Small Triple-Band Meandered PIFA for Brain-Implantable Bio-telemetric Systems: Optimization of Substrate/Superstrate Effectiveness

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***Abstract*—We optimize and characterize our latest reported small triple-band implantable planar inverted-F antenna (PIFA) resonating at Medical Device Radiocommunication Service (MedRadio) band (401–406 MHz), and Industrial, Scientific, and Medical (ISM) bands (902–928 MHz and 2400–2483.5 MHz) for wireless brain implants. To this end, we used a numerical 7-layer human head model to assess the impact of the substrate and superstrate properties on the peak gain of the antenna. Our results have demonstrated the gain improvements of 2 dB and up to 4.4 dB in the MedRadio and ISM bands, respectively, by optimizing the substrate properties and removing the superstrate.**

Keywords*— *Implant antenna, meandered PIFA, triple-band antenna, wireless brain implant, implantable medical device

I. INTRODUCTION

The rapid progress in wireless implantable medical devices (IMDs) promises to revolutionize the healthcare industry. These devices provide remote monitoring of human health status and access to their physiological data in bio-telemetry systems [1]. One of the main components of these systems is an implantable antenna integrated into IMDs to establish a continuous bidirectional communication with an exterior monitoring/control unit [2]. Correspondingly, techniques and methods for miniaturization and optimization of implantable antennas have been a considerable ongoing research topic over the past few decades [2]-[3]. Particularly, multi-band PIFA has brought a compelling solution to meet designing requirements for implantable antennas with multifunctional biomedical implant communications [2]. To this context, defined resonant bands for bio-telemetry systems with versatile functions contain MedRadio band operating at the range of 401–406 MHz and the ISM band resonating at the spectrums of 433.1–434.8 MHz, 868–868.6 MHz, 902.8–928.0 MHz, and 2.4–2.48 GHz. The major challenges in designing a multi-resonant implantable antenna are the antenna dimension in terms of diminishing the implant size and achieving a proper radiation performance. Based on our previous work [2], we developed a small triple-band meandered PIFA with the volume of $11 \times 20.5 \times 1.27$ mm^3 placed in the CSF region at the depth of 13.25 mm from the body surface. We achieved the maximum simulated | measured gain of −38.5 | −43.6, −22.5 | −25.8, and −24.3 | −20.1 dBi at 402, 902, and 2400 MHz, respectively. In this work, we investigate the possible improvement beyond this performance through optimization of the thickness and relative permittivity of the substrate and superstrate, which we had considered fixed in our previous work [2].

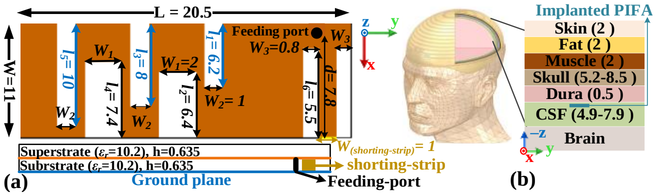

Fig. 1. The proposed meandered triple-band PIFA configuration (a), The 7-layer human head model with implanted PIFA (b).

II. ANTENNA OPTIMIZATION AND NUMERICAL ANALYSIS

A. Antenna Design Principles

Fig. 1 (a) shows the cross-sectional view of the layers and the geometry of the proposed meandered triple-band PIFA with the dimension of $11 \times 20.5 \times 1.27$ mm^3. This model integrates a 0.6 mm radius pin to feed the PIFA radiator via a 50 Ω coaxial cable and a shorting strip to link the radiating patch to the ground plane in y-z plane vertically. In the first phase, we computed the radiator dimension to resonate at the ISM band of 902 MHz applying the equation $f = C_0/\sqrt{\varepsilon_r}\,(L+W+h+W_{(\text{Shortig-strip})})$, where C_0 defines the light speed in free space, ε_r is the substrate relative permittivity, L and W are the length and width of the radiator, respectively, h and $W_{(shorting\text{-}strip)}$ denote the substrate thickness and the shorting strip width, respectively [2]. According to this formula, high-permittivity substrate/superstrate (Rogers RO3210; $\varepsilon_r = 10.2$, $\tan\delta = 0.003$, $h = 0.635$ mm) shrinks the PIFA size. Additionally, we placed a superstrate over the radiator to reduce direct contact it from the lossy surrounding tissue. Moreover, we enveloped the PIFA with silicone-coating (ε_r=2.2, $\tan\delta$=0.007) to ensure the biocompatible insulation. In

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the second phase, inserting several cutting slots into the patch led to further downsize the PIFA and widen its bandwidth [3]. After that, meandering these slots made current path longer subsequently excited the PIFA to operate at MedRadio band. In the last phase, adding one more meandered slot close to the feeding point generated the third resonance at 2400 MHz. As a result, miniature triple-band meandered PIFA brings a promising prospect for multitasking IMDs in biomedical telemetry systems.

