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A High-Gain Wideband U-Slot E-shaped Patch Antenna for On-Body Wireless Energy Harvesting Applications

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Abstract

We present an E-shaped antenna with enhanced gain and wideband characteristics tailored for on-body radio frequency (RF) wireless energy harvesting applications. The proposed structure holds promise for integration with a rectifier, thereby constituting an RF energy harvesting system. To augment the bandwidth and facilitate efficient excitation of high-order modes, a U-slot is incorporated into the E-shaped patch. To assess on-body performance, the antenna is cylindrically bent with varying radii. After undergoing severe bending conditions, the presented antenna exhibits an even broader bandwidth (4.7-9.3 GHz) compared to its original range (4.7-9.1 GHz). The maximum realized gain is above 10 dBi at 6 GHz.

1. Introduction

Radio frequency (RF) ambient wireless energy harvesting (WEH) systems employing flexible rectennas has attracted considerable interest, fueled by the increasing prevalence of wearable electronics [1]. The ability of this technology to power on-body electronics without relying on batteries has paved the way for the creation of various self-sustaining wearable devices, including hand-movement recognition sensors and wearable healthcare devices.

The flexible antenna, a crucial component of the flexible rectenna, presents numerous design challenges in the development of a flexible wireless energy harvesting (WEH) system. This complexity primarily arises from the demanding material requirements associated with flexible antenna design. Notably, the conducting layers must exhibit exceptional mechanical properties to withstand deformations such as bending, stretching, and twisting. At the same time, these materials must possess high conductivity to ensure optimal antenna performance. The deformable nature of on-body antennas introduces an additional layer of complexity to the design process. This is because the antenna's performance, including factors like antenna gain, resonant frequency, and bandwidth, undergoes substantial degradation when bent onto the human body. Addressing these challenges is crucial for advancing the capabilities of flexible WEH systems.

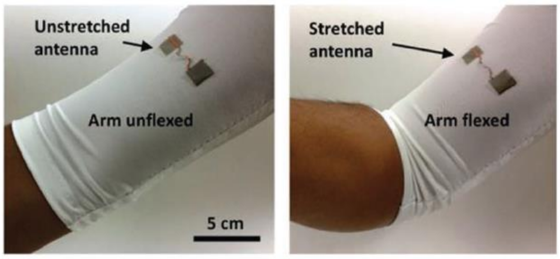


Figure 1. A stretchable monopole helical antenna can accommodate basic motions of the arm. Stretching to a strain of 30% leads to a decrease and an increase in frequency and bandwidth, respectively [1].

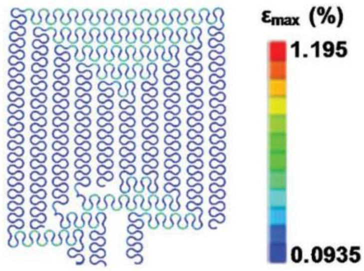


Figure 2. A stretchable antenna with serpentine structure under different strains [3].

Numerous strategies have been proposed to address the aforementioned challenges. Some involve the design of antennas with a 3D flexible structure using conventional materials. One notable approach involves the development of a helical spring monopole antenna, representing an initial endeavor to achieve flexibility through a 3-D antenna structure [1], as depicted in Figure 1. The antenna is crafted to twist out-of-plane, alleviating stress. Consequently, the physical length of the antenna remains unchanged during stretching. The elongation is solely a result of the lateral spring undergoing restructuring. This distinctive feature proves highly advantageous, as it ensures that antenna performance, particularly the resonant frequency, remains unaffected by stretching.

Some researchers have discovered that antennas with a serpentine structure can exhibit excellent flexibility and stretchability, even when using conventional metals [2][3], as shown in Figure 2. The advantage of antennas with serpentine structures lies in their ability to maintain a relatively stable resonant frequency and bandwidth upon deformation. The serpentine structure facilitates current propagation in both horizontal and vertical directions. When the antenna length is elongated, its width will shrink according to Poisson's ratio, providing a counterbalance for the change in electrical length due to stretching. These antennas use stretchable elastomer as dielectric and conventional metals with stretchable 3-D structures to achieve flexibility and stretchability.

