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C-band Hexagon Slotted Textile Antenna Design with Jeans Substrate for Satellite Communication Applications

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---ABSTRACT---
This paper presents the design of a hexagonal slotted circular flexible textile microstrip patch antenna that is used for C-band satellite communication applications. In the proposed antenna design, a textile material blue Jeans fabric with relative permittivity 1.67, loss tangent of 0.01 and the thickness of 1 mm is used as the substrate with an overall dimension of 40×38 mm2. The textile material is used as it is washable, wearable, flexible and very economical. Self-adhesive Copper tape is used to make the patch and ground of the antenna that is fed through a microstrip inset feed line. The proposed antenna contains a hexagonal-shaped slot on the patch and a partial ground configuration for getting better bandwidth and gain. The antenna has been designed and simulated using CST microwave Studio software. The simulated antenna performance parameters like return loss, bandwidth, VSWR, gain, efficiency, radiation pattern and surface current are presented. The antenna is resonating at 4.28 GHz and operating in the frequency range of 2.91 -5.2 GHz, with reflection coefficient of -24.42 dB, and a bandwidth of 2.29 GHz. The peak gain of the antenna is 3.42 dBi and radiation efficiency of 87.3% at 4.2 GHz. The proposed antenna covers C-band and with its compact size, wearability and wide bandwidth capabilities, the antenna proves to be a suitable candidate for C-band satellite communication applications.

Keywords - **Circular Patch; Jeans Substrate; Wideband; Wearable Antenna; C-band Satellite Communication; CST Studio**

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I. INTRODUCTION

It is impossible to imagine life on Earth without satellites. Satellite use is essential to maintain our way of life. Satellites can be used for a variety of purposes, such as communication, navigation, positioning, and surveillance. The use of C-band satellite communications is advantageous for high-speed data, phone, and video communication applications. The first frequency band designated for commercial satellite telecommunications is the C-band for communication. Terrestrial microwave radio relay chains were already using the same frequencies. For their downlinks and uplinks, almost all C-band communication satellites operate in the frequency range of 3.7 to 4.2 GHz and 5.925 to 6.425 GHz, respectively. C-band satellite communications currently require wideband antenna technology [1].

For existing and upcoming satellite communications applications on a variety of platforms, including cars, fishing boats, ships, aircraft, and submarines, wide-band antenna technology is currently crucial. These days, platforms are utilized for a variety of tasks, including geographic scanning, mining, depth detection, underwater scanning, and looking for other items like ships, mountains, and erratic geographic areas. It takes effective wide-band antenna technology to carry out such tasks on a variety of platforms. Wearable antenna is mainly used in wireless network for mobile communication, navigation, medical field and military. Flexible electronic or wearable systems require the integration of flexible antennas operating in specific frequency bands to provide wireless connectivity which is highly demanded by today's information-oriented society. The typical existing narrow bands for wireless system are WLAN (2.4–2.484 GHz/5.15-5.35/5.725–5.85 GHz), WiMAX (2.5–2.69 GHz/3.3-3.8 GHz/5.25-5.85 GHz), E band application (2–3 GHz) and C-band satellite communication (3.8-4.2GHz). Flexible wearable antennas are used in body centric wireless communication related to inter human and intra human connectivity for various medical and non-medical applications.

A rapid growth in the field of wireless communication system is emerging recently. Microstrip patch antennas are commonly used in wireless application due to its advantages such as low profile, high broadcast efficiency, light weight, low profile, conformal and planar structure, compactness, low cost and ease of addition with microwave circuit. Now a day's Compact microstrip antennas are getting much more awareness due to the increase in demands of small size antennas used in private and marketable purposes [2]-[4]. The main disadvantage of this type of antenna is its narrow bandwidth. This problem can be avoided to a greater extend by increasing the thickness of substrate, by using shorting pins, or by changing patch shapes [5]. There are a variety of methods adopted to increase the bandwidth of microstrip antenna such as enlarge the substrate thickness, use of a low dielectric constant substrate, use of a variety of feeding techniques and impedance matching use of slot antenna geometry and numerous resonators. But the bandwidth and size of the antenna is jointly conflicting property that is enhancement of one deteriorates the characteristics of others [6]-[8].

