Compact Beam Steerable Pixel Antenna

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***Abstract*—Beam steerable antennas are indispensable for various applications, which includes wearable and on-body biomedical devices as well as wireless devices. Researchers had shown a great interest to implement beam steering in antenna. But most of the design do not provide full beam steering in the horizontal plane. An end-fire beam steerable planar single layer printed antenna was introduced, which can steer beam around 300° in azimuth plane. This antenna has a dimension of around 165 x 100mm^2. To make it a potential candidate for biomedical application the size should be reduced without affecting its gain significantly. In this work, in order to reduce the vertical size microstrip feed, λ/4 impedance transformer, and balun are rearranged in the same horizontal line. Also a modified bow-tie dipole is used as a driven element. With the modified design the size of antenna has reduced to 127 x 90mm^2. Simulation results indicate that antenna provides a gain of around 7.8dBi at 2.5GHz and has low SLL.**

***Index Terms*—Reconfigurable antenna, beam-steering, pixel antenna.**

I. Introduction

Planar millimeter-wave antennas are important for low-cost communication and sensor systems and these have been traditionally achieved using microstrip, dipole and slot antennas on dielectric substrates. However, these antennas result in a broadside pattern which may not be compatible with azimuthal switching beam systems. For end-fire radiation patterns, the most widely used antenna is the tapered-slot antenna, but it suffers from a relatively high cross-polarization level and occupies a lot of space on the substrate. As an alternative, Yagi-Uda antennas operate as end fire arrays, which have reduced length compared with TSAs and can also have high gain. They have been utilized in numerous applications where directional radiation is necessary for point-to-point wireless communications.

But individual end-fire planar antennas usually have a fixed beam direction. But if such antennas have some form of beam-steering capability would be useful in a wide variety of wireless systems. For example, beam-steering capability has a crucial role in biomedical applications, where an increasing number of health care monitoring systems use wireless body area network technology. In body area network technology, several on body and off body devices continuously monitors patients physiological data such as breathing, electrocardiogram (ECG), heart beat, glucose level, etc and sent data to dedicated medical data servers wirelessly for further analysis. In such scenario, beam-steering can be used to enhance the performance of the communication system.

The beam-steering capability of antennas is traditionally provided by using multiple antenna elements in an array and incorporating phase shifters. This technique can lead to large overall antenna sizes if several array elements are required and also, the use of phase shifters will also increase cost and losses. Over the years, several other techniques have been exploited to implement beam steering in biomedical antennas, but most of which do not cover the entire azimuthal plane.

II. Literature Review

The different beam steering antennas without phase shifters, and optimization algorithms in reconfigurable antennas are described.

An approach used for beam steering without using shifters is using tunable surfaces[2]-[3]. In [2] authors proposed a beam steering technique without using phase shifters, which is achieved using special texture on a conducting periodic surface under the antenna. In this technique, a resonant textured surface is loaded with varactor diodes. The reflection phase of the surface can change as a function of frequency, by varying the bias voltage across the varactors.

Another approach used was reconfigurable antenna based on parasitic element theory[4]-[5]. In [4] author proposed an similar approach for designing electronic beam steering arrays with reactive parasitic elements. For demonstrating the method, an example of a circular array formed by capacitively tuned monopoles is taken. The related capacitances were found out straightforwardly and there was no need for any optimization techniques. The resulting beams were steerable.

Another approach includes a modified version of the tunable structure known as pixel surface[5]-[7],[15]. In [6] author presents a multifunctional reconfigurable antenna array (MRAA) based on parasitic layer and is designed using four identical multifunctional reconfigurable antenna (MRA) elements. Corresponding to three steerable beam directions (θ_{xz}= -30°,0°,30°), each MRA can produce eight modes of operation with linear and circular polarizations in the x-z plane. In y-z plane, another two steerable beam directions (θ_{yz}= - 30°,30°) with linear polarization is obtained. In this approach, an individual MRA has an aperture-coupled patch antenna as the driven element and a parasitic pixel layer. The parasitic pixels are placed above the driven element. This parasitic layer contains a grid of 4x4 electrically small rectangular shaped metallic pixels. The adjacent pixels in the design can be connected/disconnected by means of switches, this results in reconfigurability in beam-direction and polarization. The main challenge in parasitic pixel design is that optimization is required.

In most of these antenna designs, do not have wide steering range[8]-[9]. In [1] an end-fire beam steerable antenna is described. The antenna can steer 300°in the azimuthal plane. To make it a possible potential candidate for biomedical application, the design should be more compact. In this paper, a compact beam steerable antenna with wide scanning angle is proposed.

