

Ning LIU, Yinghua LU, Sihai QIU, Peng LI

Electromagnetic properties of electro-textiles for wearable antennas applications

© Higher Education Press and Springer-Verlag Berlin Heidelberg 2011

Abstract Wearable, textile-based antennas get more and more attention for body-centric communications because it could be easily worn on body and integrated into clothes. Electro-textiles (e-textiles) are used as antenna patch and ground plane. The electromagnetic properties of the textiles play important roles in antenna design and performance. This paper focuses on the study of the electromagnetic properties of e-textiles for wearable antennas applications and mainly discusses the electromagnetic properties of e-textile cell and the influences of different woven densities and different e-textile materials to antenna performances. Simulation and measurement results show that if the e-textiles adopt woven pattern, then when the distance between two conductive fibers is within 2 mm, the e-textiles could be regarded as metal plane to design antennas. In addition, the results show that metal-plated woven fabric could be used as metal plane to design antennas, while non-woven fabric shows distinct differences.

Keywords wearable antenna, electro-textile (e-textile), electromagnetic properties

easily worn on body and integrated into clothes. The electromagnetic properties of e-textiles play important roles in antenna design and performance. In Ref. [6], Ouyang et al. proposed a waveguide-based cavity method to measure the high-frequency properties of e-textiles. In Ref. [7], Banaszczyk et al. discussed the current distribution within woven e-textile sheets using a computer program. They took the conductivity of the fibers, the contact resistance between the fibers, the contact angle between the fibers and the electrodes, and the size and the aspect ratio of the textile sheets into account. However, the inductance is not discussed. In Ref. [8], Ouyang et al. compared two different e-textile antennas made of the same e-textile material but of different structures. To the best of our knowledge, in this area, no published paper has been found in China yet. This paper focuses on the study on the electromagnetic properties of e-textiles for wearable antennas applications, mainly studies the electromagnetic properties of e-textile cell, and calculates the basic resistance and inductance in a grid as well as discusses the influences of different woven densities and e-textile materials to antenna performances.

1 Introduction

Electro-textiles (e-textiles) have appeared for a period of time; however, they are mainly used as electromagnetic shielding materials [1]. In recent years, as the development of the fourth generation of mobile communications (4G), wearable antennas, especially textile antennas, get more and more attention [2–5]. E-textiles are used as antenna patch and ground plane, while non-conductive textiles constitute antenna substrate. This type of antenna could be

2 Study on electromagnetic properties of e-textile cell

In general, there are two main methods that could render a textile material electrically conductive: 1) by applying a conductive coating on the surface of a non-conductive textile after it is formed and 2) by incorporating conductive fibers (e.g., via interweaving or via embroidery) into the textile structure. Any textile structure, including knitted, woven, or non-woven textiles, can be thus made electrically conductive [6,8–10].

Because the textile adopting woven pattern has more intersections and is tighter, which means less distances between metal grids, as shown in Fig. 1, it is adopted in this paper to study the electromagnetic properties of e-textiles.

We assume that the e-textiles are woven pattern, with

Received May 25, 2011; accepted August 8, 2011

Ning LIU (✉), Yinghua LU, Sihai QIU, Peng LI
School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China
E-mail: nliu@bupt.edu.cn



Fig. 1 Woven pattern of fabric

woven density N ppi, and the conductive fibers are made of copper, with diameter of $80\ \mu\text{m}$. In this case, the distance between two conductive wires could be expressed as

$$d = \frac{25.4 - 0.08N}{N - 1} \text{ mm.} \quad (1)$$

The calculated distances between conductive fibers at different woven densities could be seen in Table 1.

Table 1 Distances between conductive fibers at different woven densities

N	$d/\mu\text{m}$
20	1253
50	437
100	176
150	90

Wearable antennas are often used in the ISM band, especially 2.4 GHz, so we take $f = 2.4$ GHz into account. While $f = 2.4$ GHz, $\lambda = c/f = 125$ mm, at this time $\lambda/10 = 12.5$ mm, the electrical dimensions of the e-textile cells are electrical small, so we should construct lumped-parameter electric circuit models.

As described above, if we take the woven density $N = 50$ ppi, the distance between conductive fibers is $d = 437\ \mu\text{m}$. The skin depth of copper at 2.45 GHz is $\delta = 1/\sqrt{\pi f \mu_0 \sigma} = 1.35 \times 10^{-6}$ m ($\sigma = 5.8 \times 10^7$ S/m, $\epsilon_r = 1$, $\mu_r = 1$). At this time, $r_w/\delta \approx 30$ (r_w is the radius of the conductive fiber).