The development of wearable technology has gained significant attention in recent years, driven by the increasing demand for smart and flexible electronic devices. Among the various components required for wearable devices, antennas play a crucial role in enabling wireless communication. This paper presents a novel design of a compact jeans textile wearable antenna that offers miniaturized structure and excellent performance for wireless broadband applications.

Textile antennas are a special class of antennas that are partially or entirely made out of textile materials, in contrast to conventional antennas, which consist of rigid materials. The reason behind the use of textile materials in antennas lies in the application for which they are intended, being smart textile systems and body-centric communication. Smart textile systems represent a new concept of garments that, in addition to traditional functions such as protecting the body against the environment, also offer additional functionality such as sensing, actuating, and communication, realized by wearable devices that are integrated into the "smart" garment. Sensing functions are realized by sensors integrated into the textile garment's material and are intended to detect the state of the wearer (ie, body temperature, heart rate, position) and/or the state of the surrounding environment (ie, external temperature and humidity). Actuating functions are enabled by garment-integrated actuators that provide signals and/or alarms in order to inform, command, or warn the wearer about certain events regarding his/her state or the state of the surrounding environment. Finally, communication is realized in a wireless way by means of an integrated wearable textile antenna in combination with a wearable transceiver. Such a kind of wireless communication takes place between the human body and the surrounding environment and is also referred to as body-centric communication.

In [9], Textile Antenna for Microwave Wireless Power Transmission to gain efficient power has been proposed. [10] proposed a compact microstrip antenna for C band application and shown a properly designed E shaped antenna with microstrip line feed provides a bandwidth enhancement by reducing the ground plane and cutting slots on the arm of E-shaped patch. The design of a horizontal slot micro-strip Patch antenna with a dual slot inset feed mechanism is presented in [11] for C band application. Authors found that the patch's horizontal slot and dual point feed mechanism increased bandwidth and improve return loss. A rectangular twin patch antenna with a resistive loading method has been proposed as a wide band multiband antenna for S-band and C-band satellite communications to achieve a wider bandwidth in [1]. A compact crescent moon shape patch antenna for C-band application is presented in [12]; the antenna resonates at frequency 7.5 GHz which covers a bandwidth of 3 GHz extending from 5.59 GHz to 8.59 GHz, and has maximum directivity of 4.791 dBi.

As a wide-band antenna for C-band satellite communications, a new design of circular patch antennas with a hexagon slot on the patch and partial ground approach has been put forth in this work. In the proposed antenna design, a textile material blue Jeans fabric is used as the substrate. The textile material is used as it is washable, wearable, flexible and very economical. Self-adhesive Copper tape is used to make the patch and ground of the antenna. The antenna is fed through a microstrip inset feed line. Hexagonal-shaped slot on the patch and a partial ground configuration are incorporated in the design for getting better bandwidth and gain.

This work is organized into five sections. Section I offers a brief introduction to the subject. Section II provides how the antenna design is made in the simulation software with the help of initial dimensions and design parameters. Section III provides the simulation results, which show the various antenna performance parameters like return loss, bandwidth, Voltage Standing Wave Ratio (VSWR), gain, directivity, surface current density, efficiency, and radiation patterns. Apart from this, all these parameters are analyzed to determine the performance of the designed antenna. Section IV provides the conclusion of the proposed work.

II. Design of Proposed Antenna

The proposed circular microstrip patch antenna is designed using CST Studio Suite 2023 software. Once the design is complete, the antenna can be simulated in the software to estimate its real-world performance. For antenna design, it is assumed that the dielectric constant of the substrate (ε_r), the resonant frequency (f_r in GHz), and the height of the substrate h (in mm) are known. Then a set of simplified equations of cavity model is used for calculating design parameters of circular microstrip patch antenna as follows.

