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Barium titanate–silicon elastomer based body coupled antenna for wearable microwave head imaging applications

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ABSTRACT

This paper presents a flexible monopole antenna fed by a coplanar waveguide (CPW) feeding line with a barium titanate ($BaTiO_3$) silicon-elastomer impedance matching layer for microwave head imaging applications. The operating frequency bandwidth of the proposed antenna is 614 MHz which is from 0.475 GHz to 1.089 GHz. In biomedical microwave sensing and imaging applications, the major challenge is the high power loss due to reflection between the body and the antenna due to impedance mismatch. Therefore, the proposed $BaTiO_3$ silicon-elastomer composite is designed to have dielectric property of 20 which acts as an impedance matching layer for the monopole antenna. The proposed antenna has dimensions of 70×30×6 mm. The flexibility of the antenna is provided by the use of the silicon elastomer. It has been shown that the power radiated into an artificial head phantom improved by almost 160% as compared to antenna without impedance matching layer. Moreover, the SAR level is 0.0286 W/kg when 1 mW of power is transmitted, which is well below the limit set by the regulation. This makes the antenna suitable for wearable biomedical applications due to its wideband characteristic and improved power penetration into human head.

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1. INTRODUCTION

Microwave imaging and sensing (MSI) has been extensively explored and implemented in medical applications, including the detection of breast and lung tumors, traumatic brain injuries, and stroke [1]–[4]. These non-ionizing microwave devices are considered safe for body imaging and could be used to complement existing modalities like X-ray, computed tomography (CT), and magnetic resonance imaging (MRI). Although promising, challenges related to the high energy loss in the body at microwave frequencies combined with inefficient sensing devices have prevented viable solutions. Improving the efficiency of the sensing devices for MSI applications is thus critical to ensuring correct diagnosis is obtained and appropriate treatments can be given to patients [5]. Even though existing head imaging technologies like CT and MRI are capable of accurately diagnosing brain traumas like strokes and brain tumors, they have a number of drawbacks such as being expensive, heavy, and mostly stationary [6], [7]. Yet, radar-based microwave imaging technology may provide a low-cost, non-invasive, and non-ionization method to replace these current imaging techniques. Unfortunately, because of the significant reflections of the body surface, microwave imaging equipment experiences a considerable signal loss. This problem might result in incorrect disease diagnosis, such as false-negative cancer detection results.

Furthermore, the previously existing antennas have limitations such as rigid structure and bulky. Wearable fabric antennas have been proposed to overcome these particular problems [8]. Polyethylene terephthalate (PET) substrate is also utilized for antenna design to overcome this limitation [9]. Different types of antennas have been investigated for biomedical imaging applications such as 3-D compact patch antenna [10], e t-slot shaped rectangular patch [11], microstrip leaky wave antenna (LWA) microstrip [12], patch antenna with defective ground structure (DGS) [13], wideband monopole antenna [14], [15], and antipodal Vivaldi antenna [16]. A study in [6] described a microwave head imaging system that sends and collects backscattered signals using an array of antennas on a realistic head phantom. The system was tested to find a target that simulates a hemorrhagic stroke. Although a promising result was shown, the proposed antenna is rigid and not flexible which makes it unsuitable for wearable applications. To overcome the rigid properties of the antenna, different types of flexible materials have been utilized by researchers [17], [18]. However, the high loss due to impedance mismatch between the antenna and the human body was not addressed.

In this paper, a coplanar waveguide (CPW-fed) flexible monopole antenna that operates between 0.475 GHz to 1.089 GHz is proposed. To reduce the power loss transmitted by the antenna to a human head due to high reflection caused by the impedance mismatch between the head and the antenna, an impedance-matching layer made from barium titanate ($BaTiO_3$)–silicon elastomer is integrated with the antenna [19]. $BaTiO_3$ is a high dielectric constant material that is needed to realize the proposed high permittivity impedance matching layer. The effectiveness of the use of the impedance matching layer is then shown on an artificial human head phantom in commercial electromagnetic software, CST microwave studio. The antenna and the impedance matching layer dimension, bending configuration, and artificial head phantom are discussed in section 2. Section 3 consists of the simulation result and discussion. Finally, section 4 concludes the paper with future recommendations.

