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An efficient non-invasive waveguide based horizontal impinging of microwaves for efficient power transfer in human body

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ABSTRACT The paper presents a non-invasive wireless power transfer technique that facilitates horizontal propagation of electromagnetic (EM) waves within the tissue layer of the human body. The horizontal propagation is achieved by using a modified aperture open-ended circular waveguide as the radio front-end and a wave launcher for impinging the EM wave at a desired angle. The EM wave, then with a dominant horizontal component, takes advantage of the sub-dermal fat channel, a parallel plate-like channel formed by the sandwiched low dielectric fat layer between the high dielectric skin and muscle layer. This horizontally propagating wave can be utilized to power multiple implants from a single external source for overcoming the challenges associated with transmitter-receiver alignment in medical implants. The wave launcher is designed for an operating frequency of 2.4 GHz, which is in compliance with the ISM band, and attributed to the optimal frequency for through-body power transfer. This paper further contains an elaborate discussion on the design of the wave launcher including the SMA to wave launcher transition and the results of its numerical study. The design is then validated based on the return loss and electric field intensity in the multilayer heterogeneous medium replicating the human tissues.

INDEX TERMS Electromagnetics, Fat intrabody communication (Fat-IBC), Implantable medical devices, Wireless power transfer, Circular waveguide.

I. INTRODUCTION

RECENT developments in wireless technology has led to revolutionary advancement in many fields, including healthcare [1]–[4]. In body-implanted medical devices (IMDs), the use of wireless power transfer (WPT) has emerged as an effective alternative to traditional batteries. The bulky batteries have a limited lifespan [5]–[7] and are a major roadblock in the miniaturization of implants which is quintessential for targeted therapy [8]. However, with near field coupling, which is the most prominent WPT technique the miniaturization is limited to superficial depth attributed to low operating frequency (100kHz to 50MHz) and inherent transmitter and receiver asymmetry in miniaturized IMDs [9], [10]. While the far-field coupling comes with low power transfer efficiency and risk of unwanted exposure to electromagnetic (EM) waves [11], [12]. On the other hand, Poon *et al.* showed that operating at higher frequencies (low GHz range) can improve the efficiency of power transfer in a biological medium, ascribed to the optimum frequency (3-9 GHz) for the dielectric characteristics of most tissue types [13].

With low microwave frequency, a separation of a few centimeters will correspond to the midfield region and the energy transmission occurs as a combination of the evanescent near-field in air and generative far-field in tissue. This approach overcomes the difficulty of powering deep-seated miniaturized implants [14]. However, the patterned metallic structure used in midfield WPT modulates the field in the tissues to focus on a specific location [15], requiring a precise transmitter and receiver alignment. Additionally, there can be only a one-to-one connection between a transmitter and receiver which limits scalability. Therefore, promoting the horizontal propagation of electromagnetic waves within the body can be an effective solution to address these challenges.

Electromagnetic wave propagation within the human body differs significantly from propagation in free space due to the complex heterogeneous structure of the body [16]. From the electromagnetic point of view, the human body is a heterogeneous medium with dielectric properties dependent on frequency, temperature, and humidity. The skin and muscle with high content of water exhibit high dielectric value whereas, fat with low water content has low dielectric value [17]. When the waves are introduced with dominant vertical components as in the case of most WPT techniques [15], [18]–[22] the body will behave just like a stratified medium and the tendency will be to go deeper into the layers. However, for waves with dominant horizontal components, the low dielectric fat layer sandwiched between high dielectric skin and fat layers forms a parallel plate-like transmission line [23], [24]. The parallel plate formation termed as *fat channel* makes the electromagnetic wave to propagate within the fat layer (horizontal propagation) for a usable distance. However, in [23] fat channel propagation was achieved by placing the transmitter along the fat layer, which at the application level will result in an invasive power source.