Radius of the circular patch is given by [14]

$$a = \frac{F}{\left[1+\frac{2h}{\pi F \varepsilon_r}\left(ln\{\pi F/2h\}+1.7726\right)\right]^{0.5}} \quad (1)$$

where, a is radius of patch, h is the thicknes of dielectric substrate, ε_r = relative dielectric constant of substrate and F is logarithmic function of radiating element given by

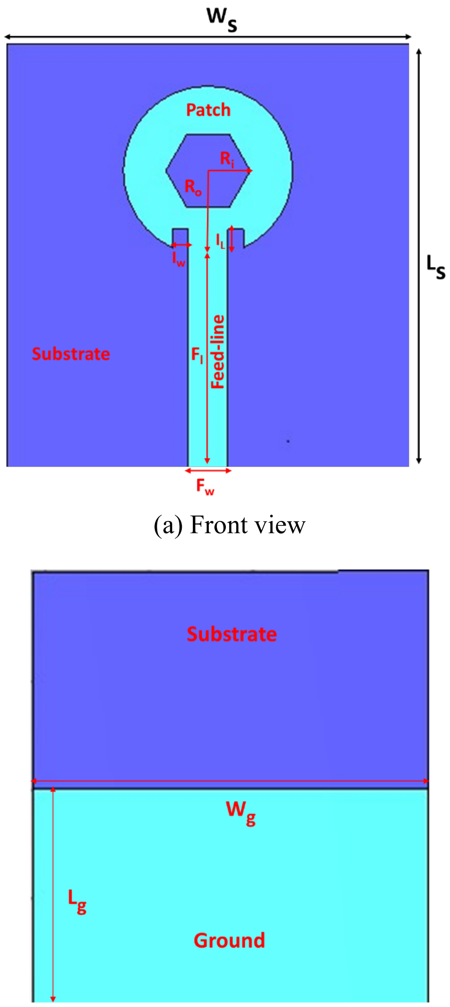
$$F = \frac{8.791\times10^9}{f_r\sqrt{\varepsilon_r}} \quad (2)$$

where f_r is resonance frequency

Length and width of the substrate can be calculated by

$$\text{Substrate length, } Ls = 2 \times 2a \quad (3)$$

Substrate width, $Ws = 2 \times 2a$ (4)



(a) Front view

(b) Back view

Fig.1 Geometry of the proposed circular patch antenna.

Once we get calculated values of the antenna design parameters to achieve the desired bandwidth, trial and error method is used to improve the performance of the proposed antenna along with its size reduction and finally the proposed shaped patch was achieved to optimize the results. The geometry of the proposed circular patch antenna is shown in Fig. 1. The outer radius of the circular patch (R_o) is taken as 8 mm and the antenna is printed on a textile material blue Jeans fabric with relative permittivity 1.67, loss tangent of 0.01 and the thickness of 1 mm is used as the substrate with an overall dimension of 40 mm×38 mm. The dimension of partial ground plane, which is printed in the bottom side of the substrate, is chosen to be 20mm×38mm. A hexagonal slot is cut inside the circular patch with the radius of inner circular patch slot (R_I) 4 mm and length of each side of hexagon slot is 4.18 mm. Then the full ground plane is cut to a partial ground to enhance the performance of the proposed antenna. An inset-fed microstrip feed line with dimensions 20mm×3.7mm is used with the circular patch to achieve the impedance matching 50Ω between the patch antenna and the transmission line. The detailed dimensions of the proposed antenna are shown in Table 1.

Table 1 Dimensions of Proposed Antenna.

Parameters	Values (mm)
Width of Substrate, W_s	38
Length of substrate, L_s	40
Substrate thickness, h	1
Outer circle patch radius R_o	8
Inner circle patch slot radius, R_i	4
Length of each side of hexagon slot	4.18
Length of feed line, F_l	20
Width of feed line, F_w	3.7
Inset fed gap length, I_L	2.5
Inset fed gap width, I_w	1.5
Length of partial ground, L_g	20
Width of partial ground, W_g	38

The selection of a specific substrate depends on the desired properties, manufacturing processes and intended applications involved. In flexible antenna design, substrate that possess the features of robustness, washability, flexibility, and stretchability with low dielectric constant, low relative permittivity, low coefficient of thermal expansion, and high thermal conductivity tend to be the most attractive material. The substrate used in textiles antennas can be natural fibers (like cotton, silk, wool, etc.), synthetic fibers (such as polyester, nylon, acrylic, and spandex), as well as blends of different fibers or mixtures of natural and synthetic fibers. Although there are several alternate materials that can be used for flexible textile antenna development, the substrate material used as in the proposed design is blue jeans.

