Metamaterial-Inspired Highly Compact Wearable Antenna for 406 MHz Cospas-Sarsat Personal Locator Beacons (PLBs)

Mehmet Doğan
Telecommunications Engineering
Istanbul Technical University
Istanbul, Türkiye
E-Mail: doganm16@itu.edu.tr

Mesut Kartal
Electronics and Communication Engineering
Istanbul Technical University
Istanbul, Türkiye
E-Mail: kartalme@itu.edu.tr

***Abstract*—This paper proposes a highly miniaturized wearable antenna for 406 MHz Cospas-Sarsat Personal Locator Beacons (PLBs). To overcome the physical size constraints of the 74 cm wavelength, a metamaterial-inspired design technique is employed. The design achieves approximately 95 percent size reduction while maintaining the required radiation efficiency for satellite uplink. Results demonstrate that the antenna is designed/aimed to mitigate the frequency detuning caused by human body proximity. This compact, flexible solution ensures reliable signal transmission in critical search and rescue operations.**

Keywords-wearable antenna; metamaterial; 406 MHz; Cospas-Sarsat; Personal Locator Beacon; miniaturization.

I. INTRODUCTION

The international Cospas-Sarsat (Cosmicheskaya Sistema Poiska Avariynyh Sudov / Search And Rescue Satellite-Aided Tracking) satellite system has been instrumental in saving thousands of lives worldwide by detecting and locating emergency beacons since 1984. This satellite communication network is exclusively reserved for emergency distress signals and is accessed through specific devices depending on the domain: Emergency Locator Transmitters (ELTs) in aviation, Emergency Position-Indicating Radio Beacons (EPIRBs) in maritime environments, and Personal Locator Beacons (PLBs) for individual use [1]. Currently, most PLBs available on the market are housed in bulky, walkie-talkie-style form factors. Transitioning these life-saving devices into a wearable, ultra-lightweight form would significantly enhance their ease of use, portability, and global adoption among outdoor enthusiasts and personnel in hazardous environments.

However, realizing a wearable PLB presents a significant physical challenge due to the operating frequency. Cospas-Sarsat beacons transmit at 406 MHz in the UHF band, which corresponds to a free-space wavelength of approximately 74 cm. Designing an efficient antenna that fits on the human body at this wavelength requires advanced miniaturization techniques.

Several approaches have been explored in the literature to achieve antenna miniaturization in the UHF band. One traditional method involves the use of high dielectric constant substrates to reduce the physical dimensions of the antenna [2][3]. Unfortunately, this approach inherently traps the electromagnetic fields within the substrate, leading to a substantial degradation in overall antenna gain and radiation efficiency. Another commonly utilized method is the implementation of fractal geometries to increase the effective electrical length within a constrained physical area [4]. While fractal antennas can achieve a size reduction of approximately 30 percent, their complex structures are costly to manufacture and introduce severe reliability and yield issues in large-scale mass production.

To overcome these critical limitations, this paper adopts a metamaterial-inspired antenna design approach, a concept pioneered by Ziolkowski [5]. Unlike previous miniaturization methods, metamaterial-inspired structures offer extreme size reduction which is often exceeding 80 percent, while maintaining a high degree of implementation simplicity and manufacturing cost-effectiveness. By leveraging this technique, this study proposes a compact and flexible wearable antenna tailored specifically for 406 MHz Cospas-Sarsat applications, ensuring reliable performance and resilient signal transmission. In order to demonstrate the suitability of the metamaterial-inspired approach originally proposed in [5] for wearable electronics, this study investigates its implementation on a flexible Polyimide substrate and evaluates the resulting performance through full-wave simulations.

Despite the significant advantages of extreme size reduction, the metamaterial-inspired approach inherently presents certain limitations. The highly reactive nature of electrically small antennas makes them particularly sensitive to environmental factors. In wearable applications, the close proximity of the human body can introduce frequency detuning and alter radiation characteristics [6]. Additionally, extreme miniaturization typically yields a narrow operational bandwidth and necessitates careful assessment of Specific Absorption Rate (SAR) compliance to ensure human safety [7].

