Fawaz, Mariam, Phillips, Shaun, Horne, Robert and Sanz-Izquierdo, Benito (2025) *Printed Bidirectional Stretch Antenna Sensor*. In: 2025 International Conference on Electromagnetics in Advanced Applications (ICEAA). .

2025 International Conference on Electromagnetics in Advanced Applications (ICEAA) | 979-8-3315-4472-0/25/$31.00 ©2025 IEEE | DOI: 10.1109/ICEAA65662.2025.11306045

Printed Bidirectional Stretch Antenna Sensor

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***Abstract*— This paper presents an antenna-based bidirectional stretch sensor for real-time wireless sensing applications. The proposed design utilizes an antenna structure with two orthogonal dipole elements operating at different frequency bands to independently sense strain in two perpendicular directions. One pair of elements is configured to operate at 2.4 GHz, while the other operate at 5 GHz. The antenna is fabricated using direct ink writing (DIW) with stretchable silver ink on a flexible thermoplastic polyurethane (TPU) substrate, enabling the mechanical flexibility required for stretch sensing. Under applied stress, the antenna's physical dimensions change, leading to a shift in its resonant frequency. This frequency shift is observed to be linearly correlated with the applied strain along either axis (x-axis or y-axis). Experimental results show that for stretch levels ranging from 0% to 10% of the original dimensions, the resonant frequency shifts by approximately 6% in the x-axis direction and 7% in the y-axis direction, respectively. The proposed design demonstrates potential for applications requiring simultaneous stretch sensing and wireless communication using the same antenna structure.**

***Index Terms*— Dipole, dielectric, TPU, antenna**

I. INTRODUCTION

RAdio frequency (RF) sensors have gained significant attention in recent years due to their versality and ability to provide wireless, real-time monitoring across various domains. Different domains include healthcare, environmental monitoring, structural heal assessment and industrial automation. RF-based sensors offer enhanced accuracy, efficiency and the capability of being integrated with modern wireless systems. Among RF sensors, strain sensors play a crucial role in monitoring mechanical deformation in structures, materials and even in biological systems. Conventional strain sensing techniques often require wired connections, which limit their deployment in remote environments. Such challenges are addressed by using RF stretch sensors by leveraging wireless communication and passive or semi passive designs for strain measurement. RF stretch sensors offer key advantages like remote monitoring, less power consumption, and enhanced durability. Several studies have examined the development of stretchable antennas in health monitoring in forms like electronic skin [1], smart textiles [2] and biosensors enabling applications like wireless electrocardiography (ECG), hydration tracking, telemedicine systems and continuous glucose monitoring.

In terms of antenna-based stretch sensors, a microstrip patch antenna strain sensor was designed based on the relation between the length of the microstrip and the resonant frequency of the design in [3]. A 0.1% tensile strain results in 3.6 MHz decrease in the resonant frequency of the antenna. This frequency shift is large enough to detect small strains making the microstrip patch antenna a viable strain sensor. Another study reported the changes to the length and width of a patch antenna that occurred due to the applied strain in the range of (0%-2%) resulted in a down shift in the resonant frequency in the range of 5.8 GHz to 5.7 GHz [4].

This paper proposes a printed antenna on stretchable material for bidirectional stretch sensor applications. The design consists of two orthogonal dipoles with a common feeding point. Each pair of dipole elements is designed to operate at distinct frequency bands, ensuring elective strain detection along both axis X and Y. One pair is designed to operate at 2.4 GHz and the other at 5 GHz. The design senses change the applied strain in both directions (bidirectional). Direct ink writing (DIW) printing technology with stretchable silver in on a TPU substrate was employed to fabricate the sensor. This fabrication method is cost effective and saves time compared to other fabrication techniques like screen printing. Furthermore, it is a high-resolution method as there is no cleanup and no material wasted or contaminated after each use of the machine.

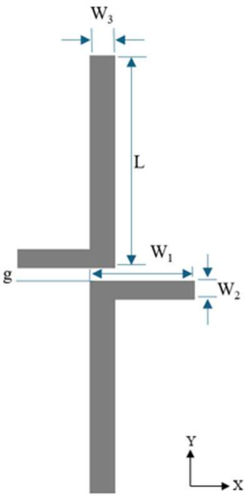


Fig. 1. Antenna design.

