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***Abstract*- The development of wireless systems for fifth-generation technology (5G) has enabled the use of textile antennas for a wide range of applications, and it has now become one of the world's most in- demand technology. As the number of wireless devicesand users increase, operators would need higher channel capacity to deliver better possible service to their customers. This paper presents the generation of Orbital Angular Momentum (OAM) vortex waves with mode 1 using a wearable textile antenna. OAM introduces a new scheme called Mode Domain Multiple Access (MDMA). OAM mode is an orthogonal mode with each mode carrying individual signals. Therefore, multiple signals can be sent using the same carrier frequency without additional resources. This allows the channel capacity and spectrum efficiency to be enhanced. The proposed antenna array comprises rectangular microstrip patch elements with an inset fed technique. Felt textile fabric was used as an antenna substrate. A carefully planned feeding phase shift network was used to excite the elements by supplying similar output energy at output ports with the required phase shift value. The generated OAM waves were confirmed by measuring the null in the boresight direction of their 2D radiation patterns as well as simulated phase distribution, intensity distribution and mode purity. The antenna covered portions of the 5G n77 band with a bandwidth of 81.7 MHz and an overall gain of 2.9 dBi. This is, to the best of our knowledge, the first work on generating OAM waves using a flexible textile material.**

***Keywords*-OAM waves, wearable antenna, microstrip patch antenna, 5G communications, textile patch antenna.**

I. Introduction

Due to its extremely low latency, the current long-term evolution (LTE) system is unable to keep up with the increasing demand for higher data rates [1]. As a result, the fifth-generation new radio (5G NR) communication system was introduced, as it provides a decrease in latency by 10-time, with a 100-times traffic limit, a 10-times connection density, a 3-time spectrum efficiency, and a 100-times network proficiency. While the 3G partnership project technical specification (38.101) specifies the any range below 6 GHz band as sub-6 GHz, these can be further divided into two types: frequencies less than 3 GHz are used by 3G/4G mobile communication systems, while frequency bands such as n77 (3.3 GHz - 4.2 GHz), n78 (3.3 GHz – 3.8 GHz) and n79 (4.4 GHz-5.0 GHz) are used for 5G NR networks [2]. In recent years, the advancements in body-centric wireless communication systems necessitates the development of a new class of flexible, lightweight, and robust wearable antennas [3]. Additionally, wearable systems must be easy to operate, inexpensive, and consume minimum energy [4]. A wideband antenna is extremely desirable because it efficiently compensates on-body detuning within the operating frequency band while also allowing for high data-rate transmission [5]. Typically, designing a wearable antenna is challenging because of the human body presence and interaction with electromagnetic radiation. As a result, a low specific absorption rate (SAR) antenna that is conformal and light in weight must be studied. Several specific sections of the profession that utilize body-centric communication systems, including paramedics, fire-fighters, and members of the military services [6].