On the other hand, some researchers turn to advanced materials to achieve antenna flexibility. Antennas based on textiles [4][5] replace stretchable elastomers with fabrics and utilize conductive fiber weaving on fabrics instead of conventional metal. The performance of these antennas primarily depends on material properties such as the conductivity of the conductive fibers. Additionally, antennas built with liquid metal and nanomaterials are also designed for wearable applications. In these cases, as well, the conductivity of the liquid metal and conductive nanowires often becomes a limiting factor for the performance of flexible antennas.

Compared to antennas that achieve flexibility through a 3-D structure, the performance of flexible antennas based on advanced materials is more susceptible to degradation upon deformation. This is attributed to the suboptimal performance of advanced materials, characterized by relatively low conductivity of conducting layers compared to conventional metals like copper, and a lack of mechanisms to offset changes in the antenna's electrical length caused by deformation. Nevertheless, the flexibility and stretchability of such antennas are unparalleled.

In this paper, we present a U-slot loaded E-shaped antenna designed for on-body wireless energy harvesting applications, originally proposed in [6]. Through in-depth investigation and optimization, the U-slot loaded E-shaped antenna demonstrates the capability to achieve a relatively wider bandwidth when subjected to bending. Unlike common flexible antennas that experience performance degradation after severe bending, the designed antenna maintains stable gain, and its bandwidth even widens post-bending.

2. U-Slot Loaded E-shaped Patch Antenna for On-Body WEH Application

2.1 Starting Point: E-shaped Patch Antenna

The resulting antenna initially takes the form of an E-shaped patch antenna [7], as depicted in Figure 3. The flexible dielectric substrate (depicted in blue) is fabric pile with a dielectric constant $\varepsilon_r = 0.118$ and a loss tangent $\delta = 0.009$. The conducting layers used in simulation is lossy copper, although this combination can be replaced with conductive fabrics as conducting layers and other textile materials as dielectrics for fabrication. The ground plane serves to reduce back radiation, minimize human body interference, and enhance overall gain performance.

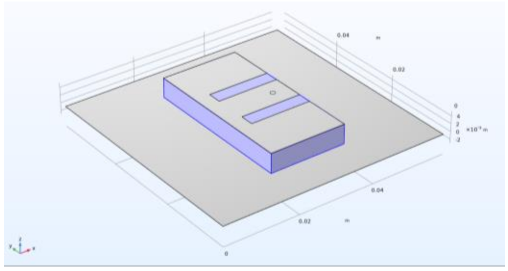


Figure 3. Initial E-shaped patch antenna.

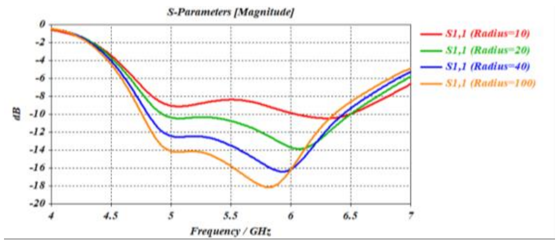
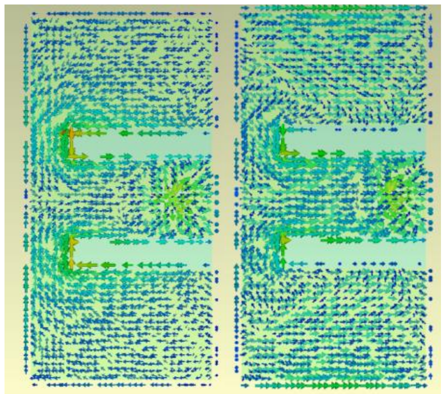


Figure 4. S11 Performane of E-shaped patch Antenna after H-plane Bending



(a) (b)

Figure 5. (a) Current Distribution at 5.0 GHz. (b) Current Distribution at 5.8 GHz

