RESEARCH ARTICLE

SPECIAL ISSUE

International Research Journal on Advanced Science Hub
2582-4376
Vol. 05, Issue 05S May
www.rspsciencehub.com

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RSP Science Hub

http://dx.doi.org/10.47392/irjash.2023.S035

International Conference on intelligent COMPUting TEchnologies and Research (i-COMPUTER) 2023

# Miniaturized slot loaded on-chip loop antenna with multi-fingered inner loop for implantable devices

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**Article History**
*Received: 28 February 2023*
*Accepted: 18 March 2023*

***Keywords***:
*Onchip antenna;*
*Slot loading;*
*Secondary loop;*
*miniaturization*

**Abstract**
*Design of implantable devices at 2.4 GHz ISM band for medical examination has been extensively researched ever since IoT has gained importance. Implantable devices need to be small and less power hungry. In this paper, a small size and highly efficient 2.4 GHz miniaturized on-chip loop antenna has been proposed and is suitable for biotelemetry applications. The substrate stack up of on chip antenna consists of 6 metal layers. Antenna is designed on the top most metal layer (M6). Miniaturization is achieved by using the principle of slot loading and multi-fingered loop loading. The proposed antenna utilizes the surface area within loop antenna to increase the efficiency of proposed antenna.The proposed antenna is simulated using Advanced Design System (ADS) tool. The gain of the simulated on chip antenna is -13.93 and efficiency is 1.91%, which is the highest gain reported at 2.4 GHz. The dimensions of the antenna is 1.5mm x 1.0 mm.*

## 1. Introduction

Body centric communication using implantable devices is a very active area of research. It has extensive applications, especially in biotelemetry, where the transmitter device implanted in a patient's body can communicate to a receiver at a distant location. The receiver can be an instrument receiving data which requires short distance communication or telecommunication with doctor, who is at another location which requires long distance communication. For any applications, a major design constraint is small chip size and low power consumption.

Implantable devices designed at ISM band of 2.4 GH used for short communication range within 2 meters can utilise on chip antennas for achieving reduced chip size. Antennas designed inside a chip are references as on-chip antennas (Cheema and Shamim). On-chip antenna design and integration is an active area of research in the recent past. The main advantage of on chip antennas is that global signal distribution problem can be reduced in ICs (Zhang and Liu). On chip antennas also do not require bond wires, bond pads or extra pins.

At low frequencies, resonant antennas are very large in size, while electrically small antennas, have low efficiencies. So, they are designed to suit short-range communication. Antennas designed inside a package can also be used for integration. They have higher size compared to chip antenna, and hence better efficiency, but they have to include the bond wires and bond pads inside the chip (Zhang and Liu). So, they are preferred for long range communication.

### *1.1. Overview of reported on chip antennas*

Due to chip size compatibility of high frequency antennas, the antennas designed at higher frequencies, especially greater than 20 GHz have better radiation efficiency compared to low frequency antennas. A dual band meander-line monopole antenna has a gain of -10 dB at 28GHz and 0 dB at 60 GHz (Tabesh et al.), clearly indicating the high gain at higher frequency. A dipole antenna designed at 2.45 GHz has an efficiency of 0.6%, which is very low (Sun, Li, and Babakhani).

For low frequencies, to increase the gain, miniaturization techniques are to be adopted. The major techniques used are meandering, slot loading, use of substrates with high permittivity and fractal antennas. (Karim et al.). In (S. Mandal et al.), slots and notches were introduced to achieve miniaturization. In (Zhu et al.), use of high permittivity substrate helped the on-chip antenna to radiate more, due to less confinement of the radiations in the substrate. In (Wang and Arslan), artificial conductor loading was introduced to increase the efficiency.

### *1.2. Challenges in designing low frequency on-chip antennas*

The challenge of designing low frequency antennas are to increase resonant frequency without consuming a large chip space. Die size increment leads to increase in cost. Also, many miniaturization techniques increases loss resistance $R_l$. Increase in loss resistance reduces radiation efficiency $\eta$ since $R_l$ is inversely proportional to antenna efficiency (Steven and Best). $\eta$ increases if antenna radiates more, i.e. radiation resistance $R_r$ is more. So, new designs have to be developed with small size, higher resonant frequency and improved radiation efficiency.

