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Performance enhancement of implantable medical antenna using differential feed technique

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ABSTRACT

The health care industry is continuously revolutionizing and advancing towards developing more efficient system suitable for human body. Today implantable devices have become a more interesting topic in health care services which primarily started with the pacemakers. Since then it is continuously evolving due to its non-invasive nature, instant monitoring and diagnosis, and periodic simulation. The main goal of these implantable devices is to efficiently monitor or inspect various ailments in the body and then transmits this to the server or base station. For proper communication between the implant and the base station, antenna design is of prime importance. In this paper MEMS based differentially fed dual band antenna has been proposed and can be used both in Medical Implant Communication Service (MICS) band for transmission of data and industrial, scientific and medical (ISM) band for wake-up purpose. The proposed antenna has been simulated for free space scenario and has been found to radiate in both MICS & ISM band with S_{11} of –17.62 dB and –14.31 dB respectively. Subsequently the antenna is inserted within a skin mimicking model with equivalent dielectric features and the results show variation in radiation characteristics between free space condition and within skin phantom. The design of the antenna has been optimized in such a way that minimum deviation occurs between the two conformal conditions. With the use of differential feeding technique performance of the antenna is quite enhanced in terms of various parameters when compared with single feed.

1. Introduction

The journey of biomedical implants started with the pacemakers in the early 1960s which was basically wearable and battery powered that was developed by Medtronic which improved the lives of millions of people till date [1]. Implantable devices are now used to prepare a virtual environment to stimulate, monitor and diagnose the various organs inside the body. The implantable sensors work on the principle of electrochemical sensing in which sensors generate current/voltage proportional to glucose, temperature, pH, and cardiac pressure, and transmit this information to the base station via antenna. Antenna is an essential component in the transmission of data from implants to the outside environment through wireless links which is known as bio-telemetry. Earlier designs mainly focused on the industrial, scientific and medical (ISM) band for medical telemetry operations, but recently medical implant communication service (MICS) band (402–405 MHz) has been allocated which is regulated by the United States Federal Communications Commission and the European Radio Communications Committee for bi-directional bio-telemetry operations [2]. The 3 MHz band allows 10 channels with a bandwidth of 300 KHz each in order to maintain simultaneous operation among multiple implantable medical devices within the same area, and to minimize interference with other services. The MICS band allows low noise propagation through human body and is viable with low power implanted device circuits [3]. According to Med Radio rules the wavelength for free space is 74 cm whereas for ISM bands it is around 12 cm [4]. From these recommendations there is a need to miniaturize the antenna so that it can be properly embedded inside the human body conforming to its bio-compatible properties and other values like gain, SAR, bandwidth, directivity, etc.

The study of electrically small antennas and its radiation characteristics started in mid-40s where the volume of the antenna is directly proportional to the radiation power factor, the product of efficiency & bandwidth of the antenna [5]. Various miniaturization techniques has been proposed in literatures like the use of high permittivity dielectric substrate, lengthening the current flow path on the patch surface, and inserting shorted pins between the ground & the patch plane resulting in decrease ineffective size of the antenna [6]. Inside the human body (lossy medium) the near field power of antenna increases the temperature of neighboring tissues which

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may be worthy for therapeutic treatment but has a negative impact over communication [7]. Higher frequency operation results in increase in temperature of the tissue within the proximity of the implant. The antenna designed in this paper is a simple meandered line antenna provided with a switch to make it reconfigurable. In a meandered antenna as the number of turns increases the size of the antenna reduces in the meantime [8]. The reason behind using this type of structure is to miniaturize the size of the antenna without compromising the effective radiation properties for an implantable antenna. The antenna designed in this paper radiates in MICS band for data transmission related to patient monitoring, to check the device conditions and battery health where the antenna will only transmit data until it is acknowledged by a wake up signal in the ISM band [9]. This technique resulted into saving of power in the implanted device which is of prime importance in medical applications. MEMS based switches has been used to design a reconfigurable/multi-band antenna to replace PIN diode switches or semiconductor switches due to lower insertion losses, good isolation, lower inter-modulation distortion, and less power consumption [10]. In the proposed antenna dual feed technique has been employed where the excitations of two ports are equal in magnitude and 180° out of phase, the foremost parameter being the differential reflection coefficient or odd mode reflection coefficient which can be applied to general applications [11].

2. Antenna design

2.1. Design principle

The design is based upon the phenomenon of exploiting the frequency characteristics of a slow wave structure for its implementation in implantable antenna. As the effective current length is small in case of simple patch antenna, the resonant frequency is always higher compared to meander structure based antenna [6] as shown in Fig. 1. The size of the meandered line antenna is inversely proportional to the number of turns present in the antenna so the general target is to increase the number of turns. The dimensions of the meandered line antenna are computed and approximated through the following sets of equations [8].

$$W = 0.70 \times \lambda_g \tag{1}$$

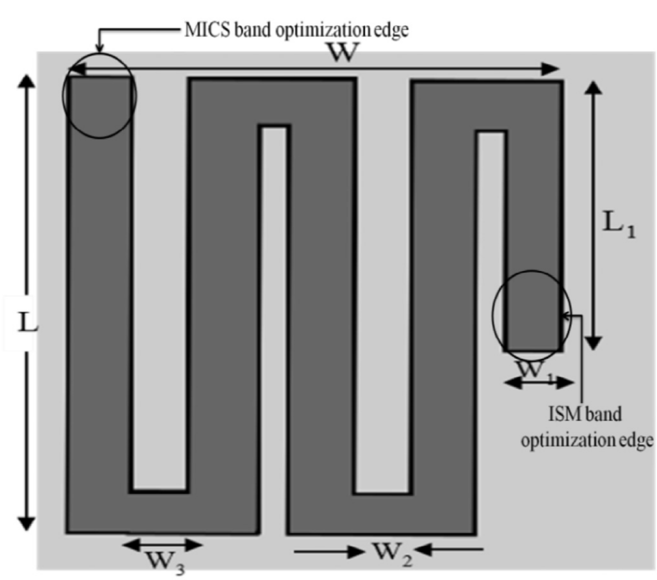


Fig. 1. Single feed layout with controlling edges for ISM and MICS bands.

$$L = 0.42 \times \lambda_g \tag{2}$$

$$W_1 = 0.05 \times \lambda_g \tag{3}$$

$$W_3 = 0.16 \times \lambda_g \tag{4}$$

$$\lambda_g = \frac{\lambda}{\sqrt{\varepsilon_{reff}}} \tag{5}$$

where λ_g is the guided wavelength, λ is the free space wavelength and ε_{reff} is the effective dielectric constant.