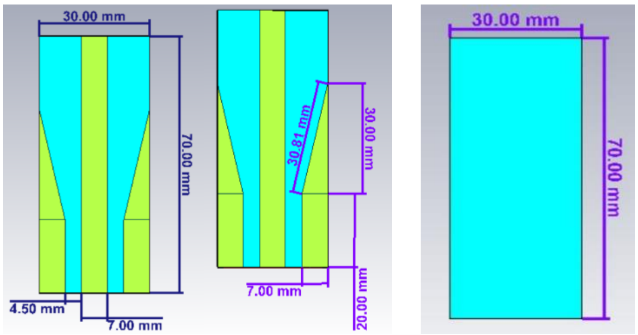
2. ANTENNA DESIGN

2.1. Antenna geometry

The antenna has been designed to be lightweight and flexible, which are the two major requirements for wearable applications. The major problem for the previous antenna for this application was rigid structure and flexibility. Moreover, a monopole antenna was selected because of its naturally low-profile architecture. Additionally, the antenna must be wideband because it is intended to be used in a radar-based microwave imaging system. The feeding line and the radiator are the two primary components of a monopole antenna. According to multiple previous studies, a working frequency range between 1 GHz and 3 GHz should be used to achieve sufficient penetration into the human head [20], [21]. The overall antenna structure is illustrated in Figure 1 proposed antenna geometry with Figure 1(a) front view and Figure 1(b) back view. To improve the bandwidth of the proposed antenna, both the feeding line and the radiating element have been optimized. Due to its wideband characteristic, a CPW feeding line has been utilized in this work [22]. The antenna was designed and simulated using CST microwave studio, a commercial electromagnetic wave simulator. The summary of the antenna parameters is given in Table 1. The length of the monopole, L is calculated based on (1) [21]:

$$L = 0.25 \times \lambda_g \tag{1}$$

Where the guided wavelength, $\lambda_{g=}1/\sqrt{\varepsilon}$.



(a) (b)

Figure 1. Proposed antenna geometry; (a) front view and (b) back view

Table 1. The physical dimension of the proposed antenna

Antenna parameter	Values (mm)
Antenna length	70
Antenna width	30
Antenna thickness	0.075
Dielectric properties	2.4
Tangent loss	0.0003
Co-planar waveguide gap	0.5
CPW feeding line length	70
CPW feeding line width	7

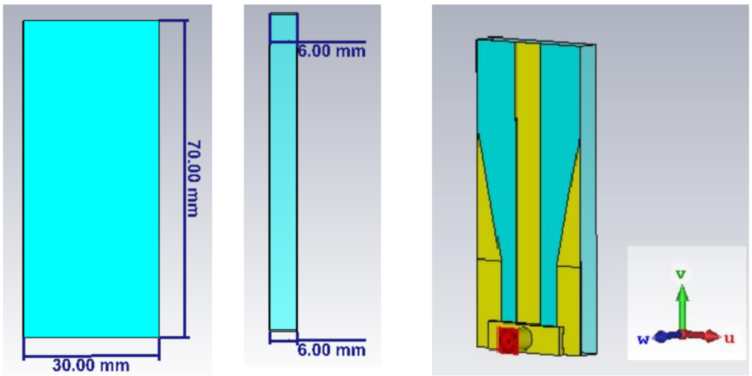
The lowest operating frequency of the antenna is obtained by first specifying its length. Then, the CPW feeding line dimension was later optimized to have a characteristic impedance of 50 Ω to obtain good reflection coefficient performance at the intended operating frequencies. Table 2 shows a comparison of the proposed antenna with other references. Different types of antennae have been used for microwave head imaging applications shown in Table 2.

Table 2. Comparison of the proposed antenna with other references

Reference	Antenna type	Substrate	Flexibility	Impedance matching layer
[23]	Meta surface	FR4	N/A	N/A
[6]	Microstrip	Roger	N/A	N/A
[1]	Microstrip compact 3D	FR4	N/A	N/A
[17]	Monopole	PET	Yes	N/A
Current work	Monopole	PET	Yes	Yes