### *1.3. Contribution of paper*

Since chip size reduction is a major feature of implantable devices, in the proposed antenna, miniaturization techniques are implemented. The proposed antenna is a rectangular loop antenna. Miniaturization techniques used are slot loading and loading of outer loop antenna by a multi-fingered inner loop. Multi fingered inner loop utilises the area inside the rectangular loop antenna, thereby increasing the efficiency without die size increment. Increased efficiency results in longer communication range. The paper is organised as follows: materials and methods, results and discussion, followed by conclusion.

## 2. Materials and Methods

### *2.1. Antenna Design*

Consider an antenna with wave number k which is related to wavelength $\lambda$ as (Shahpari and Thiel)

$$k = \left(\frac{2\pi}{\lambda}\right) \tag{1}$$

The antenna is assumed to be surrounded by an imaginary sphere, which covers the maximum dimensions of antenna. Let a be the radius of the sphere. The antenna is electrically small, if (Shahpari and Thiel)

$$k < \left(\frac{1}{a}\right) \tag{2}$$

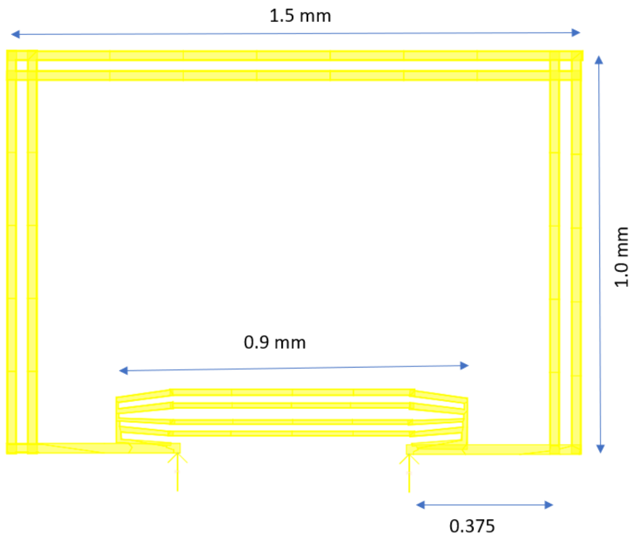


**FIGURE 1. Dimension of loop antenna**

. The proposed antenna is a rectangular loop, which is resonant at wavelength $\lambda$. For on-chip antenna, wavelength reduces by a factor of $\sqrt{\varepsilon_r}$, where $\varepsilon_r$ is the relative permittivity of silicon. At 2.4 GHz, the antenna resonates at 125mm. Hence each side will be about 32.5/3.4, i.e. nearly 10mm. Designing a chip of this dimension is not feasible

Hence, miniaturisation techniques are adopted in the proposed design. Also, electrically small antennas are very inefficient, so the efficiency is also improved in the proposed design.

The types of miniaturisation used in the design are slot loading and increasing the surface area of the proposed antenna. Increasing the surface area also increases the radiation efficiency $\eta$ of the antenna. Thus antenna radiates more. This is

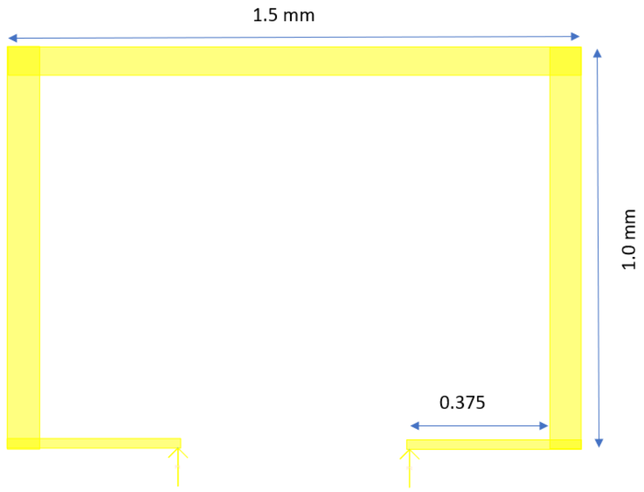


**FIGURE 2.** **Dimension of miniaturized antenna**

reported in (Hansen) (Jenilek and Capek), where it is shown that radiation efficiency is directly proportional to the surface area of the antenna.