According to the formula used to calculate the per-unit-length resistance of solid wire [11],

$$r_{\text{hf}} = \frac{1}{2r_w} \sqrt{\frac{\mu_0}{\pi\sigma}} \sqrt{f} \quad (r_w \gg \delta). \quad (2)$$

We could get that the per-unit-length resistance of the fiber is $4.54 \times 10^4\ \Omega/\text{m}$.

Consider higher frequencies where $r_w > 2\delta$, the per-unit-length external inductance is larger than the per-unit-length internal inductance by a factor of 10, and above this

frequency, the difference increases since the external inductance remains constant with increasing frequency, but the internal inductance decreases as $1/\sqrt{f}$. Consequently, the impedance of the internal inductance is usually much smaller than the impedance of the external inductance, and we may therefore neglect the internal inductance in the model.

Assuming that the two wires are separated sufficiently ($s/r_w > 5$) (s is the distance between the two wires), according to the formula that is used to calculate the per-unit-length external inductance of two parallel wires [11],

$$l = \frac{\mu_0}{\pi} \ln \frac{s}{r_w} \text{ H/m.} \quad (3)$$

We could get that the per-unit-length inductance is 0.76 H/m.

As discussed above, the resistance in a grid length is $R = 19.8\ \Omega$, while the inductance is $L = 330\ \mu\text{H}$.

3 Influences of different woven densities to antenna performances

To study the influences of different woven densities to antenna performances, we use a full-wave electromagnetic simulation software HFSS based on FEM to simulate antennas consisted of metal grids at different woven densities. We simulated metal plane antenna, 0.5-mm-long grid antenna, 1-mm-long grid antenna, 1.5-mm-long grid antenna, and 2-mm-long grid antenna, respectively [12]. The results of return loss and radiation with different woven densities are shown in Figs. 2 and 3 and Table 2.

From the simulation and comparison above, we could see that if the e-textiles adopt woven pattern, then when the grid length is less than 2 mm, and the bandwidth, radiation pattern, and radiation efficiency are nearly the same as the metal plane antenna; however, when the grid length

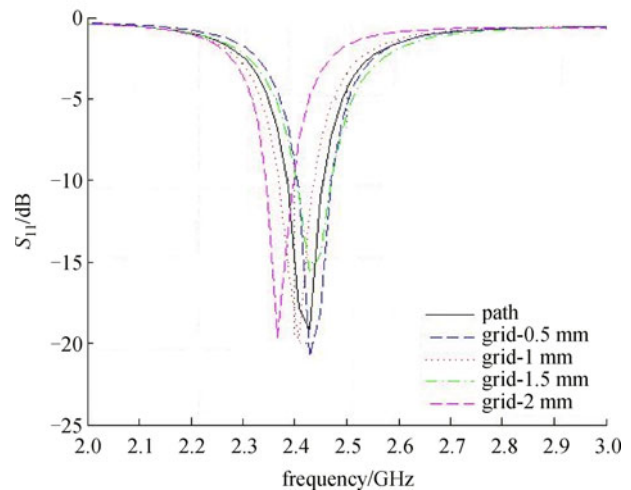


Fig. 2 S_{11} of different antennas

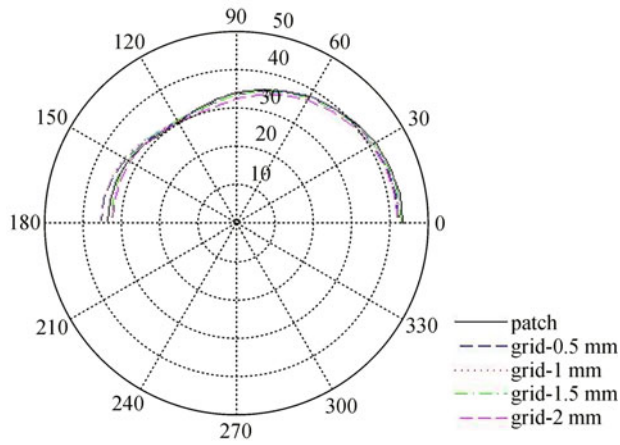


Fig. 3 Radiation pattern of different antennas

Table 2 Radiation efficiency comparison of different antennas

antenna pattern	radiation efficiency/%
metal plane antenna	49.9
0.5-mm-long grid antenna	45.4
1-mm-long grid antenna	45.1
1.5-mm-long grid antenna	45.3
2-mm-long grid antenna	39.2

reaches 2 mm, there is an obvious offset in the frequency band as well as decreased radiation efficiency.

