Radiation Patterns of an RF Energy Harvesting Necklace on Human Body Phantom

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***Abstract*— The far-field electromagnetic radiation patterns of different dipole antennas used for an RF energy harvesting necklace for smart jewelry are studied. Rigid Vee, U-shaped copper and flexible silver-ink dipoles are explored with and without a human body phantom. Measurements demonstrate the advantages of Vee or U-shaped dipoles for harvesting more RF energy at the sides of the human body compared to a straight dipole. The flexible RF energy harvesting necklace can produce 72.2 µW at 5.3 m from a 3 W EIRP 915 MHz RF transmitter when worn by a person.**

Keywords—Radiation patterns; energy harvesting; Vee dipole; U-shaped dipole, RF antenna.

I. Introduction

Energy harvesting and wireless power transfer, when used for wearable devices, allow wearables to operate without the need of bulky batteries. An emerging category of wearables is smart jewelry incorporating embedded health tracking and energy harvesting. Recent papers have focused on the transducers and power management circuits of energy harvesting systems for smart jewelry, e.g., [1] proposes a bracelet with a pulse-oximeter sensor powered by flexible solar panels. Other work [2] and [3] used RF energy transfer to power bracelets through integrated flexible antennas. RF energy harvesting using a necklace was introduced in [4], which tested a rigid copper U-shaped dipole antenna with a complete power management circuit on a paper mannequin. A flexible silver-ink printed dipole using a polyvinylidene fluoride (PVDF) thin film was developed for hybrid RF and vibration energy harvesting in [5]. However, the influence of the necklace antenna radiation patterns on RF energy harvesting has yet to be studied.

This work investigates the design and implementation of specific dipoles with a resonant frequency of 915 MHz for remote powering of a wearable smart necklace. An important part of this study is to accurately characterize the radiation patterns of copper Vee , U-shaped and flexible silver ink PVDF dipoles. The effect of a user's body on the antenna pattern is studied using 3D EM simulations and anechoic chamber measurements on an equivalent human phantom. The antenna design for a necklace is introduced in Section II. Section III shows the design of the human phantom and antenna measurements without and with the phantom. Finally, Section IV reports conclusions from this work.

II. Antenna Design

Vee and U-shaped dipoles for the necklace shown in Fig. 1 were designed based on a prototype linear dipole with a fixed

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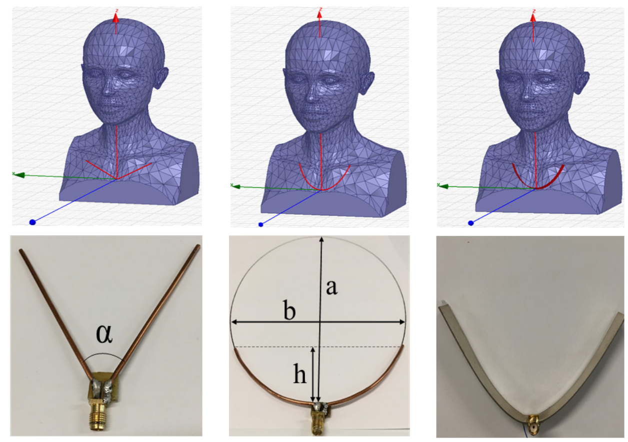


a. Vee Dipole **b. U-shaped Dipole** **c. Flex Dipole**

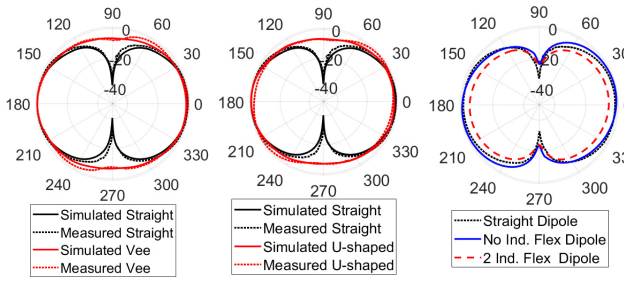
Fig. 1. Vee, U-shaped, and flex dipoles with simulated human bodies.

length of 15.7 cm to obtain a resonant frequency of 915 MHz. All of the dipoles have the same wire diameter of 2.06 mm. The Vee dipole in Fig. 1.a. is formed from two straight copper wires with various angles **α** changed from 30 to 150 degrees. The next evolution of this design, which is more ergonomic for a human wearer, is a U-shaped dipole. These U-shapes are formed from partial curves of ellipses with varying semi-major and semi-minor axes, ***a*** and ***b***, respectively in Fig. 1.b. The height ***h*** of the U-shaped dipole is adjusted so that the arc length is constant.