The initial E-shaped patch antenna exhibits two resonances (resonate at 5.0 GHz and 5.8 GHz), with a resulting bandwidth (S11 below -10 dB) between 4.7 GHz and 6.4 GHz, corresponding to a 30.6% fractional bandwidth. However, this bandwidth is relatively narrow. After bending, the antenna's bandwidth performance degrades significantly, as illustrated in Figure 4. It is evident that the matching performance deteriorates as the bending radius decreases. Additionally, it should be noted that the resonant frequency of the higher resonance blue shifts for a smaller bending radius, while the resonant frequency of the lower resonance remains stable. This can be explained by the current distribution at the two resonant frequencies, as illustrated in Figure 5. At 1st resonance (5.0 GHz), the main current flows vertically, and the bending axis is along the same direction (bent along the H-plane). Therefore, H-plane bending has little effect on the vertical current and a significant effect on the horizontal current. This is why the 2nd resonance (5.8 GHz) is severely affected, as its major current flows horizontally. The effects are reversed for E-plane bending.

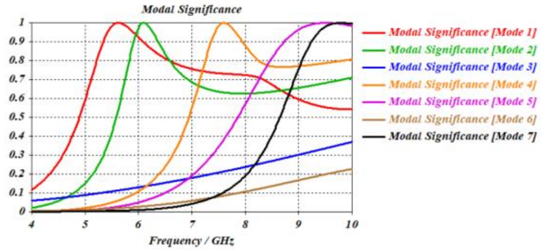


Figure 6. The modal significance of the E-shaped antenna from 4 GHz to 10 GHz

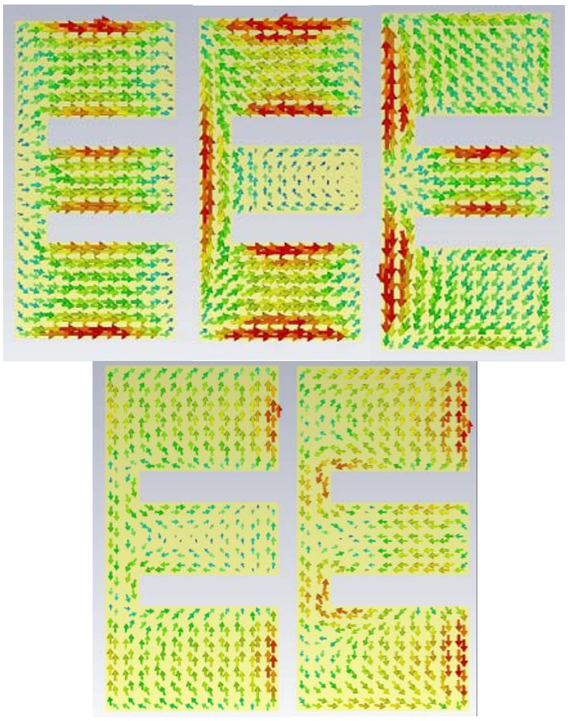


Figure 7. The modal currents of Mode 1,2,4,5 and 7 respectively.

2.2 Improved Version: U-slot Loaded E-shaped Patch Antenna

The previously designed E-shaped antenna exhibits moderate performance in terms of bandwidth, with a substantial degradation observed for small bending radii. However, it is well-established that the E-shaped antenna harbors multiple potential resonant modes [6]. Figures 6 and 7 depict the Modal Significance (MS) and corresponding modal currents of the E-shaped antenna, obtained through Characteristic Mode Analysis.

Modal significance reflects the contribution of different resonance modes to a given structure at specific frequencies. A higher modal significance indicates a greater contribution of that mode at the corresponding frequency. Upon scrutiny of Figure 7, it is evident that multiple modes exist within the frequency of interest, yet only first two modes are currently being excited. The excitation of higher modes would be extremely difficult for the current E-shape structure and coaxial cable excitation method.

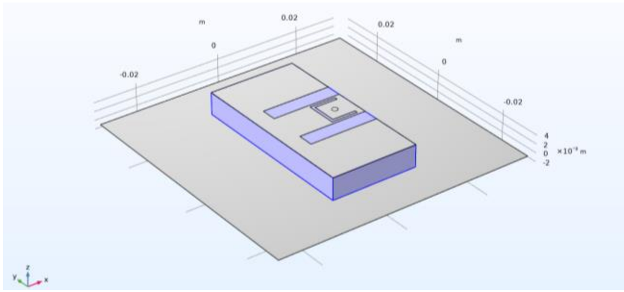
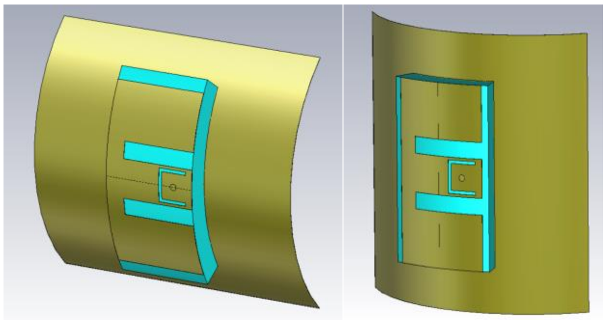