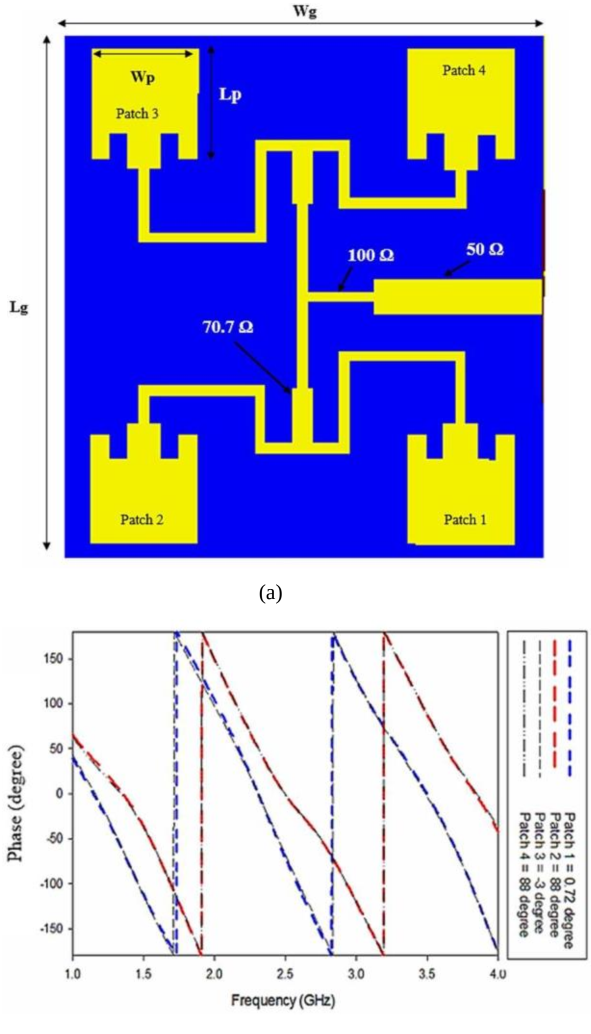
One possible method of implementing 5G wireless communication is to use OAM vortex waves rather than conventional plane waves. An OAM wave is characterized by an azimuthal phase factor $\exp(il\phi)$ and a helical wavefront. Here, the integer l is called the topological charge, and different values of l correspond to different OAM modes [7-9]. Theoretically, there are an infinite number of modes that an OAM wave can be in, and these modes are orthogonal to each other. This orthogonal feature offers a new possibility to increase spectral efficiency by multiplexing different OAM modes in the same frequency channel, which can potentially be incorporated into the 5G technology. Under a Line-Of-Sight (LOS) condition, it has been shown that OAM has a better channel capacity than Multiple-Input-Multiple-Output (MIMO) system [10 - 11].

Previous works of generating OAM waves were based on conventional substrates such as FR-4 [12], ceramic [13], Rogers [14] and FRB [15]. To the best of our knowledge, there hasn't been any published work on deploying textiles as substrate for antenna to generate OAM waves. The arrangement of this article is as follows: The antenna design is described in Section II. Section III discusses the results of the proposed design. Eventually, Section IV presents the paper's conclusion.

II. Antenna Design Methodology

In this paper, the substrate used was felt textile fabric with a permittivity value of 1.44, a thickness of 3 mm and a loss tangent of 0.044. The substrate was placed between the radiating elements and ground plane based on the concept of a microstrip patch antennas [16]. The radiating elements and ground plane were formed using Shieldit Super Electro-Textile that had a 0.17 mm thickness, and an estimated conductivity (σ) of 1.18×10^5 Sm^{-1}. For an N-element UCA, an OAM wave of topological charge l can be generated by exciting the elements with the power of equal amplitude, with a phase difference of $\Delta\phi = \frac{2\pi l}{N}$, between adjacent elements [17]. Therefore, to generate OAM mode $(l) = 1$ with four patches or elements, the phase difference has to be 90° between adjacent antenna elements.

There were four identical radiating elements placed on the substrate in a circular arrangement with a radius of 82 mm. The array radius has to be at least 0.7λ to avoid mutual coupling and shift in resonant frequency [27]. For the proposed design, λ = 85.7 mm. Therefore, a radius of 82 mm is equivalent to 0.95 λ. Therefore, the isolation among the radiating elements were good enough to avoid mutual coupling. The final antenna was carefully designed with feeding network is shown in Fig. 1 (a). The dimensions of the proposed elements were calculated and optimized based on the formulas reported in [18] and the finalized dimensions are as follows (unit in mm): Wp = 35, Lp = 35.7, Wg = 156.5 and Lg = 170. A phase difference of nominally 90° between patches 1 and 2 was obtained by altering the length of the feedline as shown in Fig. 1(a). Patches 3 and 4 are the mirror image of Patches 1 and 2. Hence, the same feeding network of patches 1 and 2 was used for patches 3 and 4 which gave a 180° phase rotation. Based on Fig. 1(b), the overall phase for patch 1 to 4 was - 0.72°, 88°, 176.4° and 268°, hence the phase differences were acceptably close to 90°.



(a)

(b)

Fig. 1. Simulated antenna (a) Front view (b) Phase among the patches

III. RESULTS AND DISCUSSIONS

The successful generation of OAM vortex waves, was verified by measuring its spiral phase distribution [19], there should be a donut shape in the intensity distribution [20 -21], a null in the centerof the radiation pattern [22] and the purity percentage of the desired mode has to be higher thanthe other modes carried by the OAM waves.