2.2. Impedance matching structure

The impedance matching layer plays an important role in improving the antenna performance during antenna placement on the head phantom for head diagnostics. To ensure the proper power penetration an impedance matching layer has been designed by using CST simulation tools which can be attached to the antenna during the practical head imaging application. Moreover, analyzing the simulation results the impedance matching layer dimension and thickness have been varied, and finalized the optimal dimension. To ensure flexibility silicon has been utilized with new materials. A new $BaTiO_3$ silicon-elastomer matching layer is proposed in this study as shown in Figure 2(a) front, back, and side view of proposed impedance matching layer and Figure 2(b) antenna with impedance matching layer. According to the literature, the dielectric constant of the human head is around 20 to 30 [24]. Therefore, the dielectric constant of the matching layer is designed to be 20 to increase the power transmitted into the human head while at the same time making sure that the dimension of the CPW feeding line is still realizable. The use of a substrate with a dielectric constant value of more than 20 would make the dimensions of the CPW feeding line to be very small and make it almost impossible to fabricate. To add flexibility to the impedance-matching layer, silicone elastomer will be mixed with the $BaTiO_3$. The final configuration of the flexible impedance matching layer is 70×30×6 mm. Table 3 shows the physical dimension, dielectric properties, and tangent loss of the impedance-matching layer.



(a) (b)

Figure 2. Proposed impedance matching layers; (a) front, back, and side view and (b) antenna with impedance matching layer

Table 3. The physical dimension of the proposed impedance matching layer

Parameter	Values (mm)
Length	70
width	30
thickness	6
Dielectric properties	20
Tangent loss	0.005

2.3. Antenna bending configuration

The proposed antenna is intended to be used for wearable microwave head imaging applications where it is required to be directly placed on the human head. Due to the curvature of a human head, it is important to investigate if bending configuration could affect the performance of the antenna. Hence, the proposed antenna has been simulated with a bending condition by considering the typical human head curvature. Figure 3 illustrates the antenna in bending configuration.

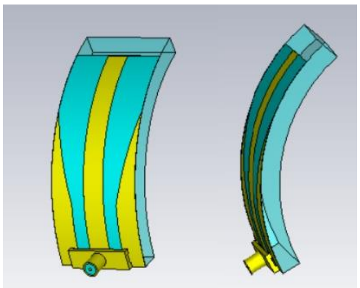


Figure 3. Bending configuration of the proposed antenna

2.4. Artificial head phantom for simulation

The main objective of this work is to design a flexible body-coupled antenna for wearable microwave head imaging and sensing applications. Firstly, the proposed antenna has been simulated in free space and the parameter results have been investigated. However, in order to properly evaluate the performance of the proposed antenna, the antenna needs to operate directly on the head phantom rather than on free space. Therefore, to ensure the antenna application is proper human head phantom model has been used from the simulator. By utilizing the simulation tool, an artificial human head is used where the dielectric properties of the head are set based on the values taken from the simulation software's library to accurately mimic the actual human head. The average dielectric constant and loss tangent of the bio-tissue are 42 and 20 respectively. Figure 4 shows the placement of the antenna on the artificial had phantom in the simulation tool.

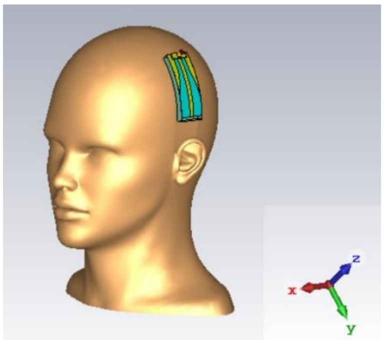


Figure 4. Placement of the antenna on the artificial human head phantom

3. RESULTS AND DISCUSSION

3.1. Impedance matching performance of the antenna

Figure 5 shows the reflection coefficient of the proposed antenna with and without an impedance-matching layer. The 10 dB return loss of the antenna with the impedance matching layer is from 0.475 GHz to 1.089 GHz with an impedance bandwidth of 615 MHz. On the other hand, the antenna without an impedance-matching layer shows worse performance across the frequencies. This indicates that the use of the impedance matching layer somehow improves the matching performance of the antenna. Another significant improvement with the use of the impedance matching layer is that the operating frequency of the monopole antenna is shifted to a lower frequency range below 1 GHz as compared to the antennas proposed in the literature for the same applications [25]. This will certainly improve the penetration depth of the proposed antenna since electromagnetic wave at the low-frequency range is able to penetrate more into the human body compared to the high-frequency range.

