patch and ground plane of metal-coated woven fabric and nonconductive fabric substrate have been developed for far-field communication, usually operating in the 2.4-GHz ISM band. Several spiral wideband antennas [6], [7] have also been developed using metal-coated woven fabric, metal printing, or embroidery of metal-coated polymer yarn. For near-field communications, a spiral inductor [8] and multi-turn loop antennas [9], [10] have been developed using metallic yarns. However, the fabrication methods of these linear-type circuits had considerable limitations in forming a precise circuit promptly.

As the characteristics of body-worn antennas are greatly affected by human proximity [11] and motion [12], broadband antennas would operate well as a wearable antenna, irrespective of the presence of a human body. Bow-tie dipole and flare dipole printed on a flexible FR-4 substrate [11] have been developed as a body-worn broadband antenna. Such antennas can also be constructed using conductive textile materials such as metal-coated fabrics or metal-coated yarns. However, the conductivity of metal-coated textile materials is lower than conventional printed circuit board (PCB). Also, they are prone to damage by bending, stretching, and abrasion. Furthermore, it is difficult to construct a homogeneous conducting plane by embroidering with metal-coated yarns.

In this letter, as a wearable broadband antenna operating at the FM broadcast band (87.5–108 MHz) with optimal wearing comfort and durability, we introduce an embroidered textile antenna using metal composite embroidery yarn (MCEY). The MCEY consists of three strands of Ag-copper filaments [13] and forms a linear circuit structure by embroidery on a textile substrate. The resulting circuit is capable of being embedded unnoticeably in smart textile systems. MCEY embroidered multiresonant folded dipole (MRFD) antenna circuits may also be used as heating units to keep the wearer warm in cold environments.

II. ANTENNA DESIGN AND FABRICATION

As the human body has a very high relative permittivity, the presence of a human body close to an antenna reduces antenna efficiency and lowers the resonance frequency. These values can drop by 15% to 25% [12] compared to that measured in free space, depending on the distance between the antenna and the body. Furthermore, the movement of the body deforms the spatial geometry of the body-worn antenna and affects the performance of the antenna. Thus, a wearable embroidered FM antenna should be designed to be wider than the FM broadcast band (about 87–130 MHz) not to suffer from the detuning caused by the presence of the human body.

A folded dipole antenna is well known for its inherent wideband characteristics and, thus, is very popular for reception of FM and TV broadcast signals [14]. Before the actual MCEY embroidered MRFD antenna was produced, four types of dipole antennas—i.e., a folded dipole, bow-tie dipole,

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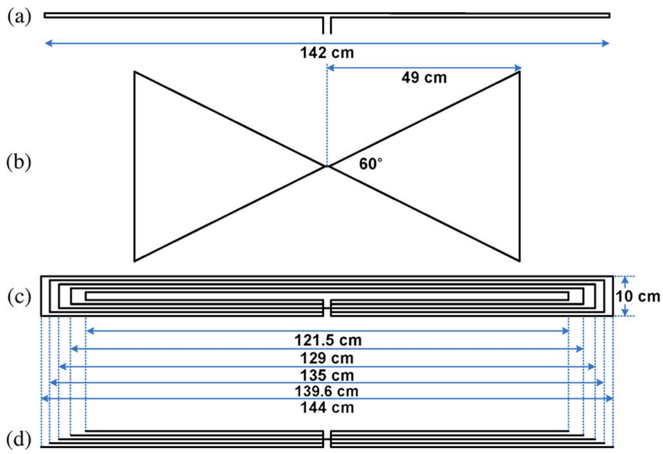


Fig. 1. Geometry of the four simulated antennas: (a) folded dipole antenna, (b) bow-tie dipole antenna, (c) five-folded dipole antenna, and (d) five-finger dipole antenna.

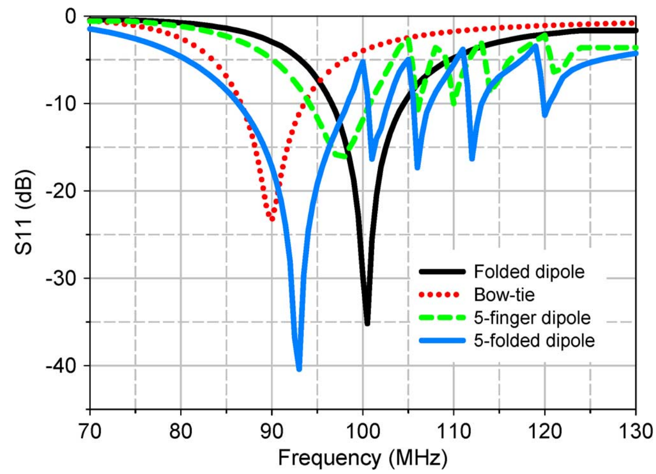


Fig. 2. Reflection coefficient simulation of the four dipole antennas for FM reception.