A. Reflection Coefficient (S11) and Bandwidth

The simulated below -10 dB impedance bandwidth of the proposed design covered 3.8159 GHz to 3.8976 GHz with overall bandwidth of 81.7 MHz. Since, the S11 value obtained was -11.3 dB hence it means sufficient power has reached from the source to the antenna. As mentioned in Section I, the 5G NR n77 band was from 3.3 GHz to 4.2 GHz. Hence,from the simulation results in Fig. 2, it can be said that the proposed antenna resonated at the n77 band.

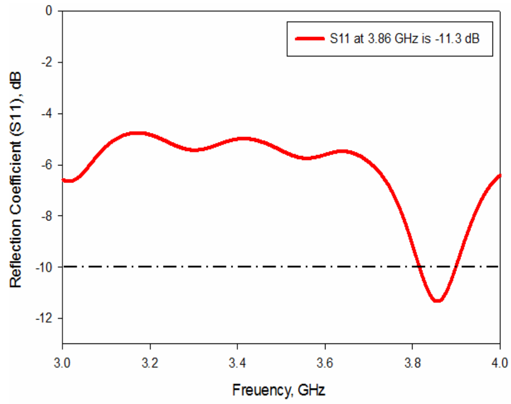
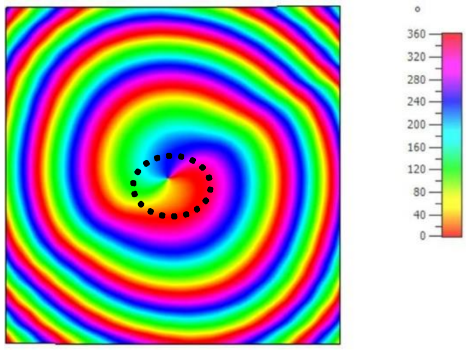


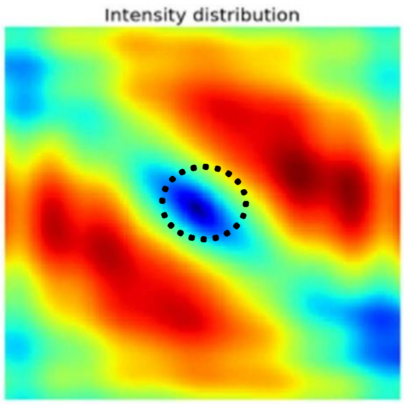
Fig. 2. Simulated S11 value at 5G n77 band (free space)

B. Phase and Intensity distribution

The simulated phase distribution of the proposed antenna from 0◦ to 360◦ is shown in Fig. 3 (a). It is evident that, the proposed design exhibited a spiral phase distribution with a continuous phase change of 2π around the center. This is a characteristic feature of the OAM wave. The multi-color in Figure 3 (a) implies that the phase change has taken place by 2π around the propagation axis. In addition, it can be observed from Fig. 3 (b) that there was a donut shape structure at the center. The black dot inside the blue circle shape of the beam demonstrates the intensity of the generated OAM mode. This black dot is the “Phase Singularity Point” which indicates that the wavefront is twist or spiral. Therefore, both spiral phase distribution and donut shape intensity were evident from the simulated results. This confirms the generation of OAM Mode 1 using the proposed design.



(a)

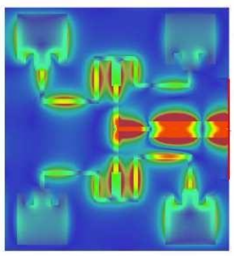


(b)

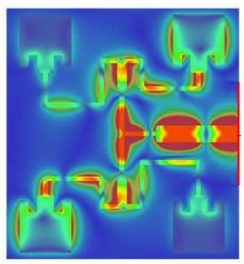
Fig. 3. Simulation results at 3.86 GHz (a) Phase distribution (b) Intensity distribution

C. Current Distribution

The simulated current distribution of the proposed textile design at 3.86 GHz is shown in Fig. 4. From Fig. 4 (a), it can be observed that the current distribution for Patches 1 and 3 takes place together along the edges while there is no distribution for Patches 2 and 4. Furthermore, it can be seen from Fig. 4 (b) that the current distribution is along the edges of patch 2 and 4 while there is no current distribution along the edges of Patches 1 and 3. It is due to the difference in phase and feedline length. The current distribution at the edge of the patch element was observed in [23] as well.