In the medical field, noninvasive methods are paramount for reducing the risk of infection, minimizing patient discomfort, and speedy recovery. Thus, a noninvasive powering method is crucial for active IMDs that rely on external energy sources for operation. Some of the recent studies have ventured into non-invasive wave impinging for Fat-IBC, contributing significant insight into this area [25]–[27]. However, these techniques introduce waves vertically into the fat layer, which could be a reason for the weak coupling. To address this, we propose a modified aperture open-ended circular waveguide-based radio front-end, from here on mentioned as wave launcher, that promotes dominant horizontal propagation of the EM wave for implant powering. The proposed method leverages the advantage of the fat channel technique and midfield WPT. The organization of the paper is as follows. Section II describes the design and optimization. The results achieved from the simulation study are elaborated in section III, followed by conclusion in section IV.

II. INCLINED APERTURE CIRCULAR WAVE LAUNCHER

Previous studies have emphasized the potential of employing an open-ended circular waveguide to introduce electromagnetic waves into the human body [28]–[31]. The easy manufacturability and economic feasibility also motivated the selection of the open-ended circular waveguide. The fundamental principle postulates that waves inherently emerge orthogonal to the aperture of the waveguide. Consequently, manipulation of the aperture allows for control over the direction of the wave launched from the open end of the waveguide. This could be achieved by either tilting the waveguide at a desired angle or modifying the waveguide aperture by cutting it at a desired inclination angle. While the former will reduce the design complexity, the aperture modification is favored as the tilt will require calibration in each use.

The initial step in designing the wave launcher involves determining the operating frequency and corresponding dominant mode cut-off frequency. As the proposed wave launcher

TABLE 1. Dominant mode cut-off Frequencies for variable radius

Radius (mm)	First Dominant mode (TE11) (GHz)	Second Dominant mode (TM01) (GHz)
29	2.09	2.74
30	2.02	2.65
31	1.95	2.56
32	1.89	2.46
33	1.84	2.40

TABLE 2. Design modification with dielectric filling

Design Parameters	Old Value	New value	Variation
Dielectric Filling (ϵ_r)	No filling	2.1 (Teflon)	NA
Radius (mm)	45.05	31	-14.05 (31.2%)
Cutoff Frequency, TE11 (GHz)	1.950	1.9554	+0.0054
Cutoff Frequency, TM01 (GHz)	2.5474	2.5598	+0.0124
Guided Wavelength (mm)	214.28	148.67	-65.61 (30.6%)

is only an aperture-modified open-ended circular waveguide, it will retain the same dominant modes (TE_{11} and TM_{01}) as those of a regular open-ended circular waveguide. The dominant mode operation ensures maximum power transfer [32]. Considering factors such as the industrial, scientific, and medical (ISM) band, tissue characteristics, and optimal frequency for transcutaneous powering an operating frequency of 2.4 GHz and a cut-off frequency of 1.95 GHz have been chosen. Operating at non-ionizing radio frequency ensures safe interaction with biological tissue, and small temperature variations from this interaction can be regulated by the body in the same way as temperature increase during physical exertion [34]. However, with the chosen operating frequency the dimensions of an open-ended circular waveguide will be large in comparison to human body parts. One of the most often used methods for size reduction is filling the waveguide with a suitable dielectric material [32]. In this work, Teflon, with dielectric value(ϵ_r) 2.1 is chosen because of ease of availability. The dielectric filling not only influences the dimension of the waveguide but also affects the window between the cut-off frequency of the dominant modes. Subsequently, the dominant mode cut-off frequencies ($f_{c_{TE11}}$ and $f_{c_{TM01}}$) are computed as a function of radius (r) using the equation for a dielectric-filled circular waveguide [32], given in (1) and (2).

$$f_{c_{TE11}} = \frac{p'_{11}c}{2\pi r\sqrt{\epsilon_r}} = \frac{1.841(3\times10^8)}{2\pi r\sqrt{\epsilon_r}}. \quad (1)$$

$$f_{c_{TM01}} = \frac{p_{01}c}{2\pi r\sqrt{\epsilon_r}} = \frac{2.405(3\times10^8)}{2\pi r\sqrt{\epsilon_r}}. \quad (2)$$