To improve the flexibility of the necklace, [5] proposes a flexible silver-ink U-shaped dipole. The flex dipole is fabricated from the silver top and bottom electrodes of a sandwiched PVDF piezoelectric thin film. Due to the ultra-thin sandwich structure, the flex dipoles can generate electrical power from low frequency vibrations originating naturally from the human body [5]. To achieve a 915 MHz resonant frequency, the length of the flex dipole is set to 15.3 cm. The width and thickness of the flex dipole are 12 mm and 0.31 mm, respectively. To increase the vibration power from the flex thin film, two 10 mH inductors are added to connect two pairs of top and bottom electrodes.

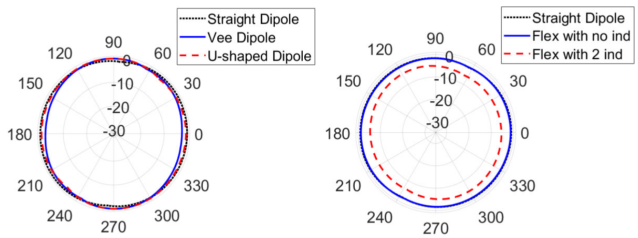
III. Simulation and Experimental Results

Human body phantoms for simulations and experiments are shown in Figs. 1 (top) and 6 (left), respectively. A hollowed plastic mannequin is filled with a phosphate-buffered saline solution (P38135 from Sigma Aldrich) to mimic a human body. The dipole antennas were attached to the chest of the phantom. The phantom was then placed on the platform in an anechoic chamber. A yagi antenna was used as a 915 MHz transmitter driven by a 30 dBm RF power amplifier. To compute the theore-



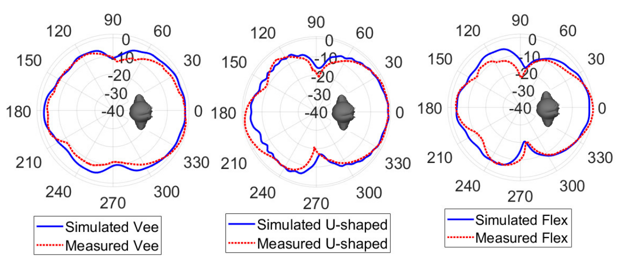
a. Vee Dipole b. U-shaped Dipole c. Flex Dipole

Fig. 2. Dipole antenna E-plane patterns (no human body phantom).



a. Vee and U-shaped Dipole b. Flex Dipole

Fig. 3. Dipole antenna H-plane patterns (no human body phantom).

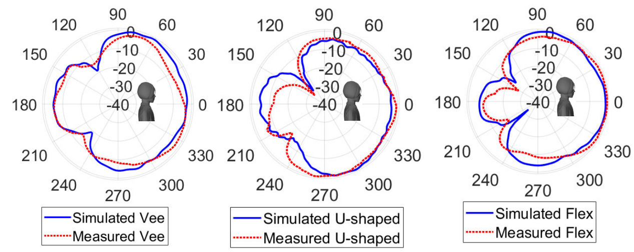


a. Vee Dipole b. U-shaped Dipole c. Flex Dipole

Fig. 4. Dipole antenna E-plane patterns (with human body phantom).