Table I
DIMENSIONS OF DESIGN

Parameter	L	W_1	W_2	W_3	g	t	p
Value(mm)	27.5	13	3	4	1	0.1	200

L: Dipole length, W: width, g: gap, t: thickness of the substrate and antenna, p: Periodicity.

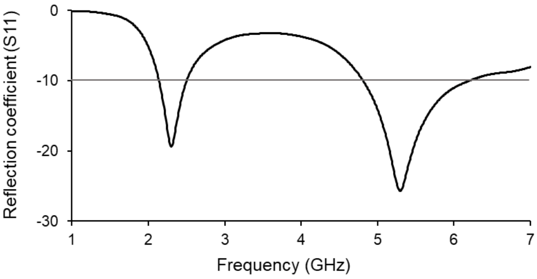
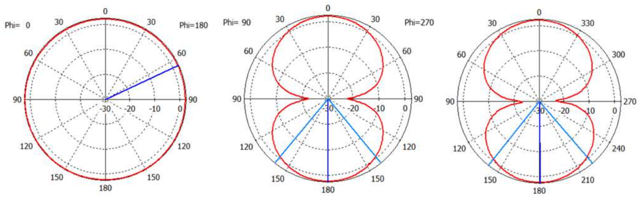
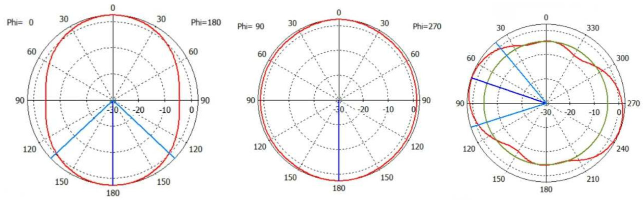


Fig. 2. Simulated S11 for unstretched antenna stretch sensor.



(a) xz plane (b) yz plane (c) xy plane

Fig. 3. Simulated radiation patterns a 2.3 GHz without stretch.



(a) xz plane (b) yz plane (c) xy plane

Fig. 4. Simulated radiation patterns a 5GHz.

II. ANTENNA DESIGN

The proposed antenna strain sensor is based on the resonant frequency shift of two orthogonal half wavelength dipole antennas. The substrate used is Thermoplastic Polyurethane (TPU), the material was chosen due to its mechanical and chemical properties that align with the requirements of flexibility of design as well as its high robustness properties [6]. All dimension parameters are mentioned in Table 1 and shown in Fig. 1 that illustrates the schematic of design.

Simulations of the design using CST Microwave Studio™ yielded two resonant frequency bands at 2.3 GHz and 5 GHz under no applied stretching, as shown in Fig. 2. The lower band is generated by the larger dipole element aligned along the y-axis, while the higher band is produced by the smaller dipole aligned along the x-axis. The –10 dB bandwidth at the lower frequency band is approximately 16%, effectively covering the 2.4 GHz ISM band. At 5 GHz, the –10 dB bandwidth spans from approximately 4.8 GHz to 6.2 GHz, providing broad coverage suitable for WLAN applications.

While the main purpose of the antenna is to operate as a sensor, the antenna could also work as part of a communication system at the 2.4 GHz and 5 GHz bands for dual functionality. Fig. 3 shows the radiation pattern at 2.3 GHz. These patterns are mainly determined by the larger dipole and show omnidirectional characteristics in the XZ- plane.

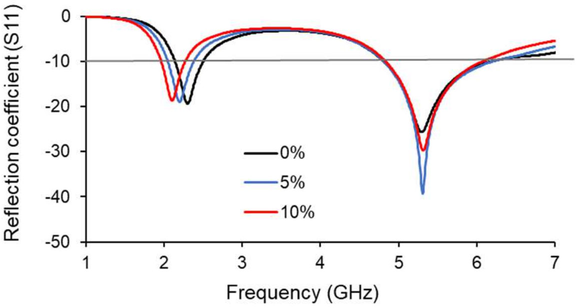


Fig. 5. Simulated effect of stretching in the Y direction on S11.