The remainder of this paper is organized as follows: Section II details the antenna design and methodology, encompassing the theoretical foundation of the near-field resonant parasitic element, the flexible wearable configuration, and the internal impedance matching strategy. Section III presents and discusses the full-wave electromagnetic simulation results, evaluating the return loss, VSWR, and far-field radiation patterns in a free-space environment. Finally, Section IV concludes the paper and outlines future work regarding human body phantom simulations and physical prototyping.

II. ANTENNA DESIGN AND METHODOLOGY

This section presents the comprehensive design methodology of the proposed metamaterial-inspired antenna, detailing its theoretical framework, material properties, and specific structural configuration.

A. Theoretical Foundation

The core of the proposed miniaturization technique is based on the metamaterial-inspired near-field resonant parasitic concept, initially introduced as the Z antenna. To bypass the extreme physical constraints of the 74 cm wavelength at 406 MHz, the design employs an electrically small, Z-shaped element [5]. A lumped element inductor connects the two halves of this structure across a central gap. The theoretical framework dictates that the resonance frequency f_{res} of the antenna is governed by its effective inductance L_{eff} and effective capacitance C_{eff}, as expressed in the following equation [5]:

$$f_{res} = (2\pi\sqrt{L_{eff}\, C_{eff}})^{-1} \quad (1)$$

The metamaterial-inspired nature of the Z-shaped element stems from its operation as a Near-Field Resonant Parasitic (NFRP) structure. At subwavelength dimensions, this loaded element acts analogously to a single metamaterial unit cell. Instead of relying on a bulk periodic medium, the Z-shaped parasitic resonator strongly couples to the highly reactive, non-radiating near-fields generated by the aperture feed. This strong electromagnetic coupling creates a highly localized artificial resonance that effectively neutralizes the inherently high capacitive reactance of the electrically small structure. Consequently, the parasitic element acts as an efficient radiator, transferring energy to the far-field while internally matching the impedance.

Because the physical dimensions of the parasitic structure are fixed, C_{eff} remains constant, and L_{eff} is primarily dominated by the introduced lumped element inductor. The resonant frequency can be precisely tuned to the required 406 MHz Cospas-Sarsat band simply by selecting the appropriate inductance value, enabling extreme miniaturization without expanding the physical footprint [8] [9].

B. Proposed 406 MHz Wearable Configuration

Unlike traditional UHF designs that rely on rigid, high-permittivity substrates, the proposed antenna is fabricated on a flexible Polyimide Printed Circuit Board (PCB) substrate with a relative permittivity (ε_r) of 3.5. This highly conformable and low-loss material ensures the device can comfortably fit on the human body for PLB applications. Furthermore, to guarantee superior performance, extreme flexibility, and high resistance to oxidation in harsh outdoor environments, gold is utilized as the conductive material for the antenna arms [10].

The antenna system comprises two primary layers. The top layer features the highly compact, gold-based Z-shaped parasitic radiator. In a significant departure from the direct coax-fed monopoles utilized in the foundational experimental validations of UHF Z antennas, this design employs an aperture coupling feeding mechanism [5]. The feeding line is isolated on the bottom layer, coupling electromagnetic energy through a strategically placed slot in the shared ground plane. This aperture-coupled approach offers an additional degree of freedom in impedance matching and enhances the isolation between the radiating element and the feed network. This architectural choice is crucial for mitigating frequency detuning effects caused by the proximity of the human body, a major challenge in wearable devices.