The cut-off frequencies corresponding to each radius value that satisfies the condition $f_{c_{TE11}} < 2.1GHz$ are listed in Table 1. From Table 1 it can be observed that for a radius of 31 mm, the dominant mode cut-off frequency is comparable to that of the initial choice of 1.95 GHz. The effect of dielectric filling

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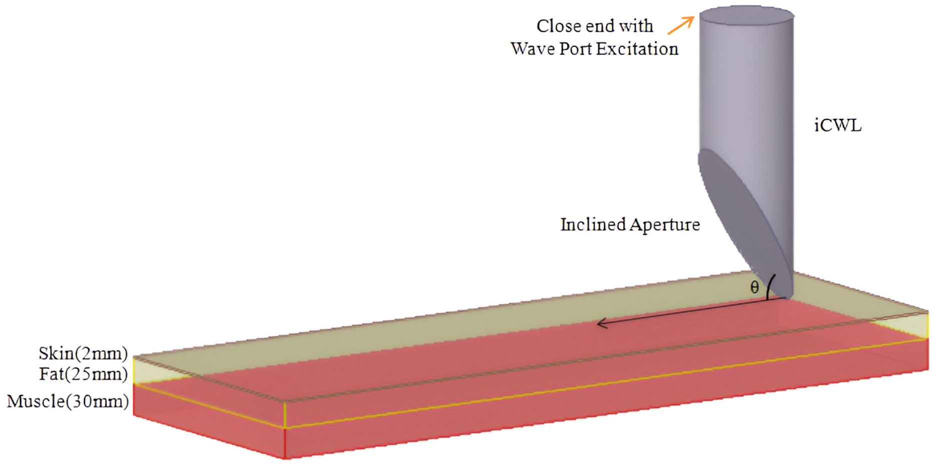

FIGURE 1. Schematic representation of the simulation model

in the wave launcher parameters is summarized in Table 2, which shows a 31% reduction in dimensions.

With the radius of the wave launcher finalized, the next step is to identify the optimum inclination angle of the aperture. The aperture inclination is the prime factor that promotes horizontal propagation of the EM wave in the fat layer. The influence of various inclination angles is studied using commercially available high-frequency system simulation software, ANSYS HFSS [35]. The simulation model consists of the wave launcher with variable aperture inclination and a multilayer transmitting medium replicating human tissue, see Fig. 1. With variation in inclination angle the length of the wave launcher also changes. The length of the wave launcher consists of two components, one along the modified inclined aperture and the other the length from the closed/short circuit end to the nearest edge of the aperture. The length along the inclined aperture is a constant for a given inclination angle, given by (3)

$$L_{inc} = 2r\tan\theta. \quad (3)$$

where, r is the radius of the close end of the wave launcher in millimeters, and θ denotes the inclination angle. The length from the closed end to the nearest edge is variable, and analysis revealed that a better return loss is achieved with shorter lengths. However, considering the structural stability and manufacturability of the wave launcher, a length of 48 mm is selected, resulting in an overall length of 48 mm + L_{inc}.

The transmitting medium in the simulation model is a rectangular block with layers of uniform dimensions stacked one over the other replicating skin, fat, and muscle layers. These layers are defined as dielectric materials replicating the properties of the particular tissue at the chosen operating frequency [36]. Further, the thickness of the layers in the transmitting medium corresponding to skin, fat, and muscle are taken as 2 mm, 25 mm, and 30 mm respectively, which is the approximate value for the cross-section of an average human thigh [23].

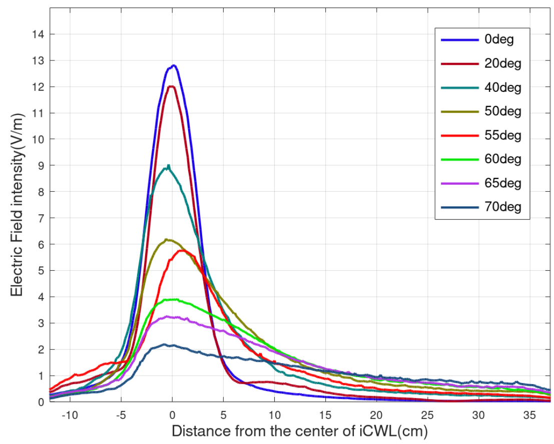

FIGURE 2. Electric field intensity measured at the middle of the fat layer, 14.5mm deep into the multilayer for various aperture inclination w.r.t distance from the center of the wave launcher.