five-folded dipole, and five-finger dipole—were designed and simulated using FEKO with reference impedances of 300, 50, 268, and 75 Ω, respectively. The MCEY includes three strands of Ag-coated copper filaments (∅: 0.040 mm) and three strands of polyester yarns (83 dtex, where dtex is a unit of the linear density of a continuous filament or yarn equal to the weight in grams of 10 km of the material) to prevent the metal filaments from extending and breaking during the embroidery process [Fig. 3(a)]. Its dc resistance, total linear density, and thickness were 3.88 Ω/m, 590 dtex, and 0.3 mm, respectively. To simplify the simulation, a copper filament with 0.3 mm diameter was substituted for the actual MCEY embroidered line.

Fig. 1 shows the geometry of the four simulated antennas. The folded dipole antenna had 142 cm dipole length and 1 cm separation distance, designed to resonate at 100 MHz. The bow-tie dipole antenna had 60° width and 98 cm length, designed to resonate at 90 MHz. The five-folded dipole antenna was comprised of five individual folded dipoles, designed to resonate at 92.5, 102, 106, 113, and 118 MHz, and the dipole lengths of the individual folded dipole components were 144, 139.6, 135, 129, and 121.5 cm, respectively. By connecting five different folded dipoles in parallel on the same plane, the bandwidth can be broadened *via* multiresonance. Maximum separation distance between two lines of the outermost folded dipole was 10 cm, and the distance between each folded dipole element was 1 cm. For the five-finger dipole antenna, the dipole lengths and separation distances were identical to those of the five-folded dipole antenna. Fig. 2 and Table I present the simulation results of the four antennas, where the multiresonant five-folded dipole antenna shows the largest bandwidth and the highest return loss.

Thus, to produce a wearable antenna that operates in the FM broadcast band, i.e., an antenna with a return loss better than 5 dB at the operating frequency region 87.5–108 MHz, a MRFD antenna with five different folded dipoles was embroidered onto a polyester woven substrate ($\varepsilon_r = 1.15$ at 10 MHz). In the embroidery process, the MCEY was used as the lower thread with 3-mm running stitches [Fig. 3(b)]. When compared to the simulated results, the resonance frequencies of the MCEY embroidered MRFD antenna dropped about 3 MHz to 8 MHz.

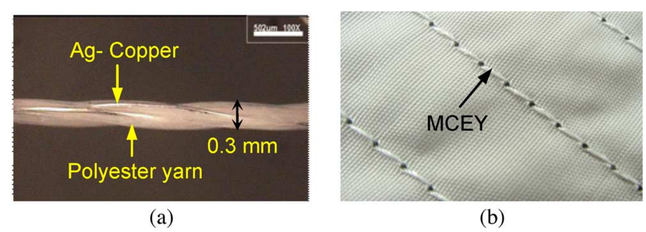


Fig. 3. Structures of (a) the MCEY and (b) embroidered line using the MCEY as a lower embroidery.

TABLE I
SIMULATION RESULTS OF THE ANTENNA CHARACTERISTICS OF THE FOUR DIPOLE ANTENNAS

Parameters \ Antenna type	Folded dipole	Bow-tie dipole	5-folded dipole	5-finger dipole
Max. S11(dB)	-35	-23.4	-40	-16
BW_{5dB} (MHz)	17	14.5	29	13.5

Therefore, the lengths of the folded dipole elements in the MCEY embroidered antenna were shortened to compensate for the frequency drop. The individual folded dipole components in the final antenna were determined to be 144, 129, 125.2, 117.2, and 108.6 cm, and the actual MCEY embroidered MRFD antenna is shown in Fig. 4. FEKO simulation, where the matching impedance was calculated using Agilent Technologies' Advanced Design System (ADS) software, gave input impedance of 268 Ω. A 1:4 balun with 75 Ω input impedance at frequency range 50 ∼ 800 MHz (DXP2ABN7514TL, MurataTM) was used to link the unbalanced signal from a network analyzer to the balanced antenna circuits, and vice versa. The 300-Ω input impedance of this balun was matched to the 268-Ω input impedance of the antenna using a lumped *LC* circuit.