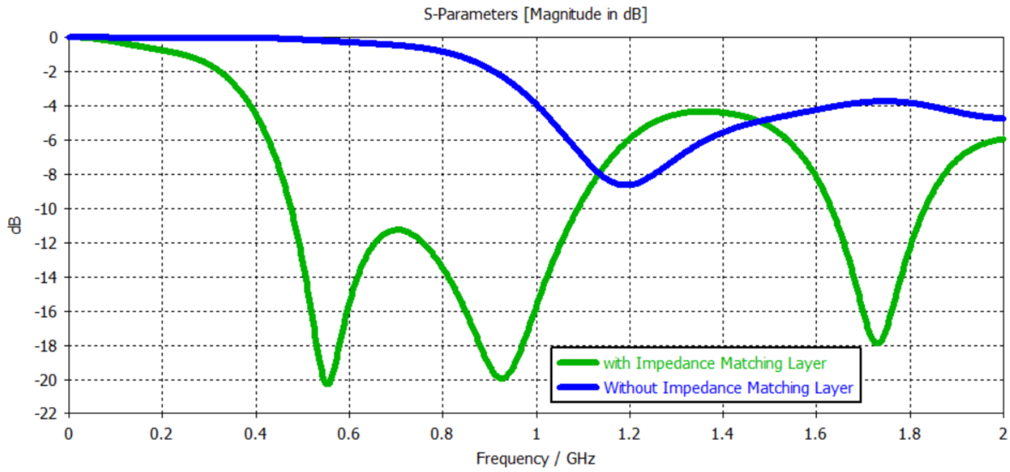
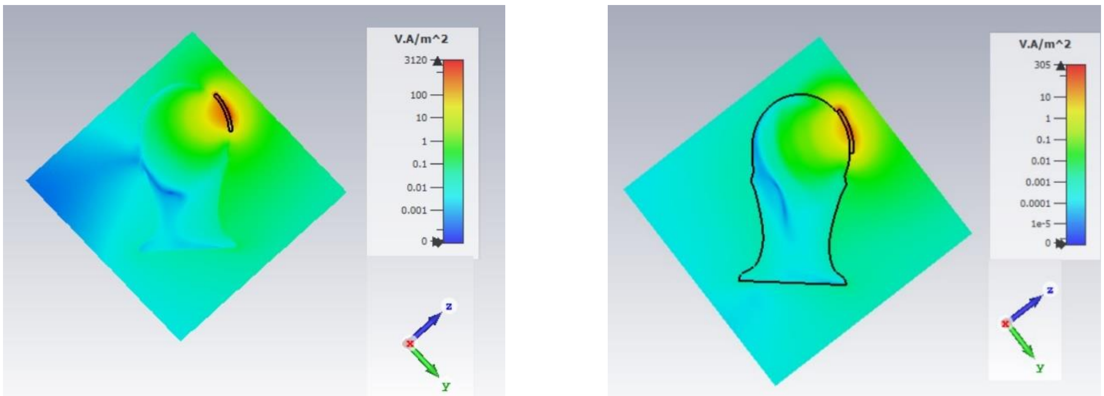


Figure 5. S-parameter of the antenna with and without impedance matching layer at the operating frequency

3.2. Investigation on the power transmission into the human head

One of the most important performance metrics that should be evaluated when designing antenna for microwave head imaging application is the power penetration into the head. This is to ensure that the proposed antenna for the mentioned application is capable to perform efficiently. Figure 6 illustrates the power flow inside the head phantom at 0.5 GHz, where Figure 6(a) with an impedance-matching layer and Figure 6(b) without an impedance-matching layer. It can be seen that more power is able to penetrate into the head with the use of an impedance-matching layer at 0.5 GHz where the maximum power is 3120 W/m^2 compared to just only 305/m^2 for the antenna without an impedance-matching layer. This is only possible with the use of high dielectric constant material like $BaTiO_3$. Also, it should be noted that good impedance matching, and the transmitted power results are achieved when the antenna is in a bending configuration rather than a flat structure. It shows that the performance of the antenna is not affected when bent to conform to the curvature of the artificial head phantom. Table 4 shows the maximum SAR values at frequency 0.78 GHz for different transmitted power.