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 10\frac{h}{w}\right]^{-\frac{1}{2}} \tag{6}$$

h = height of the substrate
ε_r = di-electric constant of the substrate
W = width of the meander line antenna

Revised approximated dimensions of the antenna are:

$$W_r = W + \Delta L \tag{7}$$

$$L_r = L + \Delta L \tag{8}$$

$$W_{3r} = W + \Delta L \tag{9}$$

where W_r, L_r, W_3 are the revised dimensions of the meandered line antenna & ΔL is the equivalent length.

$$\Delta L = 0.5 \times W \tag{10}$$

$$W = \frac{c}{2 f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{11}$$

where f_r is the resonant frequency and c is the velocity of light.

Considering the center frequency at 403 MHz the revised dimensions of the meandered line antenna are found to be W_r = 22.72 cm, L_r = 16.5 cm, W_{3r} = 10.84 cm and W_1 = 1.1 cm using the above set of equations. An antenna having the above size cannot be implanted inside human body unless it is strongly miniaturized. So in the next step the number of turns of the meandered line antenna is increased step by step and in the meantime the dimensions of the antenna is reduced proportionally. By running multiple simulations the antenna is optimized with the miniaturized dimensions.

Basically two types of phenomenon occur in meandered structures when exposed to electromagnetic waves [12]. These are: a) electromagnetic interaction between adjacent meandered slots, and b) edge effects.

When the patch antenna with one meander structure is used, it is found that the antenna radiates at a single resonance frequency (559 MHz) without shorting pins as described in Kiourti and Nikita [6]. In order to increase the overall current path length a symmetrical patch is added horizontally with the first structure. Since W > L so the structure is not added vertically because that will increase the volume of the antenna. To control the radiation performance, meander structure is important as the longer side of the meander controls the MICS band and the shorter side is responsible for ISM band which was found through optimization. Fig. 1 shows the corresponding structure of a single feed layout. To radiate in higher frequency band along with the lower band the antenna is optimized by adding a switch near the shorter strip which controls the ISM band so there is more electromagnetic interaction along the shorter edges of the two symmetrical patches. Due to this optimization, the antenna radiates around 413 MHz, 1.9 GHz and 2.72 GHz respectively which are effective for biomedical applications. Thus it can be used for data transmission, wireless transfer of power to the device and for wake up purpose.

Initially patch antenna having dimensions of $22.5 \times 22.5 \times 0.5\ \mathrm{mm}^3$ is used with a single feed and shorting pin so that the device can work in the MICS band [6]. But it is quite difficult to fabricate with the addition of shorting pins. So to simplify the fabrication process we introduce an edge feeding technique and avoid the shorting pins approach. To obtain radiation at MICS band, different modifications are done. The significant parameters required for antenna design are frequency of operation, substrate height and dielectric constant of the substrate. The antenna is fabricated on a silicon substrate having a dielectric constant (ε_r) of 11.9 and a patch made of gold of thickness 0.25 mm. The different parameters of the meander structured antenna are given in Table 1. This single patch antenna configuration cannot achieve the prescribed MICS and ISM bands simultaneously. In order to improve the radiation performance over the MICS and ISM bands, a symmetrical counterpart of the initial