In the proposed design, a hexagonal slot is incorporated to the circular patch for the first time to improve the performance parameters of the textile antenna intended to be used for Satellite Communication Applications. The proposed design is also more compact than the existing one.

III. Results and Discussion

The proposed circular microstrip patch antenna is designed and simulated using CST simulation software. An optimization between size reduction and performance enhancement is maintained in this work until satisfactory results were obtained. The performance of the proposed antenna is investigated in terms of the following parameters: return loss, bandwidth, VSWR, gain, directivity, total efficiency, radiation pattern and surface current density. The properties of the proposed antenna are discussed here.

3.1 Return loss (S11)

Return loss or S parameter indicates how much electromagnetic power from the microstrip patch antenna is returning back (reflected power) and therefore it is known as reflection coefficient. It determines the quality with respect to impedance match between the sending end (source) and the receiving end (measured load). To obtain a successful radiation mode, return loss must be below - 10 dB. Figure 2 (a) shows the S parameter versus frequency plot of the proposed antenna. It is seen that the resonance frequency of the proposed antenna is 4.2 GHz. The curve shows return

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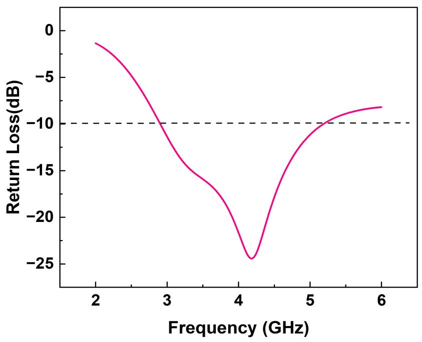
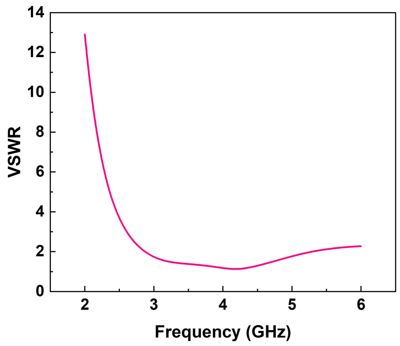
loss of the antenna is -24.42 dB at 4.2 GHz which indicates the impedance match is better and the energy loss is lesser. From Fig. 2 we can determine the bandwidth. The antenna works over the frequency range 2.91–5.2 GHz and so the -10 dB bandwidth is 2.29 GHz. This operating frequency range of the designed antenna covers the covers downlink C-band (3.4 to 4.2 GHz) of satellite communication.

3.2 Voltage Standing Wave Ratio (VSWR)



(a) Return loss



(b) VSWR

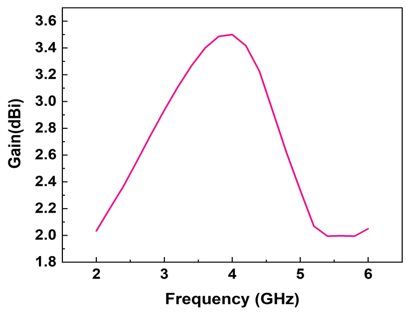
Fig. 2 Simulated (a) Return Loss and (b) VSWR of the Proposed Antenna.

The impedance mismatch between antenna and transmission line is measured by VSWR. The VSWR value of less than 2 is acceptable for a good design antenna. Fig. 2(b) shows VSWR Vs. frequency plot of the proposed antenna and it is seen that at the resonance frequency of 4.2 GHz the value of VSWR is 1.13 which much less than 2. The lower VSWR indicating better impedance match of the proposed antenna to the transmission line, and the higher the power supplied to the antenna.