(a)

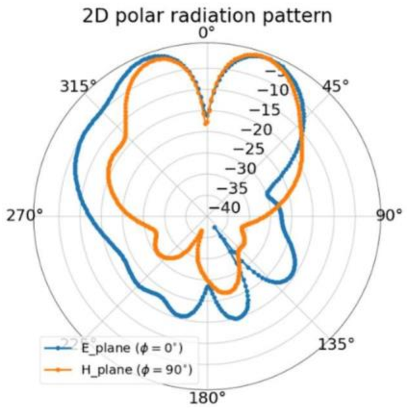


(b)

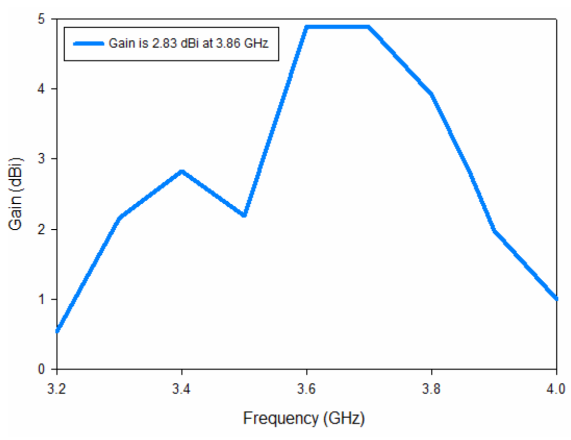
Fig.4. Current distribution (a) Patches 1 and 3 (b) Patches 2 and 4

D. Radiation pattern

An intensity null at the center of the radiation pattern or boresight direction is a characteristic of OAM waves, is apparent in the plot as shown in Fig. 5(a). The gain obtained at 3.86 GHz was 2.83 dBi as illustrated in Fig.5(b). Since the patch orientations were opposite and since there was a center null, the gain is less. Nevertheless, for the textile patch array antenna, the obtained gain was moderate considering the high loss materials such as textile fabric as a substrate.



(a)



(b) (b)

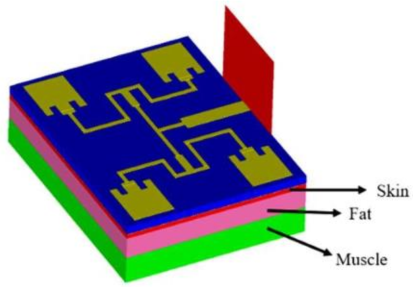
Fig. 5: Radiation pattern at 3.86 GHz (a) 2-D polar form for both E and H plane (b) Gain plot

E. Specific Absorption Rate (SAR)

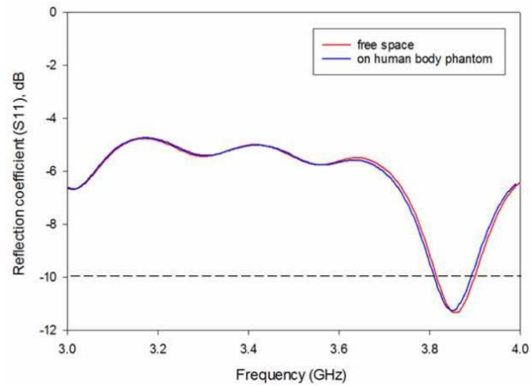
The human body phantom model is made up of three layers of human body tissues: skin, fat, and muscle, each with a thickness of 1.6 mm, 8 mm, and 10 mm respectively [24]. Table 1 lists the properties of human tissue as reported in [25]. As seen in Fig. 6(a), a simulated human body phantom is constructed in CST 2019. When the designed antenna was positioned on a human body phantom, the antenna resonance frequency shifted slightly towards lower frequency, as illustrated in Fig. 6(b). The proposed antenna, however, continued to operate on the n77 band.