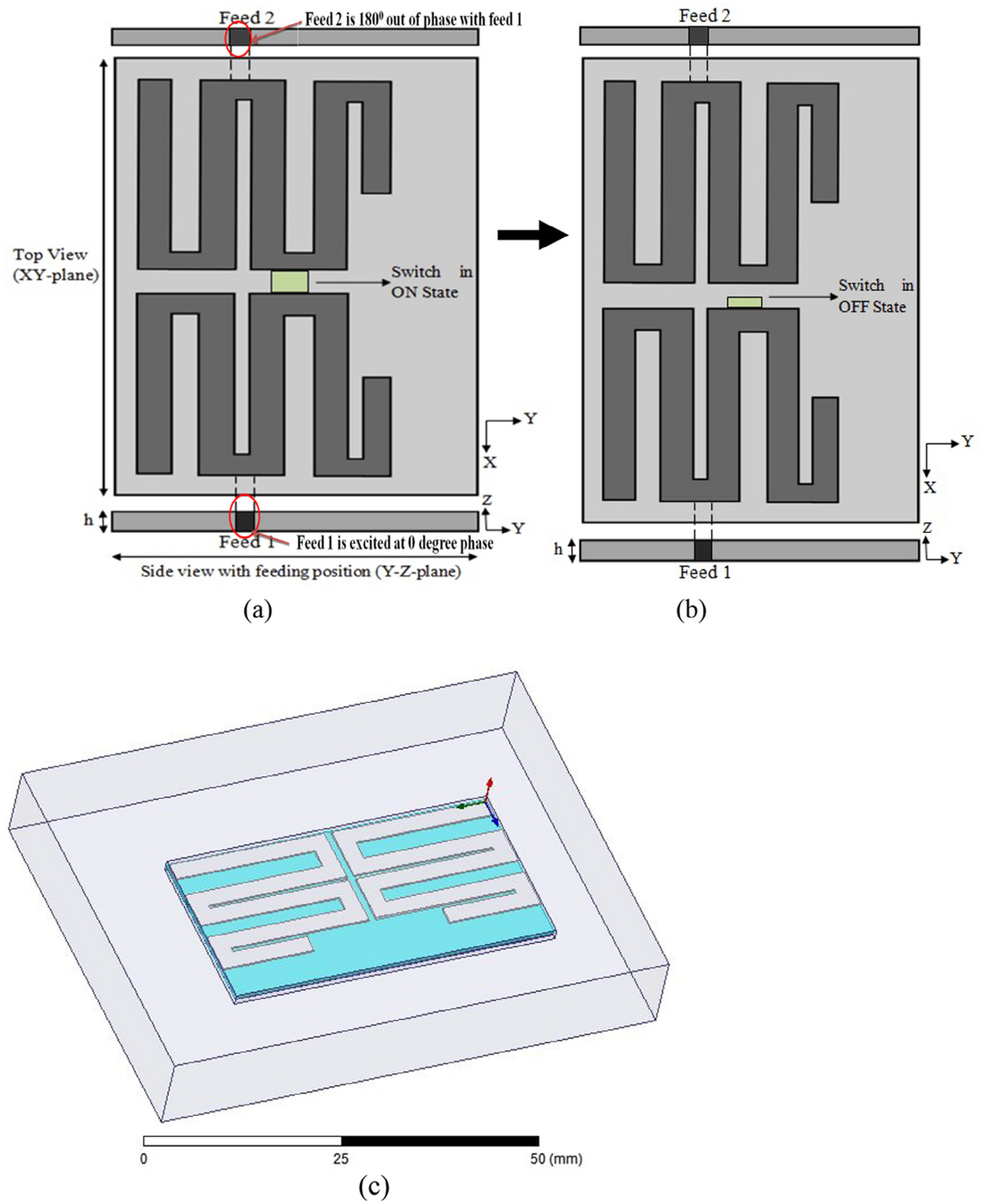


Fig. 2. Patch antenna in different configurations: (a) switch is in on state, (b) switch is in off state. (c) HFSS simulation model of the antenna.

Table 1
Detailed dimensions of the meander structure.

Symbol	Length (mm)
W	17.74
L	22
W_1	2.94
L_1	12.9
W_2	0.5
H	0.5
W_3	2.39

patch is added over the same substrate plane connected by a metallic micro-electro mechanical switch (MEMS) with differential feed technique as shown in Fig. 2a. For effective excitation in the differential feeding technique two ports were made back to back vertically along the substrate which are equal in magnitude but are 180° out of phase.

2.2. Differential feeding for excitation

To have a constant impedance matching the feed is placed near the center of the meander structure on both sides. Differential feeding technique has been used in the design where the magnitude of excitations is kept the same over the two ports but the excitations is made 180° out of phase compared to the other feed line which is shown in Fig. 2a and b. The simulation model is given in Fig. 2c. Also differential feeding technique overcomes the design complexities of matching circuit for the antenna. Using this technique the device can be operated easily in differential circuits. When the structure is not in balanced mode conversion will exist, so in this case odd mode reflection coefficient(τ_{odd}) is one of the parameters to determine the difference between balanced & unbalanced case where, $\tau_{odd} = S_{11} - S_{12}$. With the addition of MEMS switch the overall size of the antenna changes resulting in higher efficiency. The position of the MEMS switch has been optimized so that the antenna can operate both in MICS & ISM band in free space conditions as well as inside the body phantom.

2.3. Simulation environment

Electrical properties of human tissues such as: relative permittivity (ε_r), conductivity (σ) and dielectric loss tangent (tanδ) fluctuates with change in frequency.

Table 2 shows the typical values of relative permittivity, conductivity and dielectric loss tangent for skin muscle and fat at MICS and ISM bands [13].

Till date for testing of implantable patch antennas canonical phantoms are used. But the main challenge of this technique lies in the formulation of tissue mimicking materials. As reported in literatures [8,14] the tissue mimicking materials mainly comprises of deionized water, sugar and salt. It is also reported that in case of skin mimicking gel, with increase in sugar concentration level, the relative permittivity (ε_r) decreases while conductance (σ) increases negligibly. Similarly, with the increase in salt concentration level the relative permittivity (ε_r) decreases with a significant increase in conductance (σ) level [6].

Table 2
Electrical properties of biological tissues.

Biological tissues	MICS band			ISM band		
	ε_r	σ(S/m)	tanδ	ε_r	σ(S/m)	tanδ
Skin	46.7	0.69	0.79	38.1	2.27	0.33
Muscle	57.1	0.79	0.62	52.7	1.73	0.24
Fat	5.58	0.04	0.32	5.28	0.10	0.14

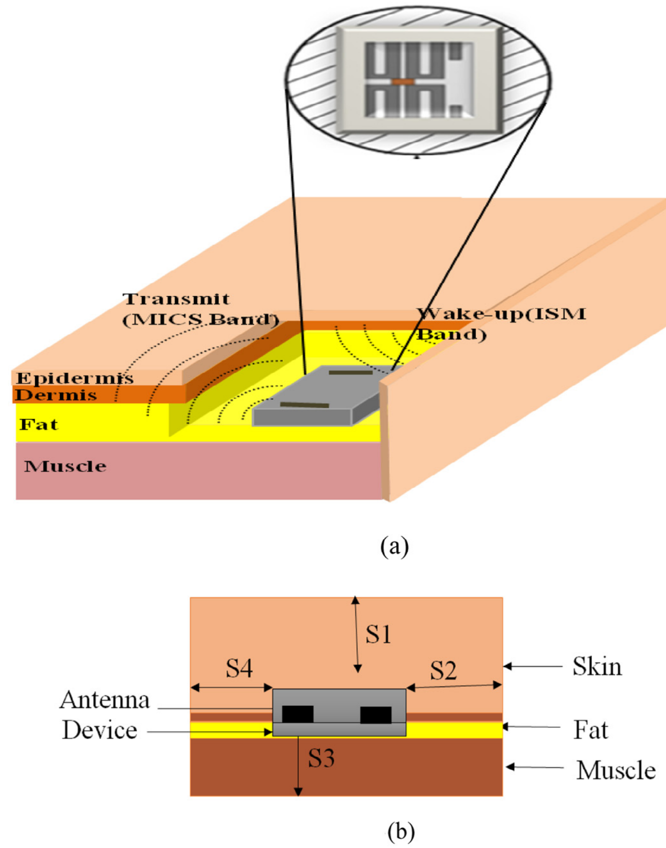


Fig. 3. (a) Human skin model with implanted device. (b) Relative placement of the antenna in single layer skin model.