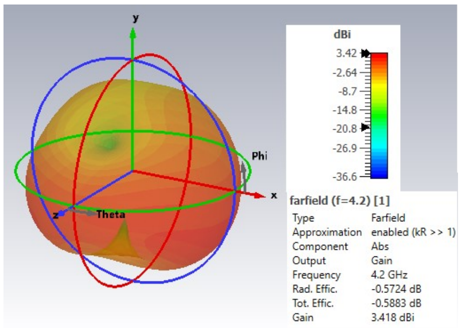
3.3. Gain

The parameter gain describes how efficient an antenna can send out or receive power in a particular direction. In other words, it indicates how much power is transmitted in a given direction to the radiation intensity that would be produced by an isotropic antenna. Figure 3(a) shows the frequency Vs. gain curve. At 4.2 GHz the gain of the proposed antenna is 3.42 dBi. A gain of 3.42 dB means the antenna radiates approximately 2.19 times more power in its main lobe direction than an isotropic radiator. This level of gain indicates moderate directionality, making the antenna suitable for applications requiring a balance between focused radiation and wide coverage. Figure 3(b) shows the 3D plot of far-field gain of the proposed antenna and the estimated peak value of gain is 3.418 dB at the resonance frequency of 4.2 GHz.

3.4 Directivity



(a) Gain Vs. Frequency



(b) 3D far-field gain at 4.2 GHz

Fig. 3 Gain of the proposed antenna.

The directivity measures how much intensely the antenna radiates power in its preferred direction and is defined by the ratio of the maximum power density to its average value over a sphere as observed in the far field. The 3D plot of far-field directivity of the proposed antenna at the resonance frequency of 4.2 GHz is shown in Fig. 4. It is noticed that the peak value of directivity of the designed antenna is 3.99 dBi. A directivity of 3.99 dB means the antenna focuses its radiated power approximately 2.52 times more in a specific direction than an isotropic antenna. This level of directivity is suitable for applications requiring moderate directional focus and coverage.

3.5 Efficiency

Antenna efficiency is defined as the ratio of the radiated power to the incident power at the antenna in percentage. At 4.2 GHz the efficiency of the antenna is 87.3%. Radiation efficiency of 87.3% is considered quite good, as it effectively converts a significant portion of the input power into radiated electromagnetic energy. Such antennas are desirable for various applications, including wireless communication systems, radar systems, and other radio

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frequency (RF) applications where signal strength and energy efficiency are critical factors. It is observed from the 3D plot of far field gain or directivity (Fig. 3 or 4) that the maximum radiation efficiency and total efficiency of the antenna are – 0.5724 dB and – 0.5883 dB at the resonance frequency of 4.2 GHz.

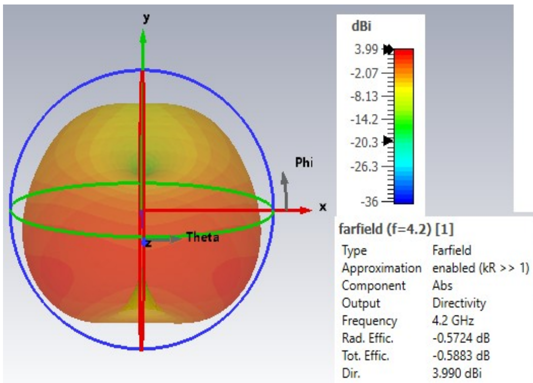
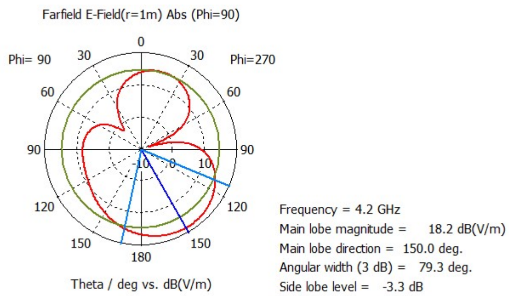
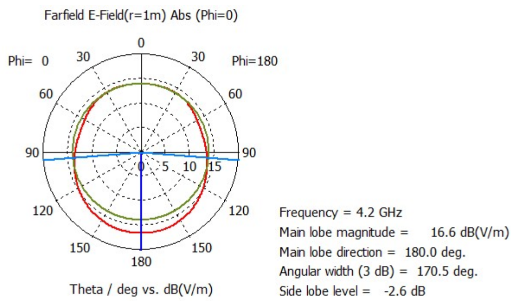


Fig. 4 3D plot of far-field directivity at 4.2 GHz.