C. Impedance Matching and Efficiency

Experimental verifications of similar UHF metamaterial-inspired antennas have proven that the near-field resonant parasitic element effectively acts as an internal matching network [8][9][11]. By appropriately tuning the central lumped inductor, the input impedance of the highly reactive electrically small antenna is matched to a standard 50Ω source without the need for any bulky external matching circuits. This approach not only shrinks the physical size by approximately 95 percent but also preserves the high radiation efficiency necessary for reliable 406 MHz satellite uplink in critical search and rescue operations.

D. Antenna Geometry and Dimensions

The overall physical footprint of the designed antenna is remarkably compact, utilizing a square Polyimide substrate with dimensions of exactly 30 x 30 mm. This extreme size reduction highlights the effectiveness of the metamaterial-inspired approach for the 74 cm wavelength constraint.

As illustrated in the top view of the antenna (see Figure 1), the gold-plated Z-shaped parasitic element dominates the top layer. To achieve the desired resonance exactly at the 406 MHz frequency, a 60 nH lumped element inductor is strategically placed and soldered across the central gap of the radiating arms. The bottom layer of the substrate (see Figure 2) houses the vertical feedline structure responsible for the aperture coupling mechanism.

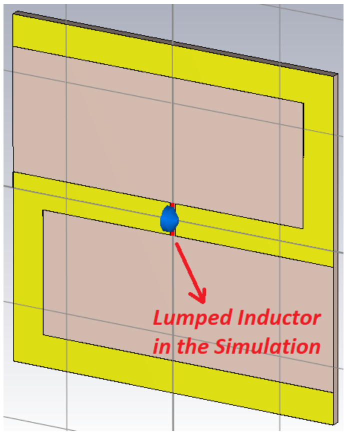

Figure 1. Top view of the proposed metamaterial-inspired wearable antenna, illustrating the gold-plated Z-shaped element and the central lumped inductor. Please note that there is a slot gap directly underneath the lumped inductor.

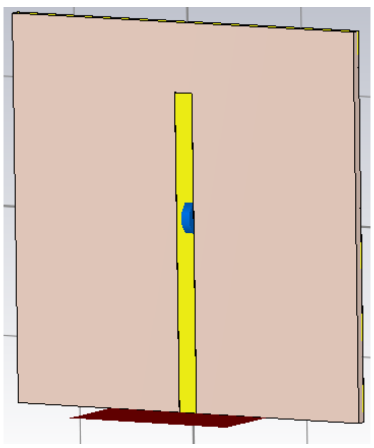

Figure 2. Bottom view of the antenna, detailing the isolated feedline structure used for the aperture coupling mechanism. The area surrounding the antenna's RF Port Excitation is represented by the Ground Plane, which is colored brown in the simulation.

The integration of the top layer's near-field resonant parasitic element with the bottom layer's isolated feedline structure establishes a highly compact and robust design. This precise architectural alignment is essential for achieving the targeted 406 MHz resonance within the constrained footprint , providing a foundation for the numerical performance analysis presented in the subsequent section.

III. Simulation Results And Discussion

To evaluate the performance of the proposed wearable PLB antenna, full-wave electromagnetic simulations were conducted. The numerical analysis was performed using CST Studio Suite Tool – Version 2024, utilizing open boundary conditions to accurately emulate a free-space environment. To precisely model the thin flexible Polyimide substrate, the sub-millimeter coupling aperture, and the strong near-field interactions around the lumped inductor, an adaptive meshing technique with local mesh refinement was employed. The primary parameters investigated in this study were the return loss (S_{11}), Voltage Standing Wave Ratio (VSWR) and the far-field radiation characteristics.

A. Return Loss

The metamaterial-inspired design, leveraging the central lumped inductor for internal impedance matching, demonstrates a distinct and sharp resonance exactly at the 406 MHz Cospas-Sarsat operating frequency. As shown in Figure 3, the simulated return loss achieves a minimum value of -12 dB, safely exceeding the standard -10 dB threshold.

