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Towards Wearable Wireless Power Harvesting using Clothing-Integrated Beamforming Structures

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***Abstract*—High-gain wide-beam off-body wearable antennas are essential for efficient wearable RF energy harvesting (RFEH). Here, we report a 5.8-GHz reflector-backed Yagi-inspired antenna with over 2 dB gain and efficiency improvement over a conventional Yagi. Using the reflector, the end-fire patterns are re-directed in the broadside off-body direction while maintaining a simulated 76% efficiency. To demonstrate the feasibility of high-gain RFEH, a beam-forming Rotman lens is designed with a relatively low insertion loss based on conventional fabrics with conductive surfaces designed to be implemented via the automated embroidery of conductive threads. This work is a stepping stone to clothing-integrated low-profile beamforming for sub-6 GHz 5G/6G applications.**

***Index Terms*—conductive textiles, rectenna array, wireless power harvester, patch antenna, wearable applications, textile beamformer**

I. INTRODUCTION

Robust and continuous wireless power collection has been the focus of various research projects for wearable applications [1]–[4]. The uninterrupted power collection potential is crucial for wearable devices that are used for medical sensing for example to monitor patient with critical health conditions. The collection of RF power to drive these devices is often done with sub-6 GHz antennas allowing for smooth prototyping of textile or fabric-based structures as the commercially available manufacturing techniques for all-textile antennas often lack high resolution [4], [5]. Sub-6 GHz wearable rectennas are either based on microstrip antennas [1], [3] or unisolated antennas directly placed on the body [2]. In the 5G mmWave spectrum, to decouple the antenna from the body, a reflector-backed Vivaldi-inspired monopole was found to outperform a standard microstrip patch by over 3 dB [4]. However, such gain enhancement technique has yet to be investigated for longer sub-6 GHz wavelengths.

High-gain rectennas enable efficiency RF energy harvesting (EH) from low-power densities but is often done at the expense of the angular coverage [6]. Multi-beam RF energy harvesting has recently attracted significant interest for improved rectenna sensitivity [6], and has been demonstrated using a Butler matrix [7], and a Rotman beamforming lens [8]. However, and despite the extensive literature on wearable textile-based rectennas [1]–[4], there are no reports of a textile-based beamforming matrix/lens. In this paper, we propose a 5.8-GHz reflector-backed Yagi-inspired antenna, with off-body broadside radiation patterns, and its array for high-gain wearable RFEH. Alongside the Yagi-inspired array, a textile-based Rotman lens is simulated based on the measured permittivity and conductivity of polyester cotton and e-textiles, respectively, demonstrating that wearable beamforming could be realized using low-cost e-textile materials.

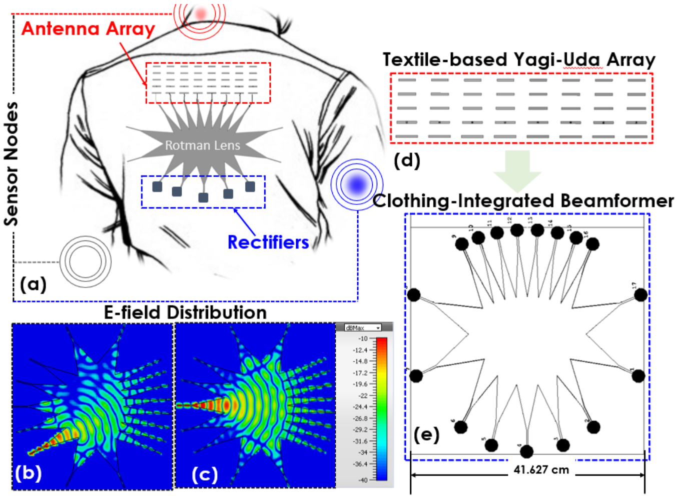

Fig. 1: (a) conceptual wearable beamforming power harvesting; (b), (c) E-field distribution of the Rotman lens; (d) reflector-backed Yagi-inspired array; (e) textile-based beamforming lens.

II. OFF-BODY HIGH-GAIN ANTENNA DESIGN

To realize a compact wearable antenna, a high-gain end-fire Yagi Uda-inspired design is selected. However, in human proximity, the end-fire design will suffer from increased absorption and a low broadside gain. The Yagi radiator is 2.2 cm-long, 2.5 mm-wide. A single reflector and three directors are used. To achieve a broadside gain insensitive to human proximity, the end-fire radiation of the Yagi-inspired antenna is transformed to a broadside off-body pattern by using a reflector placed at $0.5\times\lambda_0$, i.e. 1 cm. The antenna was designed and simulated using CST Microwave Studio. A layered tissue model is added beneath the antenna to include the human proximity losses. The polyester cotton substrate's dielectric properties were measured to be ϵ_r=1.7 and tanδ=0.017 using