The electric field intensity evaluated at the middle of the fat layer, i.e., 14.5 mm deep into the multilayer medium, at uniform distances along the length of the medium, is shown in Fig. 2. The x-axis of the plot represents the distance (in cm) along the medium, with the zero marking indicating the point in the fat layer along the vertical axis from the center of the close end of the wave launcher. The y-axis represents the electric field intensity (in V/m). Fig. 2 demonstrates that for inclination angles above 50°, the decrease in the magnitude of electric field intensity is gradual and maintains the magnitude along the length of the medium. In contrast, the decrease is steep for smaller inclination angles, indicating better horizontal propagation at higher inclination angles. However, with a higher inclination angle, the length along the inclination will also increase (74 mm for 50° to 170 mm for 70°), as given by (3), which will influence the structural stability of the wave launcher. Based on the observations made from the electric

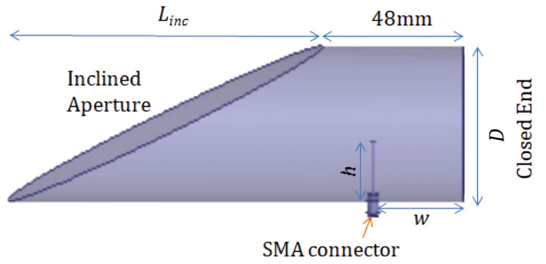

FIGURE 3. Proposed inclined aperture circular wave launcher (iCWL)

field intensity analysis and considering structural stability, an inclination angle of 60° is chosen which gives a balance between horizontal propagation and design integrity. For an inclination of 60°, the length along the inclined aperture (L_{inc}) will be 107.4 mm, as given by (3), leading to an overall wave launcher length of approximately 155 mm.

A. SMA TO WAVE LAUNCHER TRANSITION

The excitation of the wave launcher in the prior simulations was achieved using the built-in wave port feature of ANSYS HFSS simulator [35], see Fig. 1. While the usage of the wave port was adequate enough for demonstrating the proof of concept, an implementable design requires the wave port to be replaced by a physical connector, such as an SMA connector.

The proposed design utilizes the dimensions of an extended dielectric female receptacle type SMA connector to create a model that closely reflects real-world applications [37]. For the transition, the common and easy-to-implement E-plane or orthogonal transition is employed, wherein the center conductor of the probe is inserted into the waveguide, see

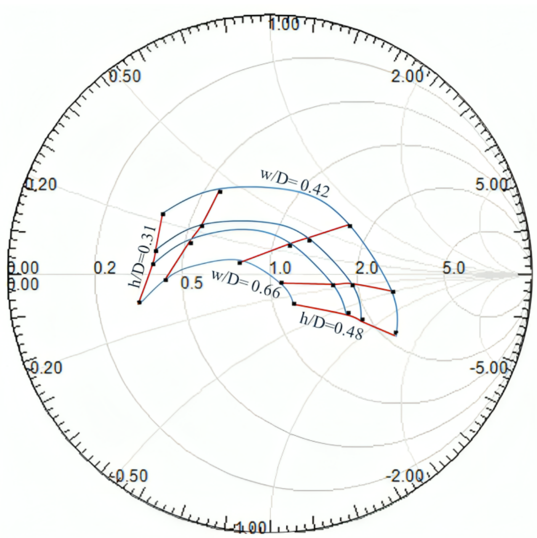

FIGURE 4. Normalised input impedance of the wave launcher radiating to free space as a function of the probe insertion depth h/D and the transition position w/D for operating frequency $f = 2.4$ GHz. ($h/D = 0.31, 0.33, 0.38, 0.44, 0.48$; $w/D = 0.42, 0.5, 0.54, 0.66$)