III. MEASUREMENTS

The MCEY embroidered MRFD antenna was attached to a jacket symmetrically, stretching from the left forearm to

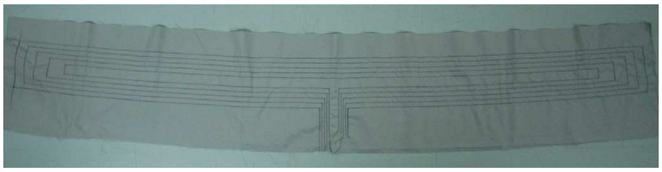
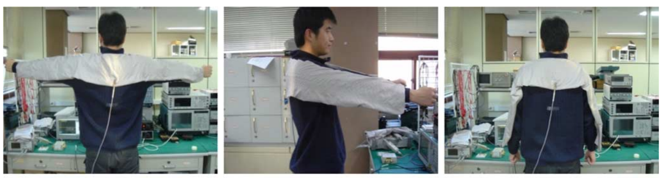


Fig. 4. MCEY Embroidered five-folded dipole antenna.



(a) (b) (c)

Fig. 5. Photographs of the body-worn embroidered antenna with different arm postures: (a) arms outstretched, (b) arms forward, and (c) arms down.

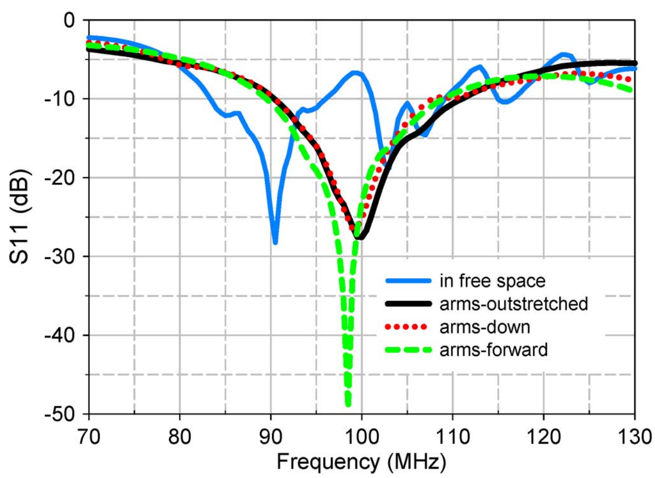


Fig. 6. Reflection coefficient measurement of the MCEY embroidered MRFD antenna both in free space and on the subject with different arms postures.

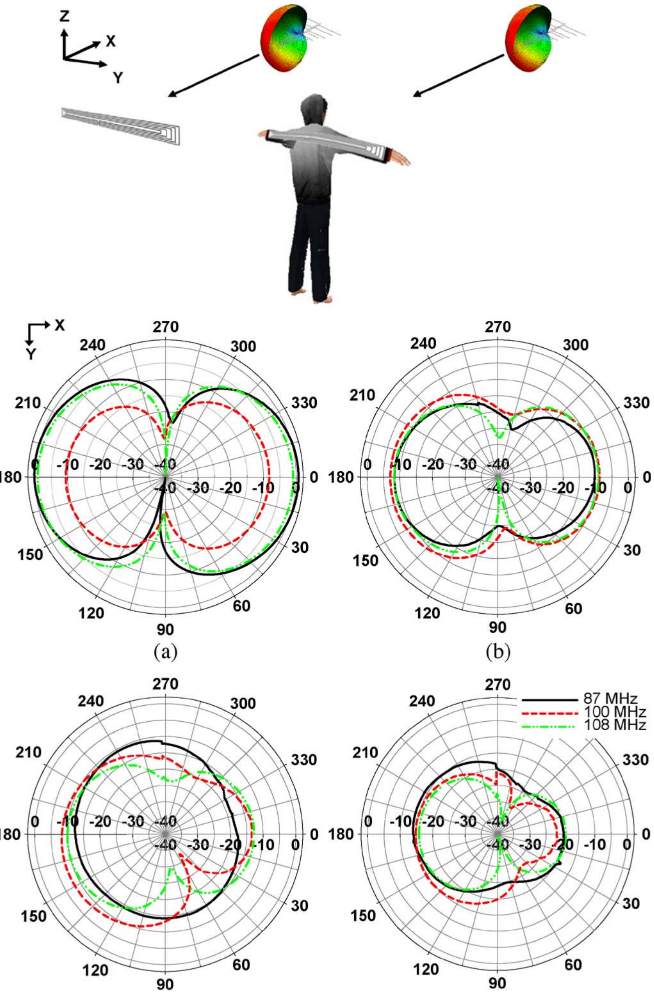


Fig. 7. Radiation patterns of MCEY embroidered MRFD antenna (a) in free space, (b) with arms outstretched, (c) with arms forward, and (d) with armsdown on the subject.