III. System Description

This section gives a brief overview of the designed beam steering antenna and its operation. The main objective of this work is to design a new compact printed beam steerable pixel antennas that can provide significant gain and full beam steering in the azimuth plane. The antenna design consists of a radiator with a half-wavelength splitting bow-tie driven dipole,a rectangular grid of parasitic pixels, truncated ground plane, microstrip feed, $\lambda/4$ impedance transformer and balun. In order to reduce size microstrip feed, transformer, and balun are arranged horizontally. The design is based on the parasitic element theory. The parasitic pixel layer and radiator is placed on the front side of the substrate while ground plane and dc bias lines are placed at the backside of the substrate which acts as a reflector. In the approach parasitic pixel layer is placed in the reactive field region of the driven element and produces strong coupling between the driven element and the parasitic pixel layer. This induces significant currents over the pixel layer, allowing the antenna radiation pattern to be beam- steered. To obtain a reconfigurable pattern that can achieve beam-steering capability, pixels are connected with switches.

A. Antenna Geometry

In this work a novel miniaturized beam steering pixel antenna is introduced. This antenna design and operation is based on the work in [1]. The design consist of a half wavelength printed driven element, a microstrip-to-coplanar stripline(CPS), microstrip feeding line, $\lambda/4$ impedance transformer, balun phase shifter and a ground plane. Fig.1. shows the geometry of the designed antenna and Table I. shows the dimensions for enabling operation at 2.5 GHz.

Rogers R04003 substrate of thickness 1mm (ε_r = 3.55 and tan δ = 0.0027) is used in the design. As in work [1], behind the driven element on the backside of the substrate a truncated ground plane is integrated and it acts as the reflector. Using a good balun design the antenna can be matched with a wide BW. For a 50Ω input impedance, W1 =

TABLE I
Dimension of proposed antenna(in mm) for enabling operation at 2.5 GHz

W_1	2	L_4	14.9	L_{dr}	60.6	W	90
L_1	17.6	L_5	28.9	L_{pi}	10	L_g	26.5
W_2	6.5	L_6	10.2	d_1	13.7	L	127
L_2	30.5	L_{cps}	19.7	d_2	5	L_f	5.5
W_k	1.4	L_{cps1}	5.5	d_3	5	W_f	2.6
L_3	28.9	W_d	16.3	g	1	W_s	0.7

2 mm is connected to the balun. The balun design includes a microstrip-to-CPS transition with 1-mm spacing. The balun design of antenna is taken from [14] and in order to simplify the design microstrip and CPS widths are made equal as BW is just 8%. The antenna is operated by exciting a quasi-TEM mode along the balanced lines connected to the dipole. This excitation is being achieved by splitting the primary microstrip line into two separate lines. To introduce a 180° phase shift one of the two lines has meandered. To match the antenna/balun impedance to 50Ω quarter-wavelength trans-former section is attached to the balun. The input impedance is affected by meander line gap spacing, through mutual coupling in the balun.

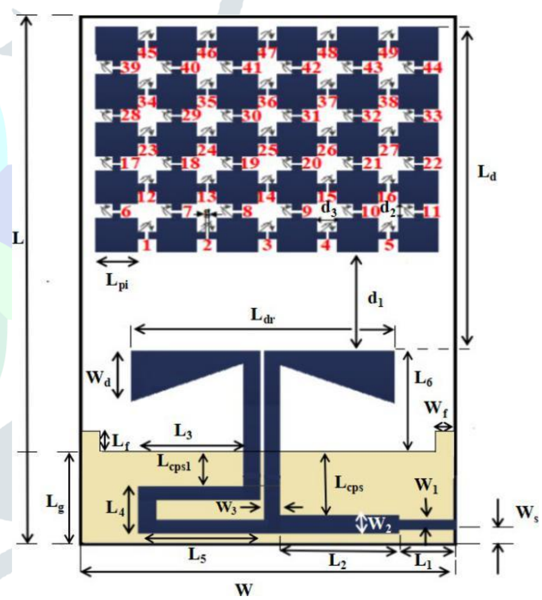

Fig. 1. Geometry of designed antenna.