(a)



(b)

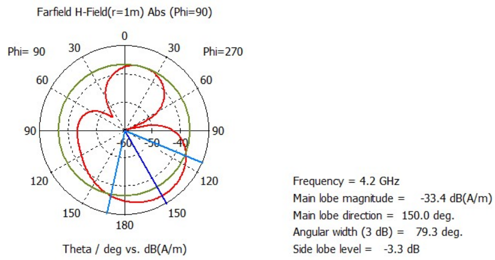
Fig. 5 Polar plot of Farfield E –field pattern at 4.2 GHz.

3.6 Radiation Pattern

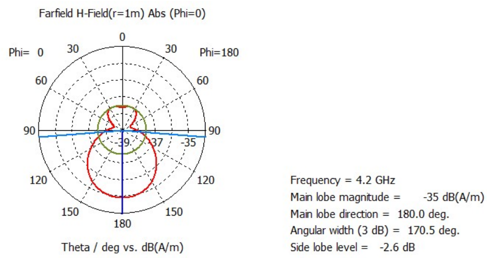
The radiation pattern is the distribution of the radiated power from the antenna (in the case of transmitting antenna), or received by the antenna (in the case of receiving antenna) as a function of the direction angles from the antenna.

E-field pattern: The polar plot of Far-field E–field pattern of the proposed antenna at 4.2 GHz is shown in Figure 5. It is seen that at phi 90 degree, the main lobe magnitude (maximum radiation intensity) is 18.2 dB(V/m), direction of main lobe is 150-degree, 3 dB angular width is 79.3 degree and side lobe level is – 3.3 dB. At phi 0 degree, their corresponding values are 16.6 dB(V/m), 180-degree, 170.5 degree and – 2.6 dB. The radiation patterns of the antenna are all observed to be omnidirectional.

H- field pattern: Figure 6 shows the polar plot of Far-field



(a)



(b)

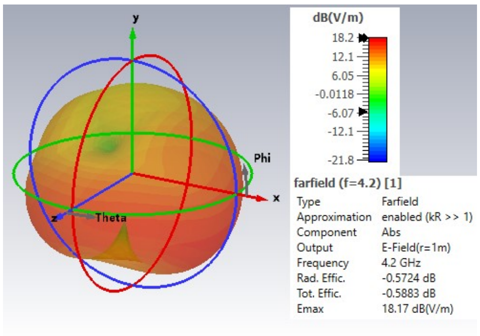
Fig. 6 Polar plot of Farfield H –field pattern at 4.2 GHz.

H–field pattern of the proposed antenna at 4.2 GHz. It is seen that when phi 90 degree the main lobe magnitude (maximum radiation intensity) is –33.4 dB(A/m), direction of main lobe is 150-degree, 3 dB angular width is 79.3 degree and side lobe level is – 3.3 dB. At phi 0 degree, their corresponding values are – 35 dB(V/m), 180-degree, 170.5 degree and – 2.6 dB.

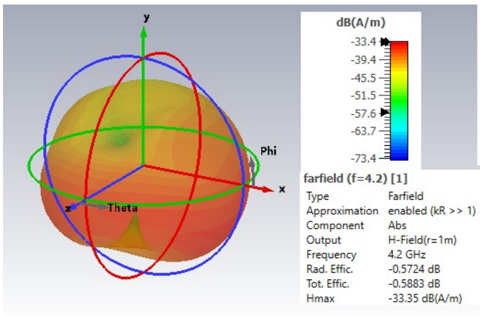
The 3D plot of Far-field E-field and H-field radiation patterns of the proposed antenna at 4.2 GHz are shown in Figs. 7(a) and (b), respectively.