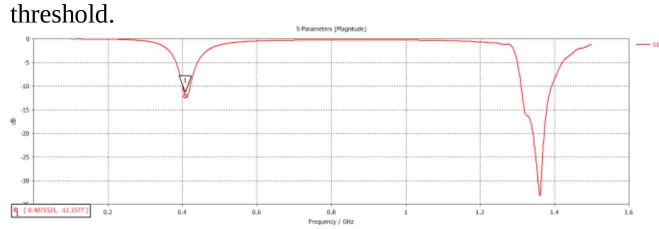

Figure 3. Simulated return loss S_{11} of the proposed metamaterial-inspired wearable antenna, demonstrating a resonance peak of -12.15 dB at 406 MHz band.

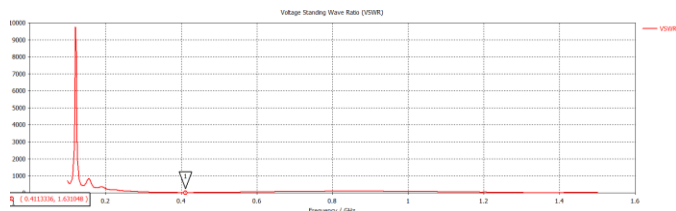

Figure 4. Simulated Voltage Standing Wave Ratio (VSWR) of the proposed antenna, indicating a well-matched value of 1.63 in the operating band.

Furthermore, to evaluate the power delivery and impedance matching quality, the VSWR of the antenna was analyzed. As depicted in Figure 4, the antenna exhibits a VSWR of 1.63 near the resonance frequency. Since a VSWR value of less than 2.0 is considered highly acceptable for practical antenna operations, this result is a strong indicator of successful miniaturization. These findings confirm that the aperture-coupled feeding mechanism, combined with the near-field resonant parasitic element, successfully matches the highly reactive input impedance of the heavily miniaturized antenna to a 50Ω source without requiring any bulky external matching networks.

B. Radiation Pattern and Gain

A critical challenge in extreme antenna miniaturization is the inherent degradation of radiation efficiency and gain. However, despite achieving an approximately 95 percent size reduction relative to the 74 cm free-space wavelength, the proposed antenna exhibits a highly stable omnidirectional radiation pattern suitable for satellite communications. The utilization of a low-loss Polyimide substrate and highly conductive gold arms ensures that the resistive losses are minimized. The simulation results indicate a peak realized

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gain of 1.1 dBi and a robust radiation efficiency of 94.4 percent.

IV. CONCLUSION AND FURTHER WORK

This paper has successfully demonstrated that the metamaterial-inspired antenna architecture, originally proposed by Ziolkowski, provides a highly viable framework for wearable electronic implementations aimed at demanding satellite communication systems.

Furthermore, considering the device's proximity to the user, ensuring electromagnetic safety through rigorous SAR compliance is a fundamental requirement. Consequently, high-fidelity simulations utilizing human body phantoms will be prioritized to guarantee that the design meets international safety standards, serving as a critical prerequisite for the successful implementation and testing of the final physical prototype. By adapting this foundational concept into a highly compact, wearable configuration specifically for 406 MHz Cospas-Sarsat PLBs, this study demonstrates the promising feasibility of achieving extreme miniaturization while delivering the desired radiation efficiency.

The designed antenna overcomes the physical size constraints of the 74 cm UHF wavelength. Our free-space simulation results validate that the antenna shrinks the physical footprint by approximately 95 percent, achieving a stable return loss of -12.15 dB and maintaining the excellent internal impedance matching and radiation characteristics essential for critical search and rescue satellite uplinks.

While the free-space performance strongly validates this miniaturization approach for satellite applications, the practical deployment of wearable antennas requires rigorous validation against human body proximity effects.

Therefore, future work will focus on extensive simulations utilizing human body phantoms to evaluate frequency detuning and SAR compliance. Subsequently, a physical prototype of the antenna will be fabricated, and laboratory measurements will be conducted to experimentally verify the simulated results.

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