The design has a grid of 5 x 6 electrically small metallic rectangular-shaped pixels which forms a parasitic layer. This parasitic pixels layer is placed in front of the driven element and is used to change the beam to the desired direction. The pixels have switch connections between them, which provides steering with very low gain fluctuation. The parasitic pixels are placed at a distance of d_1 = 13.7 mm from the main driven dipole and spacing of d_2 = d_3 = 5 mm = (λ_0/24) and g = 1 mm, as shown in Fig.1. The pixel surface dimensions are designed in such a way that the radiation coupled from the driven element to the beam-steering directions is maximized, to achieve reconfigurability. Therefore, the overall size of the pixel surface is made large enough to enable resonant structures of at least a half wavelength. While the size of the individual pixels must be small enough to finely tune the dimensions of these resonant structures. Therefore suggested pixel size should be neither too small nor too big, and it has been observed in [1] that pixel size below (λ/10) are sufficient to provide rich reconfigurability. In this work, the pixel dimension is designed as (λ/12) x (λ/12). To maximize the coupling between pixels the gap size g is designed and the final dimensions are shown in Table I. The p-i-n diode switches are utilized for the connections between pixels, for experimentally demonstrating antenna design operating at 2.5 GHz.

The vertical size of antenna is determined by the height of microstrip feed, λ/4 impedance transformer, balun and the distance from the ground patch to the director while the the horizontal size depends on the width of the ground plane and length of the driver. In order to reduce the vertical size the λ/4 impedance transformer, microstrip feed, and balun are rearranged in the same horizontal line[13] as shown in Fig. 1. This rearrangement has lead to approximately 24% reduction in vertical size. To reduce the horizontal size and improve gain the strip loading technology is an efficient miniaturization way. In this work, the vertical strips are applied to the two sides of the ground plane and also a modified bow-tie dipole is used as the driver. When the two sides of the driven dipole are loaded with strips, the original current path will be prolonged. Thus the shorter dipole can be efficiently resonant at the original resonant frequency. But in this work, since we need to include dc control lines and switches, horizontal size cannot be reduced much. The proposed design occupies an area of 127 x 90 mm^2 and is compact compared to [1].

Individual pixels of size 10 x 10 mm^2 is connected by 49 Skyworks SMP1345 p-i-n diode. To provide dc ground for each pixel, 39-nH lumped inductors interconnects the pixelated surface. In this design, 8-pF dc-block capacitors are used between the different diodes to provide dc isolation. DC bias lines are provided at the backside of the substrate. In order to avoid the effects of this layer on antenna performance, inductors are used to split the lines into electrically small sections, which ensures their RF transparency, and minimize coupling with the radiating pixel surface. For connecting dc bias lines to the p-i-n diode switches on the parasitic surface vias are plated through the substrate. The switching components and dc bias circuitry used in this work are taken from [10].

B. Antenna Operation

The designed antenna without a ground plane, balun, and pixels act as a simple dipole with a bidirectional radiation pattern and poor impedance matching. At the rear of the substrate, a reflector is constructed from a ground plane with separation L_6 = 10.2 mm from the driven element as shown in Fig. 3.1, the designed antenna becomes directive and is similar to a basic Yagi-Uda antenna without directors. The truncated ground plane is loaded by two strips at both ends BW. The length of the antenna from the main driven element, L_d is defined as

$$L_d(n) = d_1 + n(L_p) + (n-1)d_2 \quad (1)$$

where n is the number of pixel rows, d_1 is the distance between the first pixel row and driven element, L_p is the square pixel length, and d_2 is a separation between two pixel rows. In this design, d_1= 13.7 mm, d_2 = 5 mm, and g = 1 mm, as shown in Fig. 1.

The beam-steering capability of the designed antenna can be best described using the theory of reactively controlled directive arrays developed by R. F. Harrington [12]. The gain of Yagi-Uda antennas is increased by adding directors. The radiation characteristics of an antenna system as in [12], which consists of one driven antenna element and a number of parasitic elements, are shown to be controlled by impedance loading of the parasitic elements. The impedance loading happens when the EM energy generated by the driven antenna couples to the parasitic elements by EM mutual coupling. The appropriate reactive loading of parasitic elements can cause surface current on them to resonate. This may lead the antenna to radiate with high gain in a given direction. In this antenna design, a specific configuration of the parasitic pixel surface corresponds to the proper reactive loading [1], which can be obtained by connecting the pixels appropriately using switches. Since the parasitic pixels are placed at the reactive region of the driven element, strong mutual coupling takes place. This mutual coupling induces sufficient currents among pixels and the required phase shift can be made by the proper connection between pixels, thus the desired radiation pattern can be formed.