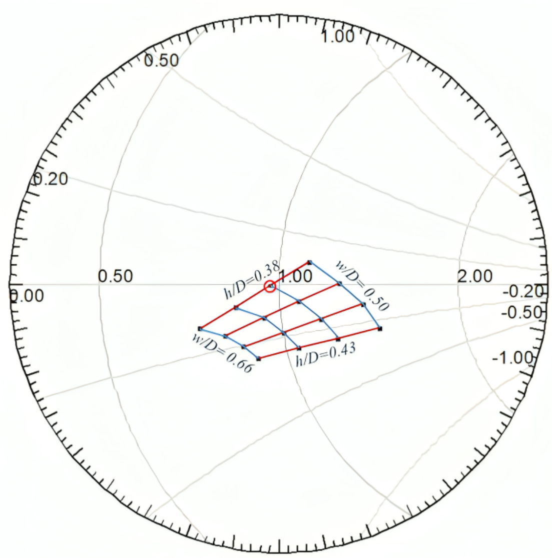

FIGURE 5. Normalised input impedance of the wave launcher radiating to the multilayer medium as a function of the probe insertion depth h/D and the transition position w/D for operating frequency $f = 2.4$ GHz. ($h/D = 0.38, 0.4, 0.41, 0.43$; $w/D = 0.5, 0.54, 0.59, 0.66$)

Fig. 3. The optimization of the distance between the closed end and the transition (w), as well as the length of the probe extending into the wave launcher (h), helps in achieving a matched transition. The normalized input impedance for various probe insertion depths (h/D) and transition position (w/D) at the operating frequency is analyzed using smith chart [38], where D is the diameter of the close end of the wave launcher. To start with, the analysis is done with the wave launcher radiating to free space, and varying insertion depth ($0.31 < h/D < 0.48$), as well as transition position ($0.42 < w/D < 0.66$), see Fig. 4. From Fig. 4, it can be observed that optimum impedance matching can be achieved in the range between $0.38 < h/D < 0.44$ and $0.5 < w/D < 0.66$.

The analysis is augmented to encompass the influence of the transmitting medium, the multilayer structure replicating human tissues, on the impedance. Fig. 5, illustrates the normalized input impedance value of the wave launcher while transmitting to the multilayer medium, for the optimum range ($0.38 < h/D < 0.43$ and $0.5 < w/D < 0.66$) identified above. From Fig. 5 it can be observed that for $h/D = 0.31$ and $w/D = 0.54$, the value of normalized impedance is approximately $1(0.9735 + i0.0091)$ implying a good impedance matching. The corresponding values of probe length and transition position are 24 mm and 34 mm respectively.

B. DESIGN VALIDATION

The proposed wave launcher is validated numerically by evaluating the return loss (S_{11}). The return loss describes the waves reflected off a load and thus serves as a metric to quantify the effectiveness of a device. A lower return loss

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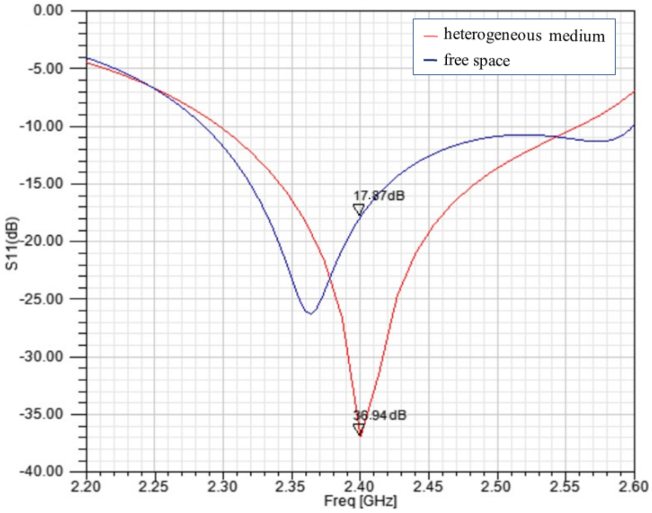