2.4. Antenna placement

Positioning the device inside the human body is one of the key factors to decide the efficiency of the whole system. Canonical models are helpful in representing the human body up to a certain levels as the body consists of different types of tissues. Also a single skin tissue further consists of different sub-layers as shown Fig. 3a.

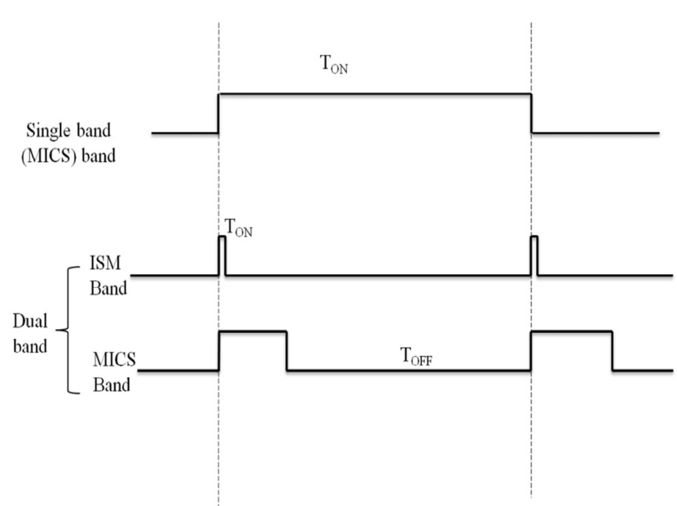
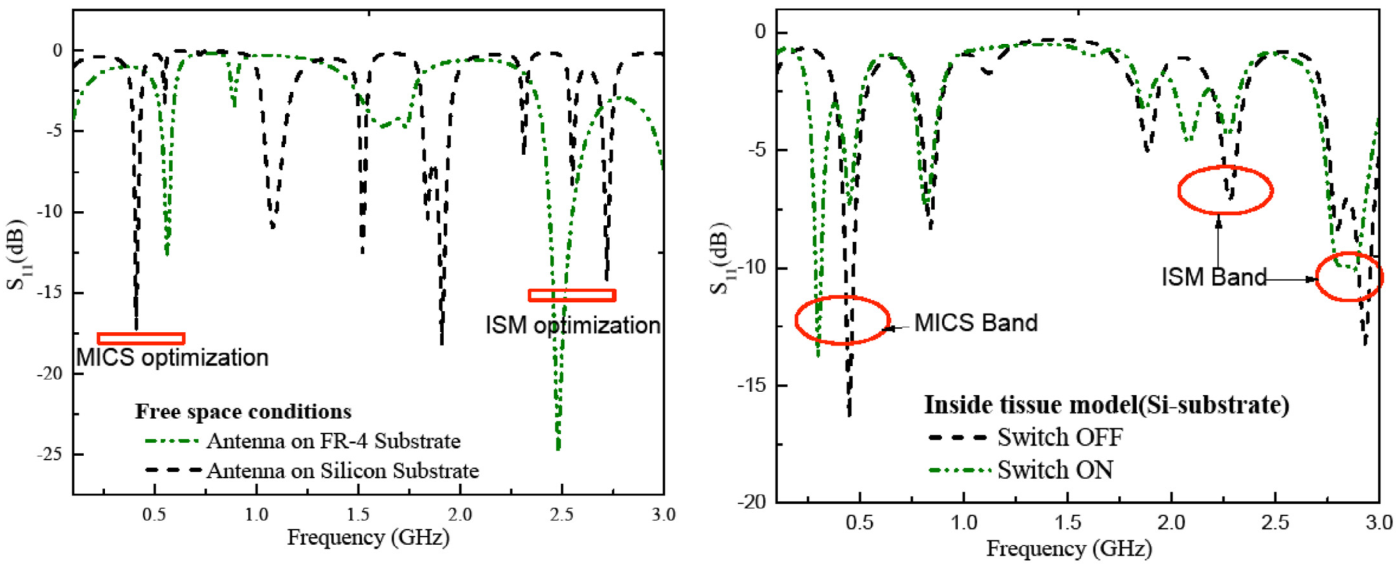


Fig. 4. Duty cycle for single and dual band antenna.

Initially the implantable antenna is placed below the dermis in the fat layer for a three layer model as shown in Fig. 3a and subsequently it is optimized and placed beneath the dermis in skin tissue which is 1.5 mm below the surface skin as given in Table 3. Simulation is done over a three layer model for dry skin as shown in Fig. 3b. The radiating boundary for x, y and z planes is $70 \times 50 \times 10\ mm^3$. The radiating boundary is surrounded over the skin layer.

Table 3
Antenna placement inside the skin model.

Symbol	Length (mm)
S_1	1.5
S_2	0.20
S_3	0.5
S_4	0.13



(a) (b)

Fig. 5. (a): S_{11} parameter in free space for silicon and FR4 substrate. (b) S_{11} parameters inside tissue model with On–Off conditions.