The gap g between unconnected pixels have an effect on antenna operation. The gap between adjacent pixels is equivalent to mutual capacitance and it has an inverse relation to the distance g. Therefore, g needs to be small to create ample coupling between adjacent pixels in a row, to form a resonant directive structure. This mutual coupling induces a significant current among the pixels in a row to create the necessary phase shift, which contributes to the total radiation pattern of the antenna.

To understand the operation of the pixels, circuit theory can be used to characterize the interactions between parasitic pixels elements and the driven element [12]. This can be done by treating the pixel antenna as a multiport network, and for this purpose port numbers are added as shown in Fig 1.(red color). To find out the reflection coefficient at the feed port, network circuit analysis can be performed and using the lumped element model of the pin diode switch [10] for the "ON" and "OFF" connections between ports. By summing the radiation patterns resulting from each port current, the overall pattern of the antenna can be found out. Radiation patterns resulting from each port can be found by exciting each port in turn, with all other ports "OFF". If $E_j(\theta = (\Pi/2), \phi)$ define the field pattern resulting from the unit current at each port in turn, with all other ports ”OFF”. If E_j ($\theta = (\Pi/2)$, ϕ) define the field pattern resulting from the unit current at port j, with all other ports ”OFF”, then the total pattern from a given set of port currents can be found by adding them together and weighing them by their magnitude and phase. It can be written as

$$E_{total}(\theta = \frac{\Pi}{2}, \varphi) = \sum_{j=1}^{49} i_j E_j(\theta = \frac{\Pi}{2}, \varphi) \qquad (2)$$

where $E_{total}(\theta = (\Pi/2), \phi)$ is the total pattern of the antenna and E_j ($\theta = (\Pi/2)$, ϕ) are like element factors in a rectangular 2-D pixel array. It is important to note that the patterns from each individual pixel, E_j ($\theta = (\Pi/2)$, ϕ), are fixed for a given geometry (independent of the connections between them), and therefore, the set of all possible overall patterns $E_{total}(\theta = (\Pi/2), \phi)$ can in principle be found from their weighted combinations. However, the difficulty is that the feeding currents to each pixel cannot be set arbitrarily and depend on the connections between pixels. Therefore, the set of possible patterns is much less than if arbitrary currents could be applied to each pixel port and this makes it difficult to analyze explicitly.

IV. Results & Analysis

The aim of the work is to implement a compact antenna that can steer the beam in the azimuthal plane with low SLL and can provide better gain. The simulation was carried out using Ansys HFSS software.

The proposed antenna was designed to operate at 2.5GHz. Rogers R04003 was used as substrate and has an overall size 127 x 90mm^2. To operate at 2.5GHz pixels are interconnected using Pin diode switches. All elements such as dc control lines, inductors and capacitors can be included in the simulation and pin diode can be modeled as lumped elements[10]. But for simplicity of design, during simulation dc bias lines are omitted.

Initially, the antenna performance with the different number of rows was evaluated. Table II shows the gain obtained with different number of rows. It tabulates simulated antenna performance at 2.5GHz. The variations observed in BW is also provided in Table II. It is clear from Table that the gain increases with the number of pixel rows and is similar to Yagi-Uda configuration. Additionally, if connections(switches ON) between pixels are optimized forward gain can be increased to around 10dBi with 5 number of pixel rows.

At the next stage of design, we had investigated the effect of switches on impedance matching. Fig. 2 represents the simulated ”ON” and ”OFF”, S11 and radiation pattern of our proposed antenna with 5 number of pixel rows. It can be determined that the BW of proposed antenna covers 2.4-2.6 GHz with a gain of 7.8dBi main lobe gain at ϕ =0°, when all switches are ”OFF”. That is the configuration with all switches are ”OFF” has little effect on matching. Similarly the configuration with all switches ”ON” has evidential effect on S11 and radiation pattern. Also, the overall BW has varied

TABLE II
PROPOSED ANTENNA PERFORMANCE WITH DIFFERENT NUMBER OF PIXELS WHEN SWITCHES ALL ARE OFF

Row	Gain(dBi)	BW(GHz)	SLL(dBi)
0	4.63	2.45-2.52	-11.44
1	5.3	2.45-2.52	-12.3
2	6.1	2.46-2.54	-14.4
3	6.4	2.46-2.53	-15.3
4	6.8	2.45-2.53	-16.7
5	7.8	2.44-2.52	-11.44

