A Yagi-Uda Antenna as an Epidermal Strain Sensor

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***Abstract*—Advances in materials and production techniques create new design possibilities and applications for microwave sensors. In this work, the design of a Yagi-Uda antenna as a strain sensor for non-invasive muscle contraction detection is presented. To monitor epidermal strain, a highly flexible polyurethane substrate measuring 35 mm × 20 mm × 200 µm is utilized. For a 10 % strain increase, the separation between the dipole elements increases by 0.1 mm. A 20 MHz shift in the resonant frequency of the antenna is observed for each 10 % step. The proposed Yagi-Uda antenna operates within the 2.4 GHz ISM band across strain values ranging from 0 % to 30 %.**

I. Introduction

The growing field of healthcare technologies has generated interest in the development of novel solutions for monitoring physiological parameters, particularly those linked to human motion and muscle dynamics [1]. Monitoring the strain experienced by these muscles during diverse activities is important for evaluating biomechanical performance, injuries, and optimizing rehabilitation strategies.

Various sensors have been employed to detect muscle contraction and motion monitoring. The most widely utilized sensor in this context is electromyography (EMG) [2], which functions by capturing the electrical signals produced by muscles during contraction. Other examples of sensors employed include piezoresistive sensors [3], conductive nanocomposites [4], and microwave sensors [5]. Among these sensors, an antenna sensor linking the strain on the skin to the level of muscle contraction is the strategy taken in this study. To create the sensor, the strain on the skin is translated as a physical change in an on-body antenna which changes its input impedance. Different kinds of antennas and microwave sensor models utilizing flexible substrates and conductive materials were studied in the literature [5] [6]. For example, a coplanar waveguide-based frequency filter is designed on an RTV silicone substrate for muscle contraction detection [5]. Similarly, a bowtie antenna printed on a flexible polyurethane substrate is proposed for on-body strain sensing [6]. Here, the utilization of a Yagi-Uda antenna for strain sensing [7] is transferred to an on-body case. A Yagi-Uda antenna is designed on a flexible polyurethane substrate and located on the human calf. To the best of the author's knowledge, this work is the first example of employing the Yagi-Uda antenna for on-body strain sensing application with a flexible substrate.

The sensing mechanism is described in Section II. The mechanical and electromagnetic simulation results are provided in Section III. The paper concludes in Section IV.

II. Sensing Mechanism

The strain sensor's design is intended for non-invasive detection of muscle contractions, and the substrate is chosen to be a highly flexible thermoplastic polyurethane (TPU). TPU is known for its exceptional flexibility and elasticity, qualities that are vital for our work where the designed sensor must adapt to the dynamic movements of muscles [8]. This choice of material aims to facilitate the sensor's adaptability to physiological movements.

The Yagi-Uda antenna as seen in Fig. 1 is used to detect the physiological movements. The antenna comprises an asymmetrical fed dipole functioning as the primary radiator, while the remaining two linear dipoles act as parasitic radiators through mutual coupling. All the conductive components are taken as 50 µm thick copper sheets. These conductive components are sandwiched between two 100 µm thick TPU substrates.

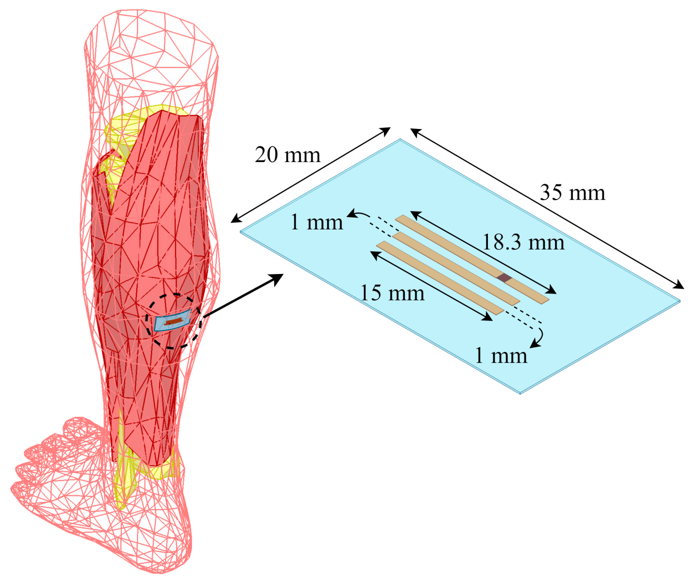

Fig. 1. The electromagnetic simulation setup and the proposed Yagi-Uda antenna with dimensions in mm.