In slot loading technique, rectangular slots are cut from the antenna. This produces longer path for current flow whereby the current distribution of the antenna increases and antenna's resonant frequency reduces. The proposed loop antenna design has rectangular slots at the three sides other than the side where the feed input is applied.

Increasing the surface area also aids in reducing the resonant frequency. In this paper, the surface area of the loop antenna is increased by introducing a multi fingered inner rectangular loop inside the loop antenna. The multi-fingered loop has a fork shape at the ends connected to the loop antenna. This

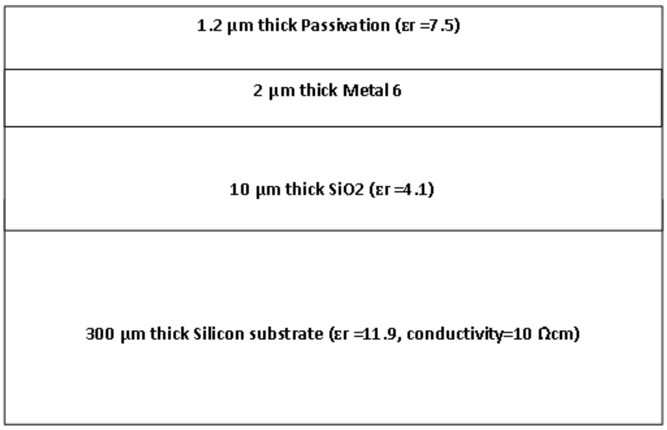


**FIGURE 3.** **Substrate stack up**

helps to increase the surface area more compared to a rectangular edge. The dimensions of the proposed antenna is 1.5 x 1 mm and the shape of the

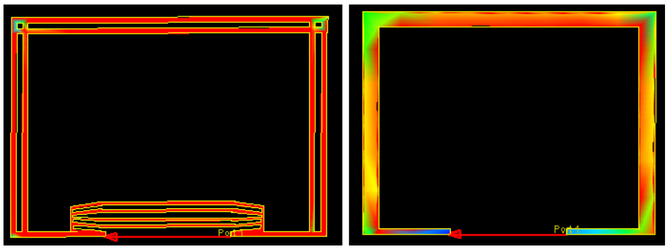

**FIGURE 4.** **Current distribution in miniaturized and loop antenna**

antenna is shown in Fig. 2. A loop antenna of same dimensions is shown in Fig.1 .

### *2.2. Simulation of on-chip antenna*

The proposed antenna is simulated in Advanced Design System (ADS) Software to find the gain, efficiency, and directivity. The substrate stack up of the simulation is shown in Fig. 3. The silicon substrate in the stack up has 300 $\mu$m silicon thickness and silicon dioxide is of 10 $\mu$m thickness. The top metal layer where antenna is designed has 2 $\mu$m thickness. A loop antenna of 1.5 mm x 1mm side is also simulated. The proposed design and loop antenna are compared to analyse the miniaturization technique effects.

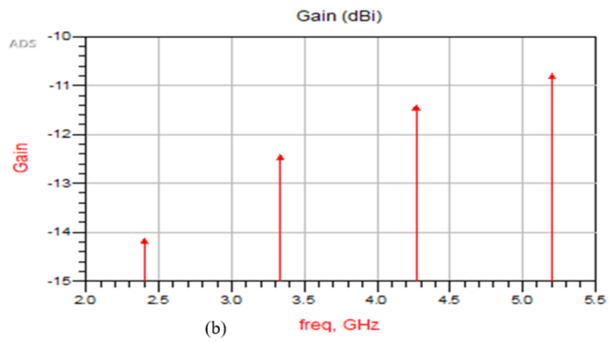


**FIGURE 5.** **Gain variation with frequency of proposed antenna**

**TABLE 1.** **Comparison of simulated antennas**

| Parameter | Proposed Antenna | Loop Antenna |
|---|---|---|
| Gain (dBi) | -14.12 | -15.17 |
| Efficiency (%) | 1.84 | 1.44 |
| Directivity (dBi) | 3.23 | 3.23 |

Figure 4 shows the current distribution of loop antenna and miniaturized antenna. It can be seen