3.7 Surface Current Distribution

Surface current distribution refers to the distribution of electric current on the surface of the antenna. Figure 8 depicts the surface current distribution of the radiating patch at the top and bottom of the antenna at the resonant frequency of 4.2 GHz. In Fig. 8, maximum currents are localized mainly in the ground, microstrip feed line, outer edge of the circular patch and the edge of the central hexagonal slot to produce resonant modes at 4.2 GHz. It is observed that the antenna exhibits impressive current distribution across its radiating element, peaking at 35.9927 dB(A/m). The magnitude of electric field is highest at the edges of the antenna. Hexagon slot and patrial ground are used to increase the electric current path, resulting in better radiation, improved gain and enhanced performance of the antennas.



(a) 3D E-field pattern



(b) 3D H-field pattern

Fig. 7 3D plot of Far-field radiation patterns of the proposed antenna at 4.2 GHz.

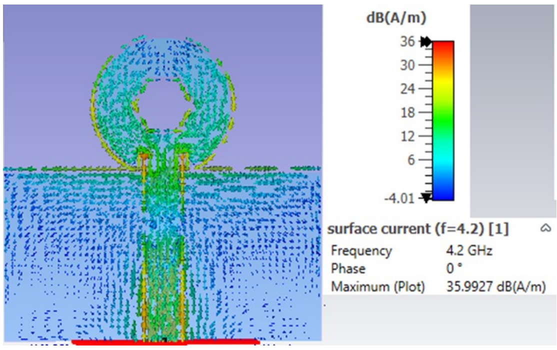


Fig. 8 Surface current distribution of the designed antenna at 4.2GHz.

3.8 Performance Comparison

Table 2 presents a performance comparison of the proposed antenna and the previously reported antenna, where the proposed model is compared with other existing work. After comparison, it is concluded that the proposed antenna obtains better impedance matching, a wider bandwidth, higher gain and directivity with a smaller size.

Table 2 Performance Comparison of the proposed antenna with existing one at 4.2 GHz.

Ref. No.	Size (mm^3)	S11 (dB)	BW (GHz)	Gain (dBi)	Directivity (dBi)
[13]	40×40×1	-19	1.15 (3.64–4.79)	NR	3.91
This work	40×38×1	-24.42	2.29 (2.91–5.2)	3.42	3.99

NR = Not Reported

IV. Conclusion

In this paper, a flexible textile microstrip patch antenna has been designed and simulated using CST microwave Studio software for C band applications. In the proposed antenna design, washable, wearable, flexible and very economical textile material blue Jeans fabric is used as the substrate and self-adhesive Copper tape is used to make the patch and ground. The antenna is compact with an overall dimension of 40×38×1 mm^3 and is excited through a microstrip inset feed line. A hexagonal-shaped slot on the patch and partial ground plane structure are incorporated for getting better bandwidth and gain. The proposed antenna is resonating at 4.28 GHz and operating in the frequency range of 2.91-5.2 GHz, with a wide bandwidth of 2.29 GHz and high return loss of -24.42 dB show good impedance matching. The peak gain and radiation efficiency of the antenna at 4.2 GHz are 3.42 dBi and 87.3%, respectively. The proposed textile antenna covers downlink C-band (3.4 to 4.2 GHz) of satellite communication, offers superior performance with its compact size, wearability, acceptable return loss and VSWR, wide bandwidth, reasonable gain and efficiency, stable radiation pattern over its whole range of frequencies, and proves to be a suitable candidate for C-band satellite communication applications.

In future work, we will focus on fabrication and testing of the proposed antenna and performance comparison of the simulated and measured results. The performance of this antenna can be further improved by cutting modified slots on the patch and ground plane, using different substrate materials. By integrating this proposed single elemental design antenna into an array on a single substrate, enhanced gain, directivity and efficiency can be obtained compared to its singular counterpart.

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