tical antenna patterns, EM simulations were performed using a 3D representation of a human body in Ansys HFSS. Figs. 2 and 3 show the simulated and measured radiation patterns of Vee, U-shaped and flex dipoles without the human phantom. In Figs. 2a and 2b, the directivity along the dipole axis of Vee and U-shaped dipole increases by 25.1 dB compared to that of the straight dipole. This allows Vee or U-shaped dipoles to obtain more power when the RF source is to the left or right of a human body. When the angle $\boldsymbol{\alpha}$ and the ratio of $\boldsymbol{b}$ to $\boldsymbol{a}$ decrease, the Vee and U-shaped dipole patterns become more isotropic. Herein, $\boldsymbol{\alpha}$ and $\boldsymbol{a/b}$ are chosen to be 90^0 and 2, respectively. Fig. 2c and 3b show that the radiation magnitude of the flex dipole with two inductors is reduced by 5.1 dB compared to the straight and flex dipoles without inductors. The inductors slightly lower the performance of the flex dipole because of series resistance and parasitic capacitance. There is a slight difference in the H-plane patterns of the dipoles in Fig. 3a. With the human body phantom, the far-field E-plane radiation of the antennas in Fig. 4 is decreased by 2-5 dB at the phantom's back. Fig. 5 demonstrates that the presence of a head and chest model significantly reduces the radiation of the dipole antenna by 15-30 dB while the radiation pattern around the neck is slightly smaller.

Finally, the flex dipole antenna in Fig. 6 is tested on a user in a typical office with a 3 W EIRP 915 MHz PowerCast transmitter. The flex dipole output is connected to a matching



a. Vee Dipole b. U-shaped Dipole c. Flex Dipole

Fig. 5. Dipole antenna H-plane patterns (with human body phantom).

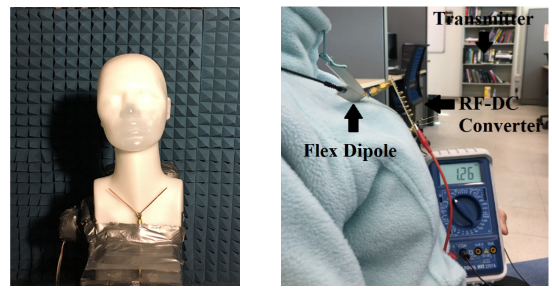


Fig. 6. Vee dipole on the phantom in the anechoic chamber (left) and flex dipole with RF-DC converter and an LED on a person.

network, a Dickson RF to DC converter, and an LED. The activated LED signifies that the receiver is still receiving power up to 2.4 m from the transmitter. With the user facing the transmitter, the bent flex dipole generates 72.2 µW across a 22 kOhm load at 5.3 m from the transmitter.

IV. Conclusions

The present work described the design, implementation and pattern characterization of Vee, U-shaped, and flex dipoles suitable for embedding in an RF energy harvesting necklace. The Vee and U-shaped dipoles offer more isotropic radiation patterns compared to the straight dipole. We have illustrated how the presence of a human body distorts the antenna patterns. The RF rectenna on a person harvests more than 70 µW at 5.3 m from the transmitter. The results demonstrate the potential of RF energy harvesting necklaces for smart jewelry.

References

[1] P. Jokic and M. Magno, "Powering smart wearable systems with flexible solar energy harvesting," 2017 IEEE International Symposium on Circuits and Systems (ISCAS), Baltimore, MD, 2017, pp. 1-4.

[2] S. E. Adami et al., "A Flexible 2.45-GHz Power Harvesting Wristband With Net System Output From −24.3 dBm of RF Power," in IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 1, pp. 380-395, Jan. 2018.

[3] J. Bito, J. G. Hester and M. M. Tentzeris, "Ambient RF Energy Harvesting from a Two-Way Talk Radio for Flexible Wearable Wireless Sensor Devices Utilizing Inkjet Printing Technologies," in IEEE Transactions on Microwave Theory and Techniques, vol. 63, no. 12, Dec. 2015.

[4] S. H. Nguyen, N. Ellis and R. Amirtharajah, "Powering smart jewelry using an RF energy harvesting necklace," 2016 IEEE MTT-S International Microwave Symposium, San Francisco, CA, 2016, pp. 1-4.

[5] S. H. Nguyen, R. Amirtharajah, " A Hybrid RF and Vibration Energy Harvester for Wearable Devices," in 2018 IEEE Applied Power Electronics Conference and Exposition, March, 2018, in press.