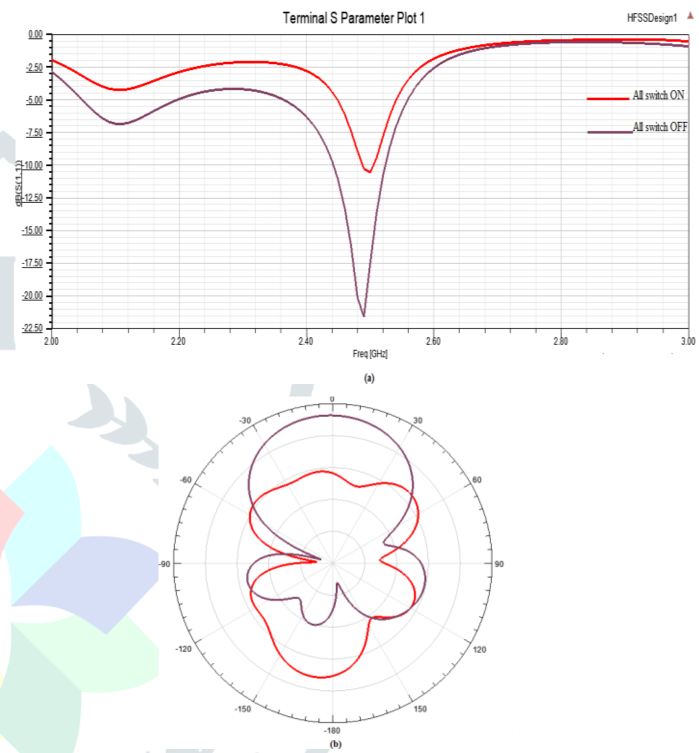

Fig. 2. Simulation result of the proposed antenna when all switches are ”ON” and ”OFF”. (a) S11 (b) Radiation pattern in the azimuthal plane at 2.5 GHz

to 2.48-2.51 GHz. So during optimization S11 should also be considered.

To verify whether the proposed antenna can steer the beam in azimuthal plane, it is tested with different pixel configurations. The proposed antenna design has tested only for 4 beam directions at angles $\varphi \in$ [0°, -30°, -90°,-150°] and θ =90°. Since the proposed antenna geometry is symmetrical along x-axis similar to end-fire pixel antenna, 7 beam direction are obtained with 4 unique pixel configurations. This antenna can steer the beam in other direction also by further optimization of pixel surface.

Fig 3 shows the simulated S11 and radiation pattern of our proposed antenna at different beam directions in xy plane. It is clear from the figure that our antenna can steer the beam in azimuthal plane with average gain of around 5.5 ±2dBi. It also has a common bandwidth of around 200MHz around center frequency 2.5GHz. To gain insight on performance of

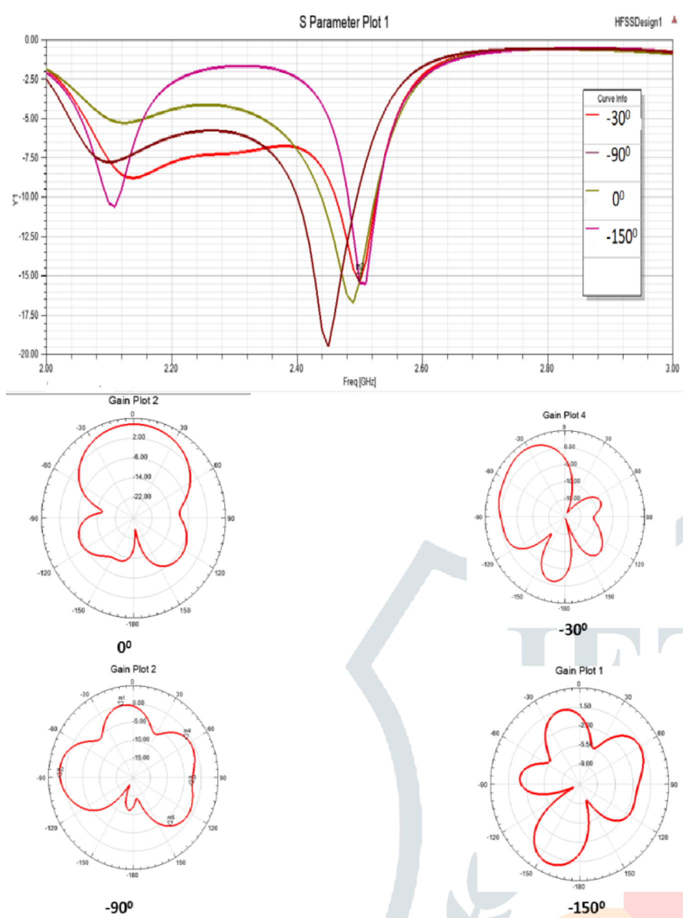

Fig. 3. Simulation result of the proposed antenna when all switches are ”ON” and ”OFF”. (a) S11 (b) Radiation pattern in the azimuthal plane at 2.5 GHz