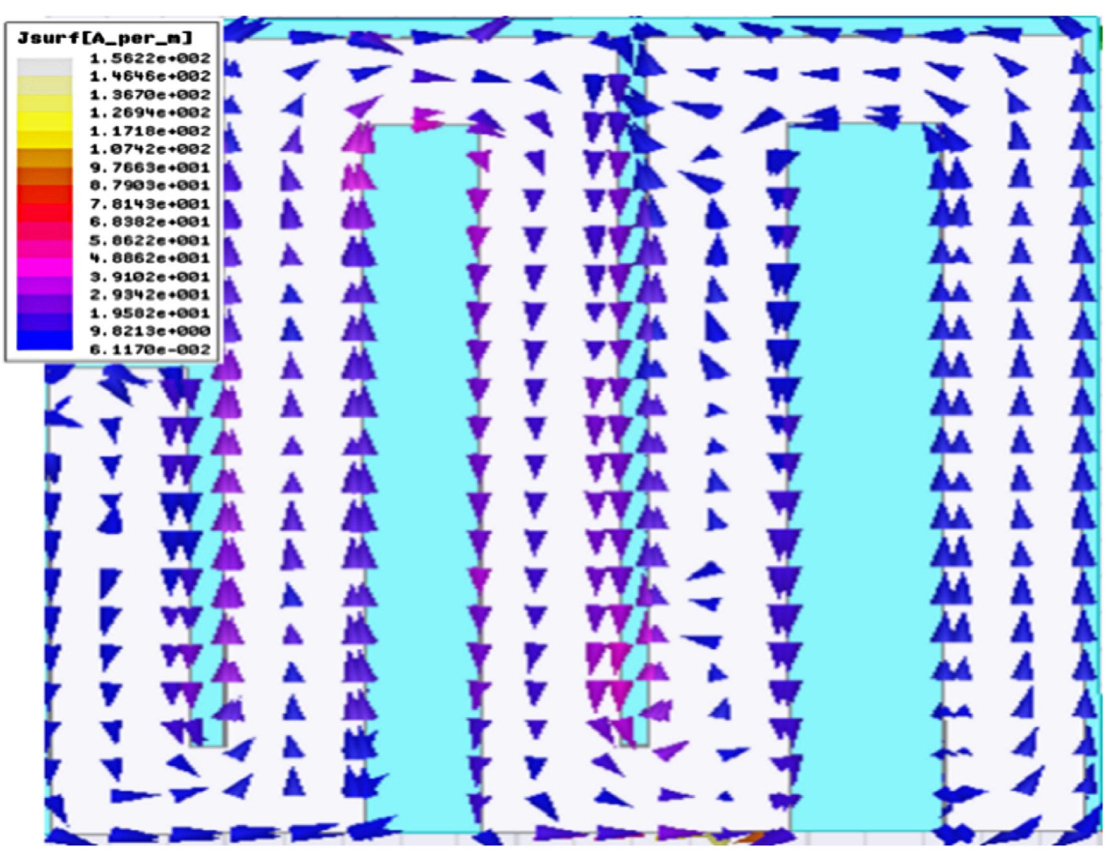


Fig. 6. Electric current distribution of a single patch.

Subject to this prevailing conditions and pertaining to the dielectric tissue properties, simulation is carried out in the HFSS software and the results are found to be up to the mark for on-body and in-body communications.

2.5. Reduction of power due to use of dual band

Regarding power reduction with the proposed antenna, it is seen that if the input power fed to the antenna is 'P' and if the power consumed/dissipated by the antenna while transmitting in MICS band is 'P_{MICS}', then the power dissipation ratio (PDR_1) of the antenna will be given as $PDR_1 = \frac{P_{MICS}}{P_{INPUT}}$. ISM band is used as a control channel to activate the device, whereas the MICS band is used to transfer data. So the power dissipation at any instant of time is much less than the former one ($P_{MICS} >> P_{ISM}$). Now the power dissipation ratio (PDR_2) of the whole system can be expressed as $PDR_2 = \frac{P_{MICS}(t) + P_{ISM}}{P_{INPUT}}$, where t is the time instance for activation of MICS band. The main function of the ISM band is to detect the wake up signal from the base station and then turn 'ON' the MICS band in order to transmit the data to the base station. The whole scenario can be depicted as shown in Fig. 4. In case of single band where the MICS band is always 'ON', the duty cycle (DC_1) can be mathematically expressed as $DC_1 = \frac{T_{ON(MICS)}}{(T_{ON} + T_{OFF})_{MICS}}$. Here the value of DC_1 is equal to 1 as $T_{OFF} = 0$, whereas in the case of dual band, the duty cycle (DC_2) for ISM band can be expressed as $DC_2 = \frac{T_{ON(ISM)}}{(T_{ON} + T_{OFF})_{ISM}}$. Here $T_{ON(ISM)}$ is very small resulting in $\frac{T_{ON(ISM)}}{(T_{ON} + T_{OFF})_{ISM}} \ll 1$, so the duty cycle for ISM band can be neglected. Whereas, the duty cycle (DC_3) of MICS band for the dual band can be expressed as $DC_3 = \frac{T_{ON(MICS)}}{(T_{ON} + T_{OFF})_{MICS}}$. Here the period of MICS band 'ON' time in the dual band is much lower than the single band, so from the above expression it can be concluded that the power dissipation in the second case is much lower than the first one ($P_{MICS}(t) + P_{ISM} < P_{MICS}$).

3. Results & discussion

Initially a single patch is excited using a single port and the S_{11} shows a single band resonance at 559 MHz with a gain of –39.96 dB. But this resultant band does not conform to the prescribed MICS band. Simulations are also performed on a low dielectric (FR-4) substrate (dielectric constant = 4.5) with the same structure, resulting in non-performance in MICS band. The size of the antenna increases with the use of low dielectric material resulting in non-applicability in biomedical implantation.