Figure 8. The final U-slot loaded E-shaped antenna.



(a) (b)

Figure 9. (a). Antenna bent along E-plane. (b) Antenna Bent along H-plane.

A strategic modification involves introducing a U-slot around the feeding position. This modification facilitates the excitation of mode 4 & 7, thereby expanding the antenna's operational bandwidth.
The final U-slot loaded E-shaped antenna structure is depicted in Figure 8. The antenna is bent along both the E-plane and H-plane, as illustrated in Figure 9, with a bending radius of approximately 35 mm, simulating the curvature of a human wrist.

3. Analysis and Discussion of the U-slot Loaded E-shaped Patch Antenna

This section discusses the antenna's off-body performance. The S11 results of the antenna undergoing E-plane bending and H-plane bending, are presented in Figures 10 and 11, respectively. Analysis of Figures 10 and 11 reveals that, contrary to degrading antenna performance, bending can enhance matching performance, resulting in a broader bandwidth. In the case of E-plane bending, a smaller bending radius notably improves matching at first three resonances (around 5 GHz, 6 GHz and 7.5 GHz). As for H-plane bending, the antenna demonstrates optimal S_{11} performance at a bending radius of 35 mm. In contrast to common antennas, which often experience a drastic degradation in operational bandwidth after severe bending, our antenna demonstrates an improvement in operational bandwidth under similar conditions.

The expanded bandwidth effectively encompasses the original range, rendering the shift in resonant frequency inconsequential. The off-body radiation pattern of the unbent antenna at 4 resonances is depicted in Figure 12.

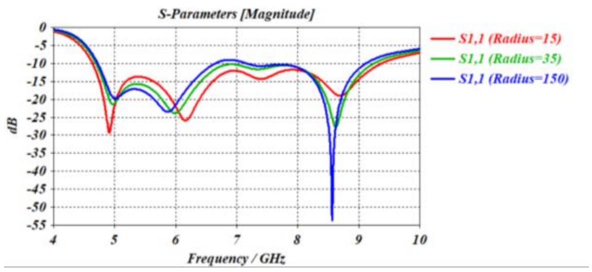


Figure 10. S11 Performane of U-slot loaded E-shaped patch antenna after E-plane bending at 3 bending radii.

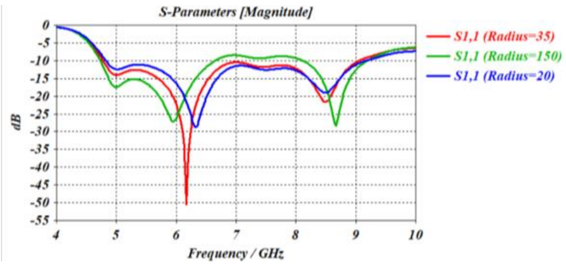


Figure 11. S11 Performane of U-slot loaded E-shaped patch antenna after H-plane bending at 3 bending radii.