The sensing mechanism relies on the mutual coupling between the primary dipole element and the parasitic dipole elements. When strain is applied to the sensor, the separation between the primary and the parasitic dipoles undergoes alteration corresponding to the strain level. This modification induces a variation in the antenna's input impedance, influencing its resonant frequency. Thus, the Yagi-Uda antenna is effectively employed as a strain sensor, where changes in the physical strain can be observed as measurable shifts in the sensor's operating frequency.

III. Results

According to the sensing mechanism described in Section II, first the mechanical simulations are conducted to anticipate any physical changes to the substrate under expected strain conditions. Then the electromagnetic simulations are conducted under the guidance of mechanical simulations.

A. Mechanical Simulations

The initial design of the planer Yagi-Uda antenna is imported to ANSYS Mechanical to observe the physical changes under strain. The reference for the strain on the skin hence on the epidermal antenna is the change in the length of the calf muscle during walking. It has been reported in the literature that the maximum elongation that the calf muscle experiences is 30 % during walking [9]. Translating that to the mechanical simulation, a force resulting in 30 % elongation is applied to the antenna's longer edge. As can be seen in Fig. 2, a 0.3 mm increase was observed in the gap between the primary and the parasitic dipoles while approximately a 10 % decrease was observed in the antenna thickness. The change in the gap is used in rest of the electromagnetic simulations while the change in the antenna thickness is ignored as its effect is found to be minimal.

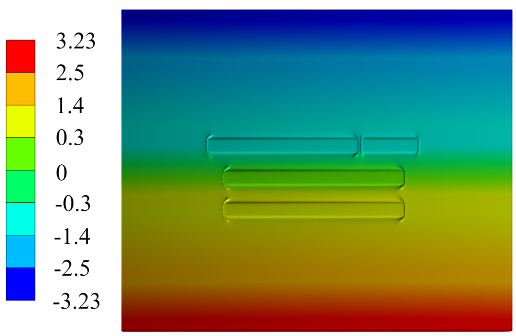

Fig. 2. The mechanical strain analysis of the Yagi-Uda antenna at 30 % elongation (in mm).

B. Electromagnetic Simulations

The separation between the primary radiator and the parasitic radiators is changed from 1 mm to 1.3 mm with 0.1 mm steps. The Yagi-Uda antenna model is parameterized for these values and numerically analyzed through Ansys HFSS. The reflection coefficient values under different strain conditions are presented in Fig. 3. As the strain increases, the increasing separation causes a shift in the resonance frequency. Every 0.1 mm change in separation corresponds to approximately 20 MHz shift in frequency.

IV. Conclusion

In this paper, a highly flexible Yagi-Uda antenna for non-invasive muscle contraction detection is proposed. A TPU substrate is utilized to ensure the antenna deforms together with the human skin. The link between the strain and the antenna's operating frequency originates from the change in the mutual coupling between the dipole elements of the Yagi-Uda antenna. The separation between the primary and parasitic dipoles for the maximum strain level of 30 % is verified through mechanical simulations. The sensitivity of the antenna to various strain levels is demonstrated through simulated reflection coefficients with an acceptable shift in the resonant frequency. The antenna is designed such that it covers the whole 2.4 GHz ISM band for all strain conditions. Thanks to its medical tape-like epidermal structure of the substrate, the antenna can be directly adhered to the body. Additionally, a wearable and flexible RF reflectometry circuit will be built to monitor frequency shifts of the Yagi-Uda antenna.

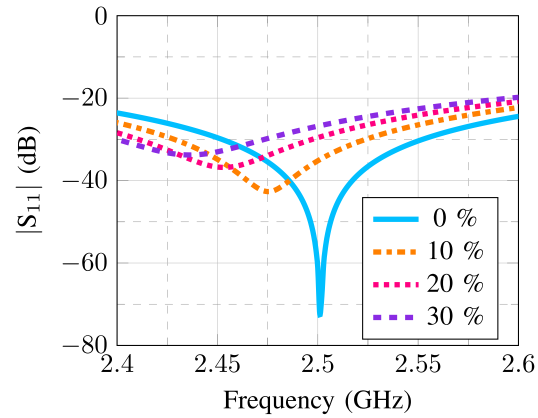

Fig. 3. The simulated reflection coefficient of the Yagi-Uda antenna under different strain levels.

Acknowledgement

This study was supported by Scientific and Technological Research Council of Turkey (TUBITAK) under the Grant Number 22AG016. The authors thank to TUBITAK for their supports.

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