In the next step a symmetrical patch is added in the same plane with dual ports on the FR-4 substrate but the antenna resonated around 2.45 GHz with –46.69 dB gain which is suitable for singleband operation but not applicable for dual band operation as the lower resonating frequency does not lie in the MICS band, as shown in Fig. 5a. So in our proposed model, silicon substrate is used with symmetrical patches connected through MEMS switch and excited by differential feeding mechanism. Simulation result shows that the

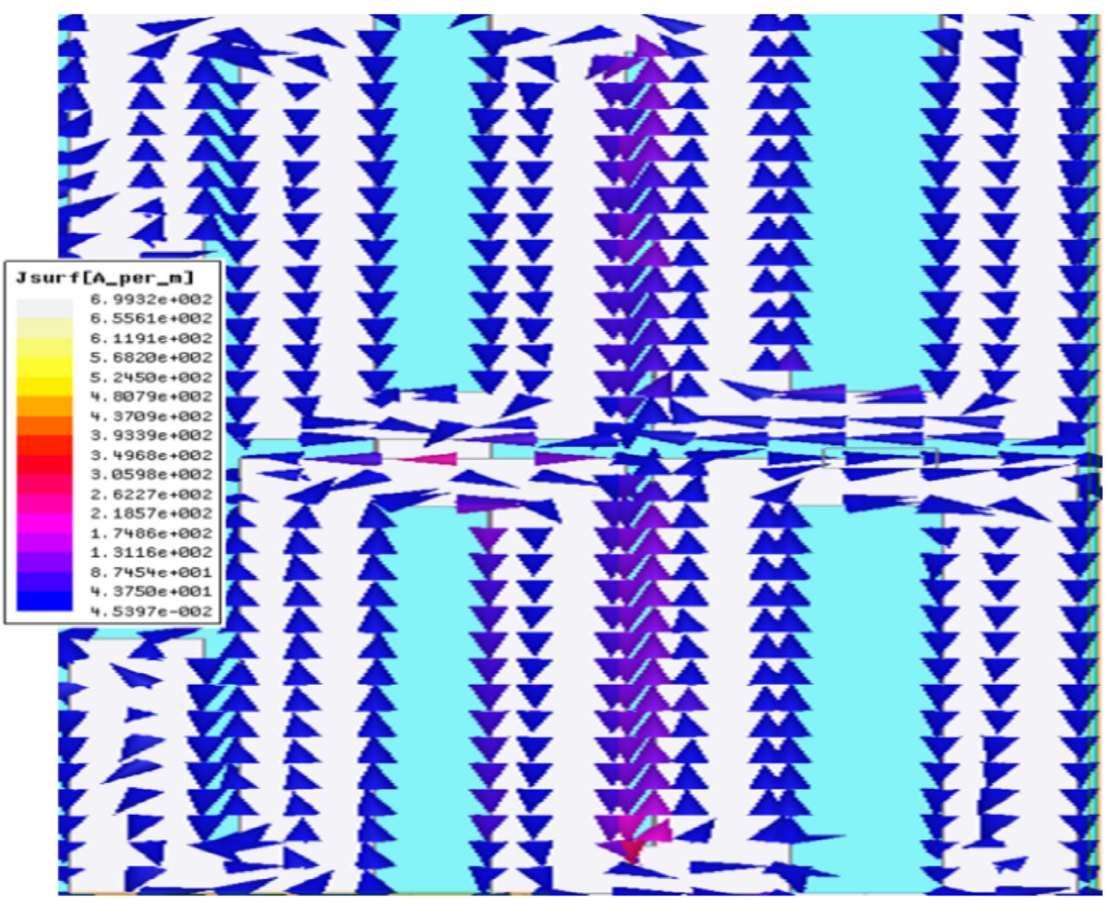


Fig. 7. Electric current distribution under free space condition.