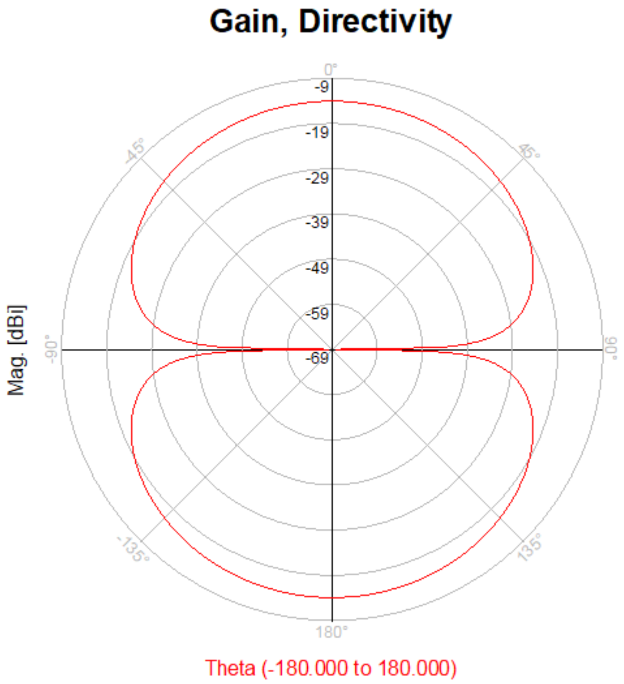


**FIGURE 6.** **Radiation pattern of proposed antenna**

that the miniaturised antenna has more current distribution due to higher surface area. The radiation pattern of the proposed antenna is shown in Figure 6 and Figure 5 shows the variation of gain of proposed antenna with frequency. It is seen that as frequency increases, the gain also increases, since for a fixed size, electrically small antenna resonates better with higher frequency.

**TABLE 2.** **Comparison of proposed antenna with reported low frequency on chip**

| Ref. | Frequenc (GHz) | Gain (-dBi) | Chip area (mm$^2$) |
|---|---|---|---|
| (Toeda et al.) | 5 | -26 | 2.55 |
| (Singh and S. K. Mandal) | 2.45 | -14 | 10.45 |
| (Marnat et al.) | 2.4 | -29 | 1.65 |
| This work | 2.4 | -14.11 | 1.5 |

## 3. Results and discussion

Table 1 shows a comparison of the miniaturized antenna with loop antenna. Though designed antenna and loop antenna has 1.5 mm x 1.0 mm dimensions, the miniaturised antenna has better radiation properties compared to loop antenna. This is due to the lower resonant frequency of the proposed antenna which is achieved due to slot loading and multifingered inner loop. An increased surface area increases efficiency of designed antenna more than a loop antenna.

The transmission range of an antenna is given by (Friis)

$$t_r\,(dB) = \lambda\,(dB) - 10.9 + 0.5(\eta\,(dB) + P_i\,(dBm) + G_t\,(dBi) + G_r\,(dBi) - P_r\,(dBm)) \tag{3}$$

where, $P_t$ and $P_i$ represent transmitted and input power, $G_t$ and $G_r$ represent gain of transmitter and receiver antenna. $P_r$ represents receiver antenna power. From (3), it can be seen that an increase in gain of the designed antenna will provide a better gain. The proposed antenna has better gain, so it can radiate more compared to a loop antenna of same size.

Table 2 gives the comparison of proposed antenna with low frequency on-chip antennas that are reported in the literature. The inference is that proposed antenna provides better gain and efficiency compared to other antennas given in the table. Better radiation properties of the antenna are due to increase in surface area of the designed antenna. Antenna designed in (Singh and S. K. Mandal) has comparable gain with proposed antenna, but size is very large. Hence, when compared in terms of size and radiation properties, proposed antenna has better radiation characteristics compared to other reported low frequency antennas. Also, as it has better gain, the transmission range will be more.

## 4. Conclusion

A miniaturized on chip antenna with small size and good radiation properties is designed at 2.4 GHz with an aim to implement in implantable devices to be used for short distance communication. The proposed antenna uses slot loading to improve current flow and improves radiation efficiency by increasing the inner surface area of loop antenna. The proposed antenna has very good radiation properties and is suitable for efficient short range communication applications.

**Authors' Note**

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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**Embargo period:** The article has no embargo period.

**To cite this Article:** , Archana S, “**Miniaturized slot loaded on-chip loop antenna with multi-fingered inner loop for implantable devices**.” International Research Journal on Advanced Science Hub 05.05S May (2023): 260–264. http://dx.doi.org/10.47392/irjash.2023.S035