TABLE III
PROPOSED ANTENNA PERFORMANCE WITH DIFFERENT SUBSTRATE AT 2.5GHz

Substrate	εr	tan δ	Gain(dBi)	BW(GHz)
FR4 epoxy	4.4	0.02	1.6	2.23-2.30
Rogers R03003	3	0.0013	7.4	2.62-2.71
Rogers RT/ duroid 5870	2.33	0.0027	7.44	2.03-2.09
Rogers R04003	3.55	0.0027	7.8	2.44-2.52

our designed antenna with different substrate a comparison is made. Table III tabulates simulated performance of designed antenna with 5 rows of pixel surface when all switches are ”OFF” using different substrate. Fig. 4 shows the simulated S11 for different substrates.

The effect of four different substrate- FR4 epoxy, Rogers R03003, Rogers R04003 and Rogers RT/duroid 5870 in antenna performance is evaluated. From Fig 4 we can see that the antenna resonates at a different frequency for different substrates. On investigating we can observe that as permittivity decreases the resonant frequency shift towards the right of center frequency(2.5GHz) and vice versa. Also from the table we can determine that our proposed antenna have maximum gain when using Rogers R04003 substrate.

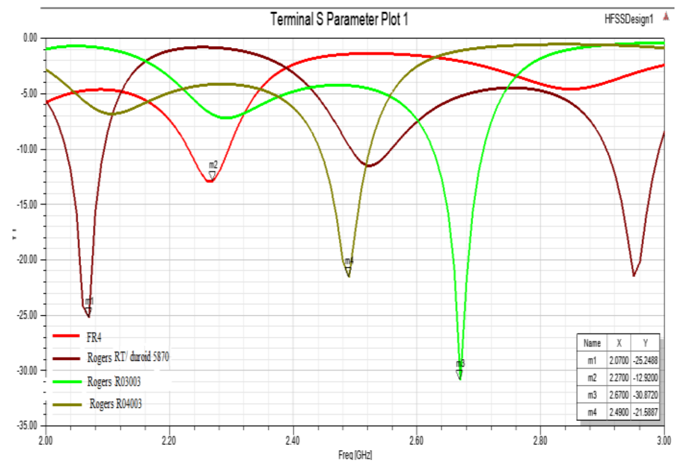

Fig. 4. Simulation S11 result of the proposed antenna using different substrates at 2.5GHz.

TABLE IV
COMPARISON OF MODIFIED ANTENNA WITH [1]

	Beam steerable antenna [1]	Proposed antenna
Size(mm^3)	165x100x1 at 2.5GHz	127x90x1 at 2.5GHz
Coverage range	φ =±150°	φ= ±150°
Pattern type	End-fire	End-fire
Gain(dBi)	8.2	7.8
SLL	low	very low
BW(MHz)	200	200

As a final note, the proposed antenna design is compared with end-fire pixel antenna in [1]. The comparison of proposed beam steerable antenna with end-fire pixel antenna is tabulated in Table IV. It shows the antenna performance including BW, gain, SLL and so on.

On comparing modified antenna with pixel antenna[1], we can conclude that similar to pixel antenna our antenna has end-fire pattern and can steer beam at wider. Even though the gain of our designed antenna at 2.5GHz is slightly lower that pixel antenna but our design is more compact and has low SLL. So the designed can be used for biomedical applications.

CONCLUSION

Beam steerable antenna with compact design, that can steer beam over a wide range can enhance the performance of biomedical devices. In this work a compact antenna that can steer beam with a reasonable gain and low SLL is introduced. The design of antenna includes microstrip feed, $\lambda/4$, balun, half-wavelength modified bow-tie driven element, truncated ground, and switches. The vertical size of the antenna has reduced by 24% by rearranging feed, transformer, and balun in a horizontal line. While horizontal size has reduced by 10% using strip overloading. Simulation results demonstrate that the designed antenna can steer beam around 300°with an average gain of 5.5 ± 2dBi and has low SLL at 2.5GHz. The designed antenna has a BW of 200 MHz around center frequency(2.5GHz). So our designed antenna can be considered as a possible candidate for biomedical applications. A comparison of the designed antenna with different substrate is also done.

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