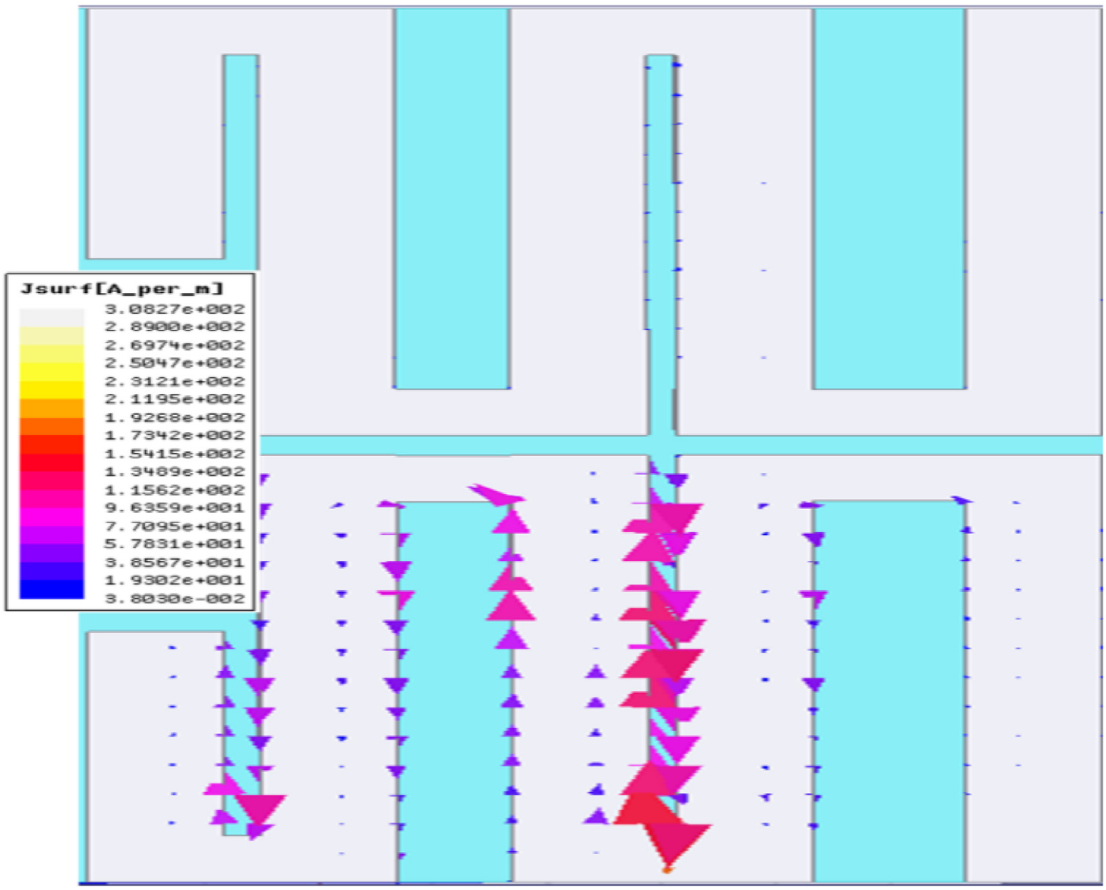


Fig. 8. Electric current distribution of the patch placed inside skin phantom.

number of radiating bands increases. Out of the two bands that are obtained only one is suitable for biomedical communication. It is found that resonance occurs only at ISM band, whereas no resonance occurs at MICS band. To include both the bands the position of the switch is varied step by step and shifted towards one side of the patch. It is found that the antenna radiates in MICS band as well as in ISM band with –40.06 dB gain. Now this optimized device is simulated under body phantom with the di-electric properties for the MICS & the ISM band under the same conditions, as stated in Table 2. But there is a deviation in MICS band due to different electromagnetic properties inside human body, as shown in Fig. 5b. To achieve the pre-defined resonating states the switch was turned OFF for decreasing the current path length and it was found that the antenna again started radiating in the MICS band along with ISM band with a gain of –29.3 dB, which is higher than the gain of the antenna discussed in Calla et al. [8]. Also the designed antenna is easy to fabricate with a good radiation characteristics than the previous one. The given configuration of the antenna can be used for transmission in the MICS band as well as for the wake up purpose using the ISM band.

We know that,

$$f_{res} = \frac{c}{2L_{eff}\sqrt{\varepsilon_{ff}}} \tag{12}$$

where f_{res} is the resonant frequency, c is the velocity of light, L_{eff} is the effective current path length over the antenna, ε_{eff} is the effective permittivity of the medium. From equation 12, it is seen that the resonant frequency is inversely proportional to the effective length of the antenna. OFF and ON states of the switch show immense effect over the resonant frequency of the antenna, as at ON state coupling between the two patches occurs via inductance, and in the OFF state condition both are coupled via capacitance [15]. This coupling effects and change in resonant frequency of the antenna can be visualized from Figs. 6–8, whereas Fig. 9 shows the graph of a perfect impedance matching.

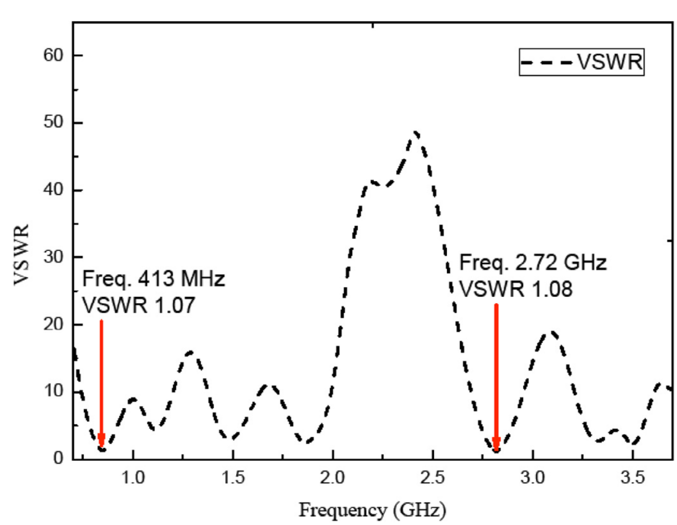
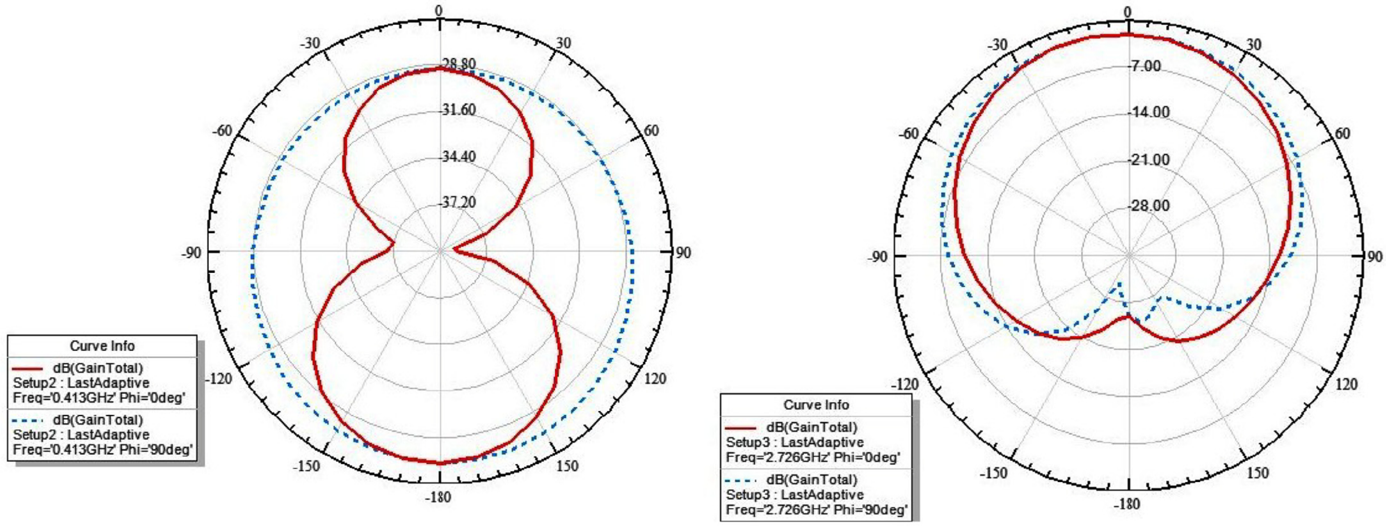


Fig. 9. Voltage standing wave ratio (VSWR) for two resonating frequency.