FIGURE 6. Return loss (S_{11}) for the optimized teflon-filled wave launcher with 60° aperture inclination when transmitting to free space and heterogeneous medium w.r.t frequency

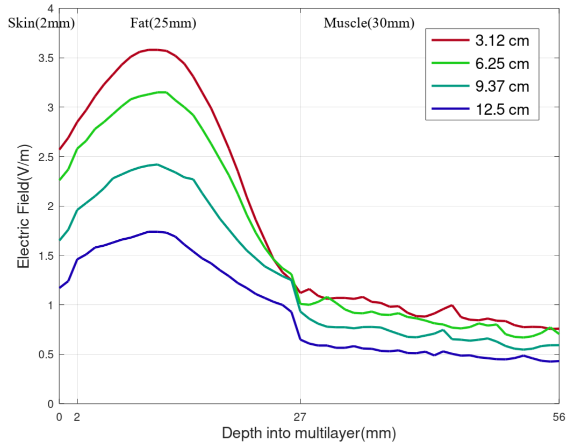

FIGURE 7. Electric field intensity measured across the depth of the heterogeneous multilayer medium at various distances away from the center of the wave launcher

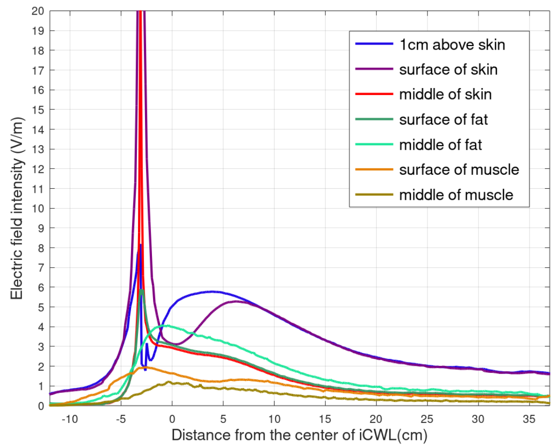

FIGURE 8. Electric field intensity measured at various layers of the multilayer medium w.r.t to distance from the center of the wave launcher

indicates better impedance matching and lesser reflection from load to source. The return loss of the proposed launcher is evaluated using ANSYS HFSS, see Fig. 6. The evaluation is done while the wave launcher is transmitting to free space as well as the heterogeneous multilayer medium. From Fig. 6, it can be observed that at the operating frequency, the $|S_{11}|$ is 36.94 dB when transmitting to the heterogeneous medium, compared to 17.87 dB for free space. The larger value of $|S_{11}|$ indicates that the wave launcher exhibits better performance when transmitting to the heterogeneous multilayer medium than to free space, which is in agreement with the proposed design. Furthermore, for heterogeneous medium the resonant frequency coincides with the operating frequency (2.4 GHz), implying the wave launcher has the lowest reflection at the operating frequency.

The proposed inclined aperture circular wave launcher design is simple and easy to fabricate. Usually, microwave-based midfield wireless power transfer techniques employ patch antennas as transmitters [39]. The design and implementation of these antennas can be cumbersome, as they are designed to be excited through multiple slots, necessitating phase and amplitude corrections for optimal operation [14], [15], [39], [40]. In contrast, the proposed wave launcher with SMA probe excitation simplifies implementation and makes it more user-friendly.

III. RESULTS AND DISCUSSION

An insight into wave propagation can be achieved by analyzing the electric field intensity within the multilayer medium. As mentioned in the previous section, the tissue layers form a channel due to the variation in the dielectric property. The low dielectric fat layer sandwiched between the high dielectric skin and muscle layer results in a parallel plate-like transmission channel. Consequently, the electric field intensity is expected to be higher in the fat layer compared to skin and muscle. To ascertain this, the field penetration into the multilayer medium is analyzed numerically. Electric field intensity is evaluated across the multilayer medium for a variable distance away from the iCWL. Fig. 7 illustrates the electric field intensity evaluated across the depth of the medium at various distances away from the center of the wave launcher. As conceptualized, the fat layer exhibits a stronger field compared to the other two layers at all distances, see Fig. 7, though the overall field density is reduced along the length of the medium.