TABLE II
ANTENNA CHARACTERISTICS OF THE MCEY EMBROIDERED MRFD ANTENNA

Para -meters	In free space		On a human body		
	Simulation	Measurement	Arms outstretched	Arms down	Arms forward
Max. S11(dB)	-40	-28.2	-27.6	-26.6	-49.3
BW_{5dB} (MHz)	29 (80-109)	41.5 (79.5-121)	>50MHz (77.5-)	>50MHz (78.5-)	>50MHz (80.5-)

the right forearm by passing over the shoulder of the jacket. Reflection coefficient was measured in free space as well as on the subject with three different arm postures, i.e., arms-outstretched, arms-forward and arms-down (Fig. 5), and the bandwidth was evaluated at 5 dB return loss ($\mathrm{BW}_{5\ \mathrm{dB}}$). The reference impedance for reflection coefficient measurement was 75 Ω.

To measure radiation patterns and gains, a log-periodic dipole array (LPDA) transmitting antenna and a standard dipole antenna were used. Radiation patterns of the antenna were measured at 87, 100, and 108 MHz.

A. *Resonance Frequency, Return Loss, and Bandwidth*

Fig. 6 shows reflection coefficient measurement (S11) of the MCEY embroidered MRFD antenna. Six resonance frequencies—i.e., 90.5, 94, 103, 107, 116, and 125 MHz—were observed in free space, five of which were originally intended. An unexpected resonance peak (90.5 MHz) that seemed to have resulted from the antenna matching circuit was also observed. The maximum return loss of MCEY FM antenna in free space was 28.2 dB at 90.5 MHz. The bandwidth at 5 dB return loss was 41.5 MHz, from 79.5 to 121 MHz in free space (Table II).

When the MCEY embroidered MRFD antenna was worn by the subject, multiresonance peaks of S11 were merged into one due to human body losses. The S11 resonance frequency appeared near the center of the operating frequency and was not strongly dependent on the arm postures (Fig. 6). The small resonance peaks observed at 103 and 107 MHz in free space shifted to the center of the operating frequency when on the subject with better impedance matching due to the body loss. The human body also had a bandwidth widening effect, where the effect was larger when the antenna was in closer contact with the body. The highest maximum return loss and lowest resonance frequency

TABLE III
MAXIMUM GAIN OF MCEY EMBROIDERED MRFD ANTENNA

Antenna's location	arm movement	Gain (dBd)		
		87 MHz	100 MHz	108 MHz
In free space	-	0.68	-8.26	-0.89
on a human body wearing a jacket	Outstretched	-8.33 (-10.37)	-7.08 (-8.82)	-8.28 (-9.13)
	Forward	-10.73	-8.06	-10.01
	Down	-13.87	-14.52	-15.79

was attained with the subject arms forward. In this position, the MCEY embroidered antenna was in close contact with the subject's back (Table II).

B. Radiation Pattern and Gain

In free space, the MCEY embroidered MRFD antenna showed a toroidal radiation pattern where the axis of the toroid centered about the folded dipoles [Fig. 7(a)]. The maximum gains of MCEY FM antenna at 87, 100, and 108 MHz were 0.68, -8.26, and -0.89 dBd, respectively (Table III).

With the presence of a human body, the radiation efficiency was reduced. When the subject's arms-outstretched, the maximum gain further dropped about 8 dB than that measured in free space. Because the antenna was located on the backside of the subject, the gain pattern was smaller when the subject was facing the transmitting antenna (at 0°) compared to when he had his back turned to it (at 180°). The numbers given in parentheses in Table III represents the maximum gain with the subject facing the transmitting antenna.

As expected, the arms postures considerably affected the radiation pattern and gain. With the subject's arms outstretched, the MCEY embroidered MRFD antenna can be considered a straight half-wave folded dipole antenna. But with the subject's arms stretched forward or straight down, i.e., when both ends of the antenna are bent almost 90° and in closer contact with the body, the radiation pattern got out of the well-proportioned donut shape and the gain further dropped. When the arms are moved, the antenna radiates in different polarization. With the arms down, part of the energy was radiated on a vertical polarization, showing the lowest gain, where the maximum gain dropped about 7 dB from that with the arms outstretched (Table III).

IV. CONCLUSION

An embroidered wearable multiresonant folded dipole (MRFD) antenna for FM signal reception using machine embroidery of metal composite embroidery yarn (MCEY) was studied. This MRFD antenna offers optimal wearing comfort, precise and prompt design variability, and simple, eco-friendly processes. The multiresonance peaks produced by the five different folded dipoles of the antenna effectively broadened the operating bandwidth, providing a wide operating band at 5 dB return loss ranging from 80.5 to over 130 MHz, irrespective of the arm movement. When the arms were moved, the antenna radiated different polarization, showing a deformed toroidal radiation pattern, and the gain of the antenna was in the range of -7.08 to -15.79 dBd. The results suggest the feasibility of the MCEY embroidered wearable RF engineering textile systems.

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