4 Influences of different e-textile materials to antenna performances

To study the influences of different e-textile materials to antenna performances, we adopt four different materials to design and fabricate four microstrip patch antennas [12]. All the geometry parameters of the four antennas are the same, and FR-4 with relative permittivity of 4.4 is used as the substrate, while copper is used as the ground plane. Copper, Nora (Ni/Cu/Ag-plated Nylon fabric with surface resistance $< 0.03 \Omega/m^2$ and total thickness 0.1 mm nominal), Kassel (Cu/Ag-plated Nylon fabric with surface resistance $< 0.03 \Omega/m^2$ and total thickness 0.110 mm nominal), and Koln (Cu-plated Nylon non-woven fabric with surface resistance $< 0.02 \Omega/m^2$ and total thickness 0.25 mm nominal) are adopted as the antenna patch, respectively. The four fabricated antennas are shown in Fig. 4.

We measure the four antennas using a vector network analyzer HP 8752C, and the results are shown in Table 3.

From the above comparison and analysis, we could see

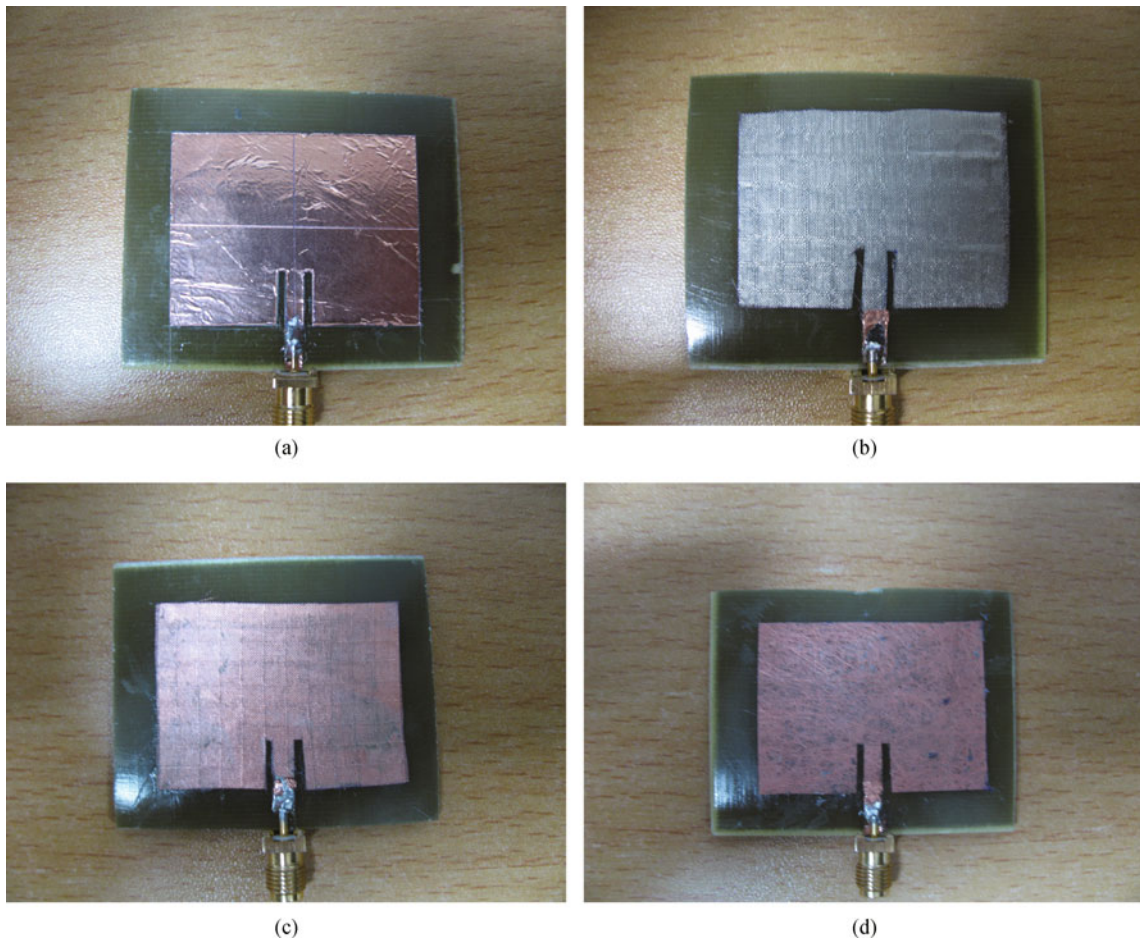


Fig. 4 Antennas using different patches. (a) Metal patch antenna; (b) antenna using Nora; (c) antenna using Kassel; (d) antenna using Koln