Table 1. Properties of human tissue

Tissue	Permittivity (εr)	Conductivity (S/m)	Loss Tangent (tan σ)	Density (Kg/m^3)	Thickness (mm)
Skin	31.29	5.0138	0.2835	1100	1.6
Fat	5.28	0.1	0.19382	1100	8
Muscle	52.79	1.705	0.24191	1060	10



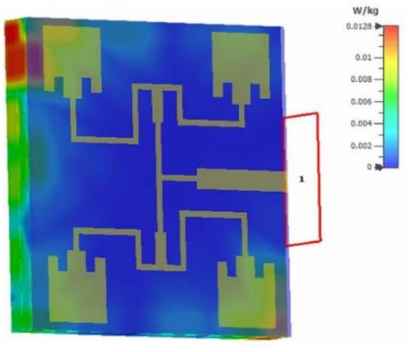
(a)



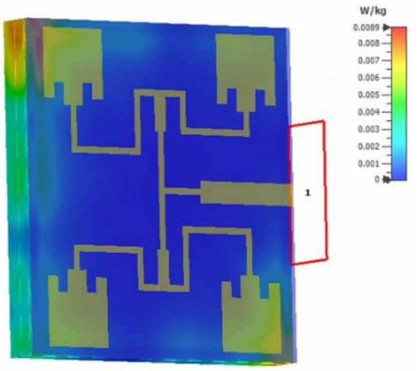
(b)

Fig. 6. Simulation result (a) body layer with the antenna placed on the phantom (b) S11 value when the antenna was placed on the phantom

As per the Federal Communication Commission (FCC) and The International Commission on Non-Ionizing Radiation Protection (ICNIRP), for 1g and 10g, the SAR value should be within 1.6 W/Kg and 2 W/Kg respectively [26]. From Fig. 7 (a) and Fig. 7 (b) that the SAR value of 1g was 0.0128 W/kg while for 10g the value was 0.0089 W/kg when the proposed antenna was placed on the human equivalent phantom. Both these values were within the accepted range which makes it suitable for wearable applications.



(a)



(b)

Fig. 7. SAR value at 3.86 GHz (a) 1g (b) 10g

F. OAM mode purity

The proposed textile antenna generated OAM Mode 1 with a purity of 41.19% as shown in Fig. 8. The sampling plane was 100 mm in radius at a distance of 500 mm from the transmitting antenna. Since the antenna was designed to produce OAM Mode 1 hence the ratio of purity is more for mode 1 when compared to the OAM wave as a whole.

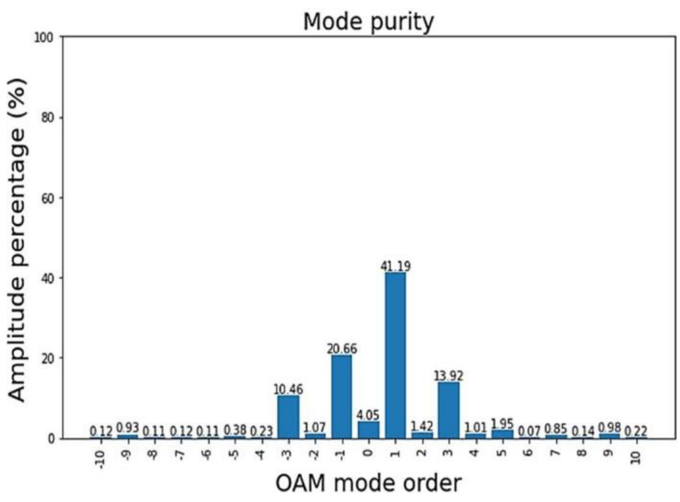


Fig. 8. Mode purity of OAM Mode 1 at 3.86 GHz

IV. CONCLUSIONS

A textile wearable antenna-based array antenna that can generate OAM waves specifically Mode 1 is presented in this paper. The successful generation of OAM wave using textile fabric was evidenced by the results obtained from phase distribution, intensity distribution, the 2-D radiation pattern and mode purity. This work is the first work on generating OAM waves using wearable and flexible textile fabric to the best knowledge of the authors. The proposed antenna is robust since as there were no major shifts in frequency when the antenna was placed on the simulated human phantom. By generating OAM waves using textile wearable antenna, the MDMA scheme can be implemented. As a consequence, the spectrum efficiency can be achieved and more users will be able use wireless devices in the future without any performance degradation since the OAM mode are orthogonal to each other. However, future researchers can work on to increase the purity and number of OAM modes for reliable information transmission as well for higher data rates. This work shall help future researchers to design an OAM based antenna for body-centric communications.

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