(a) (b)

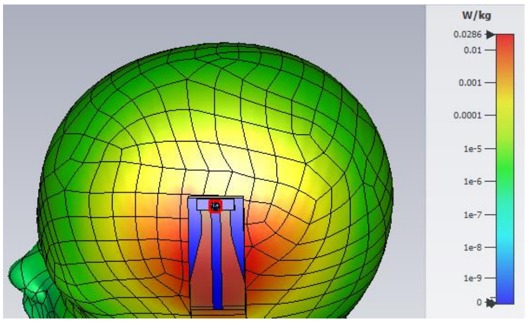
Figure 6. Simulated power flow inside the artificial human head at the 0.5 GHz; (a) with impedance matching layer and (b) without impedance matching layer

Table 4. The maximum SAR values at frequency 0.78 GHz for different transmitted power

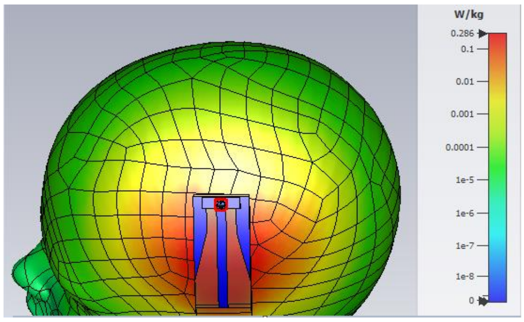
Transmitted power (mw)	Values (W/kg)
1	0.0286
10	0.286
100	2.86

3.3. Investigation of specific absorption rate in the human head

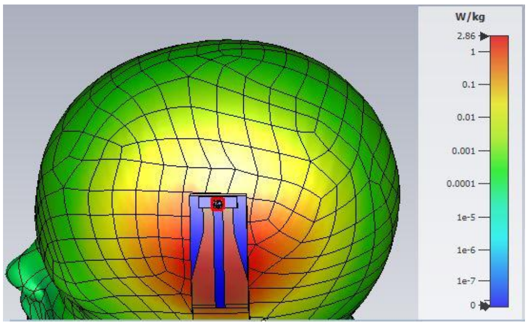
With the use of simulation, an analysis of the electromagnetic energy absorbed by the biological tissues of the human head has been conducted. A specific absorption rate (SAR) is utilized to define how much energy is absorbed by the human tissue. Although it is important to ensure there is enough power penetration into the head for the head imaging application, the SAR level set by the regulatory body must be complied with. In the simulation, the transmitted power is varied from 1 mW to 100 mW. The SAR values are then calculated for each of these power levels. The specific absorption rate (SAR) values were simulated at 0.78 GHz which is the center frequency of the proposed antenna. Figure 7 shows the simulated SAR values at 0.78 GHz for each power level Figure 7(a) shows 1 mW, Figure 7(b) shows 10 mW, and Figure 7(c) shows 100 mW. The SAR values for transmitted powers of 1 mW, 10 mW, and 100 mW are 0.0286 W/kg, 0.286 W/kg, and 2.86 W/kg respectively. The fact that all these numbers are below the limit set by the regulatory body suggests that implementing the antenna for wearable microwave imaging systems is possible. It can be observed that the SAR level increases linearly with the transmitted power. However, to ensure that any microwave imaging system operates safely, transmitted power of more than 100 mW should be avoided. Table 4 shows the summary of the SAR level at different transmitted power levels.



(a)



(b)



(c)

Figure 7. The simulated maximum SAR value at 0.78 GHz for varying transmitted power levels; (a) 1 mW, (b) 10 mW, and (c) 100 mW

4. CONCLUSION

In this work, a wideband flexible monopole antenna has been simulated with a $BaTiO_3$ silicon-elastomer based impedance-matching layer for wearable head imaging applications. The 10 dB return loss of the proposed antenna when placed directly on an artificial head phantom is from 0.475 GHz to 1.089 GHz with impedance bandwidth of 614 MHz. The impedance matching layer is made from high dielectric constant $BaTiO_3$ with silicon elastomer. The use of silicon in the matching layer provides flexibility needed by the antenna to conform to the human head while $BaTiO_3$ contributes in giving high dielectric constant value to the matching layer. The maximum power inside the head phantom with impedance matching layer increases significantly compared to the antenna without impedance matching layer. This clearly indicates that the proposed antenna is suitable for wearable microwave head imaging applications. Future attempts at the proposed antenna will involve fabricating the antenna and validating the simulation results.

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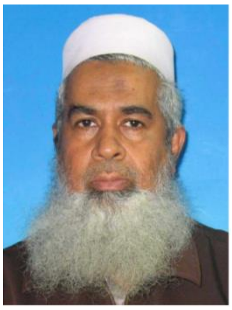

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