Table 3 Performances comparison of antenna adopting different e-textile materials

antenna pattern	bandwidth/GHz	central frequency/GHz
metal patch antenna	2.51–2.56	2.53 (–13.2 dB)
antenna using Nora	2.56–2.61	2.59 (–12.3 dB)
antenna using Kassel	2.48–2.54	2.51 (–14.9 dB)
antenna using Koln	2.71–2.79	2.75 (–15.9 dB)

that the antenna adopting Cu/Ag-plated Nylon fabric e-textile shows the most similar performance to the metal patch antenna, while the antenna adopting Ni/Cu/Ag-plated Nylon fabric also shows similar performance to the metal patch antenna; however, the antenna adopting Cu-plated Nylon non-woven fabric has distinct difference from the metal patch antenna.

5 Conclusion

This paper studies the electromagnetic properties of e-textiles for wearable antennas applications and mainly focuses on the influences of different woven densities and materials to antenna performances. According to the analysis and experiments mentioned above, we could conclude that if the e-textiles adopt woven pattern, then when the distance between two conductive fibers is within 2 mm, we could regard e-textiles as metal plane to design antennas. In addition, metal-plated woven fabric could be used as metal plane to design antennas, while non-woven fabric shows distinct differences.

Acknowledgements This work was supported by the National Natural Science Foundation of China (Grant No. 61072136) and the Specialized Research Fund for the Doctoral Program of Higher Education of China (No. 200700130046).

References

- Guy A W, Chou C-K, McDougall J A, Sorensen C. Measurement of shielding effectiveness of microwave-protective suits. *IEEE Transactions on Microwave Theory and Techniques*, 1987, 35(11): 984–994
- Locher I, Klemm M, Kirstein T, Troster G. Design and characterization of purely textile patch antennas. *IEEE Transactions on Advanced Packaging*, 2006, 29(4): 777–788
- Kennedy T F, Fink P W, Chu A W, Champagne N J, Lin G Y, Khayat M A. Body-worn e-textile antennas: The good, the low-mass, and the conformal. *IEEE Transactions on Antennas and Propagation*, 2009, 57(4): 910–918
- Hertleer C, Rogier H, Vallozzi L, Van Langenhove L. A textile antenna for off-body communication integrated into protective clothing for firefighters. *IEEE Transactions on Antennas and Propagation*, 2009, 57(4): 919–925
- Zhu S, Langley R. Dual-band wearable textile antenna on an EBG substrate. *IEEE Transactions on Antennas and Propagation*, 2009, 57(4): 926–935
- Ouyang Y, Chappell W. Measurement of electrotexiles for high frequency applications. In: 2005 IEEE MTT-S International Microwave Symposium Digest. 2005, 1–4
- Banaszczyk J, De Mey G, Schwarz A, Van Langenhove L. Current distribution modelling in electroconductive textiles. In: Proceedings of the 14th International Conference on Mixed Design of Integrated Circuits and Systems. 2007, 418–423
- Ouyang Y, Karayianni E, Chappell W J. Effect of fabric patterns on electrotile patch antennas. In: Proceedings of 2005 IEEE Antennas and Propagation Society International Symposium. 2005, 2B: 246–249
- Ouyang Y, Chappell W J. High frequency properties of electrotexiles for wearable antenna applications. *IEEE Transactions on Antennas and Propagation*, 2008, 56(2): 381–389
- Quirk M M, Martin T L, Jones M T. Inclusion of fabric properties in the e-textile design process. In: Proceedings of International Symposium on Wearable Computers. 2009, 37–40
- Paul C R. Introduction to Electromagnetic Compatibility. 2nd ed. New York: Wiley, 2006, 328–336
- Balanis C A. Antenna Theory: Analysis and Design. 2nd ed. New York: Wiley, 1996, 727–751