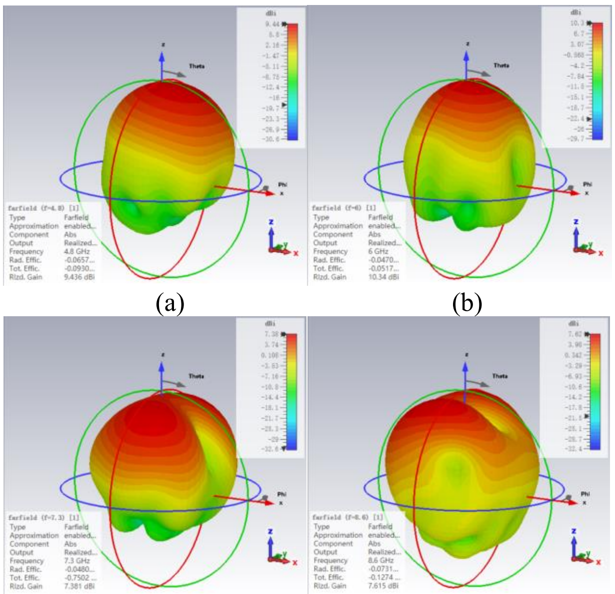


Figure 12. The radiation pattern of unbent U-slot loaded E-shaped patch antenna at (a). 4.8 GHz, (b). 6 GHz, (c). 7.3 GHz, (d). 8.6 GHz.

The realized gain of the antenna is exceptionally high at four resonances, with the first two resonances reaching a maximum gain of around 10 dBi. However, for the two higher modes, the antenna's directionality decreases, and they are characterized by a dual-lobed radiation pattern with a maximum gain of approximately 7.5 dBi.

It is noticeable that the directionality of the radiation pattern decreases with a reduction in the antenna bending radius. Nevertheless, the maximum gain and overall radiation pattern remain acceptably robust even under severe bending conditions (radius=15 mm). The reduction in directionality may be attributed to the main lobe being upright for the unbent antenna, which becomes more dispersed after bending. For the antenna bent along another axis, the effects are similar.

4. Conclusions

We have introduced the U-slot loaded E-shaped antenna for on-body wireless energy harvesting applications. The antenna's excellent gain and bandwidth performance even after severe bending conditions makes it a perfect candidate for flexible wireless energy harvesting applications. More experimental and simulation results will be presented at the conference.

References

[1] A. M. Hussain, F. A. Ghaffar, S. I. Park, J. A. Rogers, A. Shamim, and M. M. Hussain, "Metal/Polymer Based Stretchable Antenna for Constant Frequency Far-Field Communication in Wearable Electronics," *Advanced Functional Materials*, **25**, 42, October 2015, pp. 6565–6575, doi: 10.1002/adfm.201503277.

[2] Sung Sup Park et al., "Stretchable multichannel antennas in soft wireless optoelectronic implants for optogenetics," *Proceedings of the National Academy of Sciences*, **113**, 50, December 2016, doi: 10.1073/pnas.1611769113.

[3] K. W. Noh et al., "Miniaturized, Battery‐Free Optofluidic Systems with Potential for Wireless Pharmacology and Optogenetics," *Small*, **14**, 4, January 2018, pp. 1702479-1702479 doi: 10.1002/smll.201702479.

[4] F. Xu, B. Wei, W. Li, J. Liu, W. Liu, and Y. Qiu, "Cylindrical conformal single-patch microstrip antennas based on three dimensional woven glass fiber/epoxy resin composites," *Composites Part B: Engineering*, **78**, September 2015, pp. 331–337, doi: 10.1016/j.compositesb.2015.03.091.

[5] F. Xu, H. Zhu, Y. Ma, and Y. Qiu, "Electromagnetic performance of a three-dimensional woven fabric antenna conformal with cylindrical surfaces," *Textile Research Journal*, **87**, 2, July 2016, pp. 147–154, doi: 10.1177/0040517515624878.

[6] D. K. Naik, A. K. Sahu, R. K. Parida, P. Raiguru, D. C. Panda, and R. K. Mishra, "Design of a broadband U-slot loaded E-shaped patch antenna using characteristic mode analysis," *AEU - International Journal of Electronics and Communications*, **154**, September 2022, Sep. 2022, p. 154310 doi: 10.1016/j.aeue.2022.154310.

[7] F. Yang et al., "Wide-band E-shaped patch antennas for wireless communications," *IEEE Transactions on Antennas and Propagation*, **49**, 7, July 2001. pp. 1094-1100, doi: 10.1109/8.933489.

[8] E. Antonino-Daviu, A. Eid, R. Bahr and M. Tentzeris, "Flexible Antenna Design with Characteristic Modes," *2020 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, 2020*, pp. 1-4, doi: 10.23919/EuCAP48036.2020.9135608.