(a) (b)

Fig. 10. Far field radiation pattern for MICS and ISM bands (a) MICS band (413 MHz) (b) ISM band (2.72 GHz).

From Fig. 6 it can be seen that the current path length is relatively small so resonance occurs at higher frequency around 559 MHz with a S_{11} of –15.52 dB. Whereas in Fig. 7, the modified structure with one of the switches in closed condition and other in open it is found that the resonance frequency shifts towards lower value as the current length path increased respectively and the antenna radiates at 413 MHz and 2.7 GHz with S_{11} of –17.62 dB and –14.31 dB respectively. Finally when the antenna is kept inside a skin mimicking type material, it is found that the frequency band deviates from the original value. In order to cope with with this situation, the switch was kept open and the antenna started resonating again a little adjacent to the MICS band and ISM band. Also from the comparison between free space and under skin mimicking gel the percentage bandwidth increases around 67% for the body environment. From Fig. 9 it can be seen that the value of VSWR at MICS and ISM band are 1.14 and 1.55 respectively. So it can be inferred that the proposed antenna radiates more efficiently in the MICS band then the ISM band which is the prime requirement for data transmission in MICS band. The far field radiation patterns of two different excited frequencies (413 MHz & 2.72 GHz) are shown in Figs. 10 and 11 respectively. Also from Fig. 10a and b it is found that the radiation performance is direction independent (MICS –28.80 dB & ISM –2 dB) which is suitable for near communication at MICS band and also for long distance communication at ISM band. As a result the performance is found to be effective as the orientation of the human body on an average

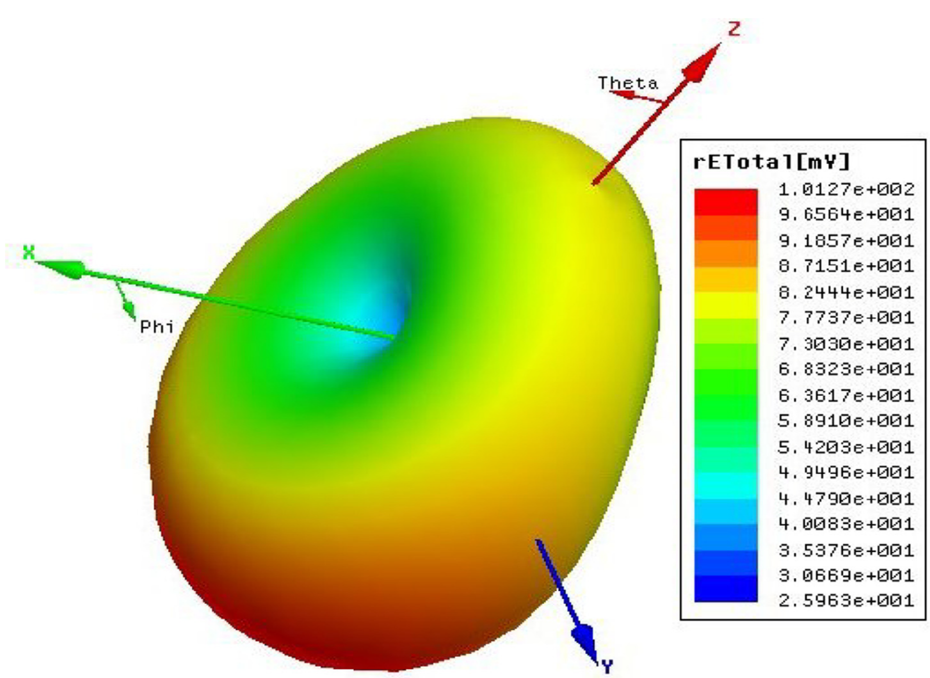


Fig. 11. Simulated 3-D radiation pattern of the optimized antenna.

Table 4
Performance comparison of single feed and differential feed technique.

SL. NO.	Feeding mechanism	S11		HPBW	Gain	Bandwidth
		MICS	ISM			
1	Single Feed	–16.2 dB	–10.6 dB	10.6O	–57.5 dB	40.1 MHz
2	Differential Feed	–17.5 dB	–14.56 dB	47O	–54.9 dB	40.3 MHz

changes every 10 seconds. Overall, the radiation efficiency of the antenna obtained is near to 11%.

From Table 4 it can be concluded that the S_{11} parameter in the case of single feeding technique is less than in the case of differential feed. Also the half power beam width is enhanced along with the gain in case of differential feeding mechanism. The enhancement of bandwidth is due to the electromagnetic coupling [16] between two meandered line counterpart when the switch is in OFF mode and in differential mode which counters the nature of low bandwidth property of patch antenna in general [17].

4. Conclusion

In this paper a dual band antenna with differential feeding technique has been proposed. The differential technique of exciting the ports allows easy connection with differential circuits resulting in reduced additional losses that are encountered while using BALUNs and matching circuits. The addition of MEMS based switches makes the antenna reconfigurable in nature. Further enhancement of bandwidth around the MICS band is also an indication to support multiple implantable devices to communicate simultaneously in the desired band with increased data rate. The designed antenna achieved the objective of power reduction in implantable devices with the application of dual bands. The gain of the antenna has been found to be satisfactory along with the S_{11} parameter and can be operated in the Med-radio band.

Acknowledgment

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