Further, the electric field intensity along the length of the medium is analyzed numerically. As anticipated the middle of the fat layer has the highest electric field intensity within the multilayer medium, see Fig. 8. However, as can be observed from Fig. 8 there is a very high electric field intensity above and within the skin at the point where the wave launcher contacts the skin (−3.1cm from the center), which is detri-

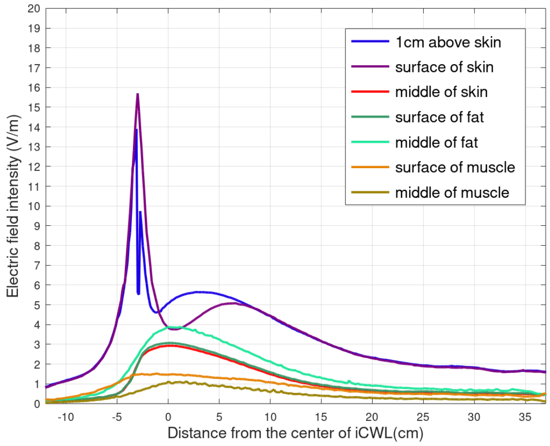

FIGURE 9. Electric field intensity measured at various layers of the multilayer medium after introducing gap w.r.t to distance from the center of the wave launcher

mental for transcutaneous powering. As a countermeasure, a gap is introduced between the multilayer medium and the tip of the wave launcher. A width of 5mm is chosen for the gap restricted by the decrease in $|S_{11}|$ by 10dB (26.55 dB from 36.94 dB). The introduction of the gap successfully reduced the field intensity spikes above the skin layer and eliminated them within the multilayer, see Fig. 9. Additionally, the introduced gap moves the radio front end further away from the body, positioning it near the Fraunhofer distance (midfield region). It is to be noted that, beyond the Fraunhofer distance the thermal effects will be insignificant. The electric field at the skin surface and in the air above still remains a major concern, as the wave transmitting above the skin will be lost, thereby decreasing the overall efficiency of the device. The unwanted wave propagation in air resembles the complexity associated with multipath signals encountered in many biomedical applications [41]. The literature available on the reduction methods of unwanted multipath focuses on curtailing the wave flow at the skin surface and in the air completely [42], [43]. On the other hand, the proposed method requires the wave to travel through air before it reaches the multilayer medium. The usage of a coupling medium can be a potential solution [41] for reducing the waves lost along the skin surface. However, further investigation is required to make sure that the initial wave propagation through air is unhindered and this can be a viable subject for future work. Meanwhile, exposure to electromagnetic waves, particularly with the spike in field intensity at the skin surface, necessitates careful evaluation of safety parameters. Future work will involve the computation of the Specific Absorption Rate (SAR) to ensure compliance with IEEE C95.1 standards for human exposure.

IV. CONCLUSION

This paper contains an exhaustive discussion on the modification of a regular open-ended waveguide into the proposed wave launcher including an effective transition from SMA. An inclined aperture wave launcher was successfully designed to facilitate horizontal propagation of waves in a heterogeneous multilayer medium, such as tissue layers. The design is then successfully validated through the numerical analysis of the return loss. The proposed wave launcher had a minimum loss at the operating frequency while transmitting to the multilayer medium. Further, the electric field intensity in the multilayer medium was studied numerically to confirm the forward or horizontal propagation of waves in the fat layer. It was observed that, while the fat layer had the highest field intensity within the multilayer medium with evident forward propagation, the field intensity in the air above the multilayer, and the surface of the skin was higher. Also, a detrimental spike in the field intensity was observed at the point of contact of the wave launcher and the medium. By introducing a gap between the launcher and the medium, the spike was eliminated within the multilayer medium and was significantly reduced in the air above. However, the field intensity above the multilayer medium remains high indicating wave propagation through the surface. Further investigation is needed to reduce the unwanted wave propagating and to ensure the proposed design compliance with SAR limits, which will be the focus of future research.

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