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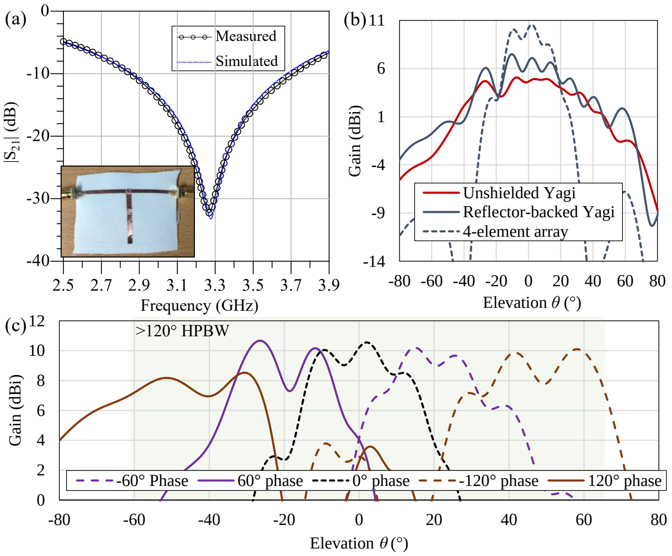

Fig. 2: The response of the Yagi-inspired off-body array: (a) T-resonator characterization of the textile substrate; (b) 5.8 GHz gain of the unshielded and reflector-backed Yagi; (c) beam-steerable textile-based Yagi array gain.

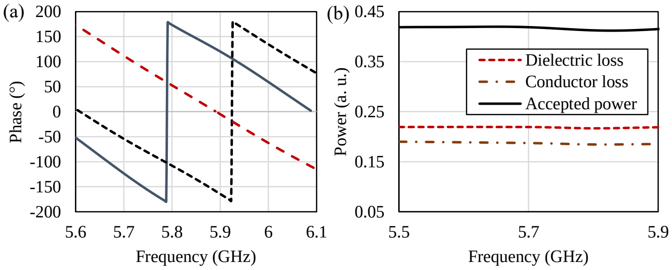

Fig. 3: Simulated Rotman lens response: (a) phase; (b) total insertion losses across all ports.

a T-resonator whose response is in Fig. 2(a). To illustrate the benefits of the Yagi reflector backing, the simulated realized gain of the un-shielded 5.8 GHz antenna is shown in Fig. 2(b), which is improved by at least 2 dB when the unconnected reflector is added.

A four-element phased array is simulated based on the proposed Yagi-inspired broadside antenna with a 20 mm element spacing, its far-field response is shown 2(c). Using a $-120 < \phi < 120$ beam-steering phase difference, the array could maintain a half-power beamwidth (HPBW) over 120° with 10.6 dBi peak gain (inclusive of antenna dielectric losses). We anticipate a peak realized gain of 13.6 dBi when the full array (8 Yagi-element) is considered.

III. TEXTILE-BASED BEAMFORMING

To realize the multi-direction wearable energy harvesting system, a beam-forming matrix or lens is required. A Rotman lens benefits from a larger surface area reducing its conductive losses compared to a butler matrix. The Rotman lens was designed and simulated using CST Microwave Studio around 5.8 GHz. The same textile substrate with a 0.5 mm height, ϵ_r=1.7, and tanδ=0.017 was used for the Rotman lens. By using a thinner fabric the spurious radiation is suppressed and the insertion losses are minimized. Fig. 2(b) and (c) show the electric field distribution over two of the lens' feed ports where a uniform distribution across all output ports is observed.

The phase response was simulated in CST and is shown in Fig. 3(a), for the ports 9, 12, and 16 (the first, center, and last port on the output). It can be seen that the textile-based Rotman lens provides the phase shift required to steer the phased array beam for omnidirectional RFEH. Observing the losses in Fig 3(b), the Rotman lens achieves an efficiency of approximately 50%. Therefore, combined with the antenna array achieving a 76% radiation efficiency, it is anticipated that the overall radiation efficiency of the array will not degrade significantly, off-setting the benefits of the wider/higher-gain beam.

IV. CONCLUSION

In this paper, we proposed a reflector-backed Yagi-inspired antenna and its array for sub-6 GHz high-gain RFEH applications. By backing an end-fire antenna with a conductive plane, the end-fire on-body radiation is transformed to a broadside off-body beam with a 2 dB higher gain. In a phased array configuration, a 120° HPBW could be achieved with a peak gain of 10.2 dBi using an all-textile antenna. To achieve multi-directional coverage, a textile-based beamforming Rotman lens was designed based on measured textile dielectric properties showing at least 50% efficiency and the required phase shift for the array. This work shows the feasibility of wearable textile-based beamforming for RFEH applications.

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