B. *Optimization Methodology, Results and Discussion*

We assessed the proposed PIFA implanted between the cerebrospinal fluid (CSF) and dura region in a 7-layer head model with the defined thickness and dielectric properties of the tissues [2] at the 13.25 mm depth, as demonstrated in Fig. 1 (b) and analyzed with the ANSYS HFSS v18 simulator. As reported in our earlier work [2], the achieved impedance bandwidths properly cover the desired resonant frequency bands. Although the introduced self-matched triple-band PIFA attained satisfactory gain values at a good directivity in the outwards direction of head tissues [2], here, we present an optimization process with the aim of possible improvement in the peak gain of the PIFA beyond our previously attained results [2]. To achieve this, we carried out optimization by studying the impact of substrate/superstrate properties numerically using the genetic algorithm (with the software default settings) in HFSS Optimetrics tool. Optimetrics modifies values of design parameters to reach the goal by minimizing a given cost function. We defined the cost function targeting at 3-dB improvement in the attained peak gain of our previous work [2] through

$$Cost = \sum_{k=1}^{M} \alpha_k \, \xi_k \left(T_k - G_{peak,k}\right)^2; \tag{1}$$

$$\alpha_1 = 1,\ \alpha_2 = 0.85,\ \ \alpha_3 = 0.65,$$

$$T_1 = -35.34\ \text{dB},\ \ T_2 = -19.43\ \text{dB},\ \ T_3 = -22.18\ \text{dB},$$

where k is the frequency index of 1,2, and 3 referring to 402 | 902 | 2400 MHz, respectively, α_k is the frequency-weight that empirically chosen, T_k is the optimization target and $G_{peak,k}$ is the simulated peak gain (dB). Moreover, $\xi_k = 0$ when $G_{peak,k} \geqslant T_k$, i.e. when the optimization target has been achieved at a given frequency, and otherwise $\xi_k = 1$. As the four variables for the optimization, we considered the substrate and superstrate permittivity ($\varepsilon_{r,sub}$ and $\varepsilon_{r,sup}$) and thicknesses (h_{sub} and h_{sup}). The search ranges for the relative permittivity were defined as $2.2 \leq \varepsilon_{r,sub}$, $h_{r,sup} \leq 10.2$. For the substrate and superstrate thicknesses, we set $0.32\ \text{mm} \leq h_{sub} \leq 1.27\ \text{mm}$ and $0.16\ \text{mm} \leq h_{sup} \leq 1.27$ mm with the additional restrictions: $h_{sup} \leq h_{sub}$ and $h_{sup} + h_{sub} \leq 1.27$. We ran the algorithm for 1568 evaluations and then selected the top-30 of the optimizer evaluations for the final assessment. As a first observation, we noted that the optimizer clearly favored maximally thick substrate irrespective of $\varepsilon_{r,sub}$ and $\varepsilon_{r,sup}$. Thus, we created a scatter plot of the optimizer results where the substrate is thicker than 1 mm as illustrated in Fig. 2. The black markers in the figure are the top-30 evaluations. This indicates that the optimizer favored low-permittivity values between 2.5 and 5.5. These observations are somewhat counterintuitive as typically high relative permittivity is considered favorable to antenna miniaturization. However, this is normally considered in free space, whereas our antenna is surrounded by the very high-permittivity biological media. Next, because the optimizer converged to maximally thick substrate, we removed the superstrate completely and set the substrate thickness to 1.27 mm (the total thickness of our initial PIFA) with the mean value of the relative permittivity of 2.7 at the lowest cost function values. It is evident from the results that removing the superstrate leads to an appreciable peak gain improvement over the foregoing results [2], with the gain difference of 2 dBi (−36.5 dBi), 0.9 dBi (−21.6 dBi), and 4.4 dBi (−19.9 dBi) at 402, 902, and 2400 MHz, respectively. Fig. 3 illustrates the peak gain values of the best optimizer results from the lowest cost function, PIFA with no superstrate and the prior result at low-band, mid-band, and high-band frequencies. Moreover, the shaded regions illustrate the top-30 optimizer evaluations. In conclusion, we demonstrated though numerical modelling that the peak gain of the our previously proposed PIFA for brain implantable microsystems can be improved by removing the superstrate layer and by replacing the previously considered high-permittivity substrate with a one having lower permittivity. Employing this structure, we are able to reach the goals of energizing the deep implants and providing data through IMD utilizing far-field wireless power transfer.

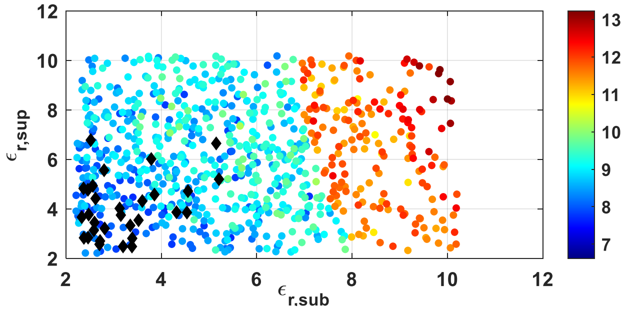

Fig. 2. Dependence of the cost function (in dB-scale) on the relative permittivity of the substrate and superstrate

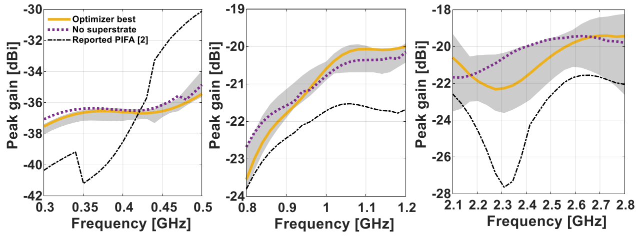

Fig. 3. Comparison of the achieved peak gain versus frequency.

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