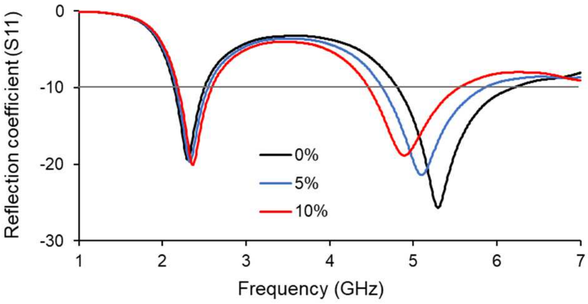


Fig. 6. Simulated effect of stretching in the X direction on S11.

The 5 GHz radiation pattern, shown in Fig. 4, is mainly influenced by the x-axis dipole. However, some pattern distortion is observed due to the physical presence of the larger dipole element. Despite this, the radiation characteristics remain acceptable for indoor wireless communication systems, where multipath propagation is prevalent.

To assess the effect of stretching on the sensor, tests were conducted over a range of 0% to 10% strain on a 200 mm × 200 mm TPU substrate, where a 10% strain corresponds to a 20 mm elongation in either the x or y direction. Due to the elastic nature of TPU, stretching in one direction causes contraction in the perpendicular direction, a behavior characterized by the Poisson's ratio. In this case, the contraction in the orthogonal axis was measured experimentally and found to correspond to an approximate Poisson's ratio of 0.3.

Fig. 5 illustrates the effect of stretching along the y-axis at 5% and 10% strain, along with the corresponding contraction in the x-axis. A linear shift in the resonant frequency is observed as the antenna sensor is stretched. Specifically, the resonant frequency decreases from 2.3 GHz (no stretch) to approximately 2.1 GHz at 10% strain. This frequency reduction is attributed to the increase in the effective electrical length of the antenna, a behavior that is consistent with expectations in stretchable antenna designs, where elongation typically leads to lower resonant frequencies. The effect of stretching in the x-direction is shown in Fig. 6. The resonant frequency shifts from 5.3 GHz at 0% strain (no stretch) to approximately 4.9 GHz at 10% strain. These results demonstrate the antenna's strong sensitivity to mechanical deformation, confirming its effectiveness as a stretch-responsive sensor.

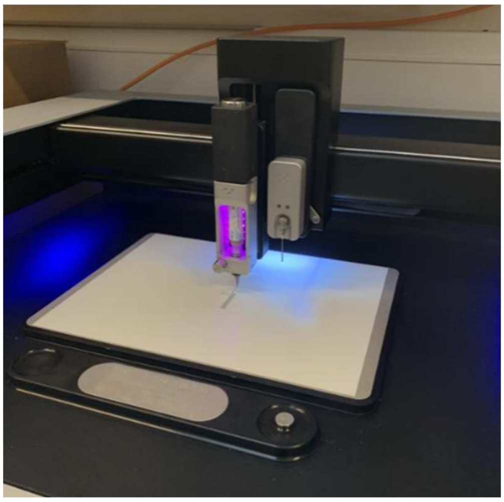


Fig. 7. Sensor printing with Voltera V one.

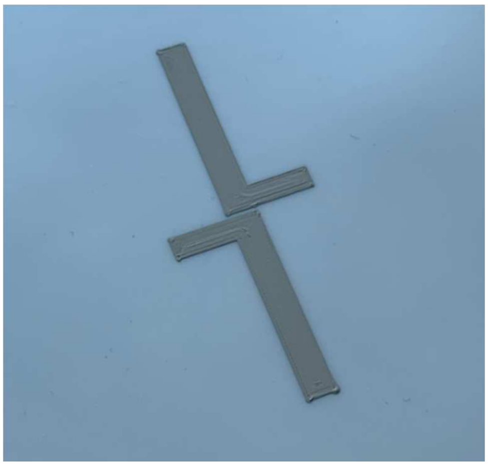


Fig. 8. Printed stretched antenna sensor.

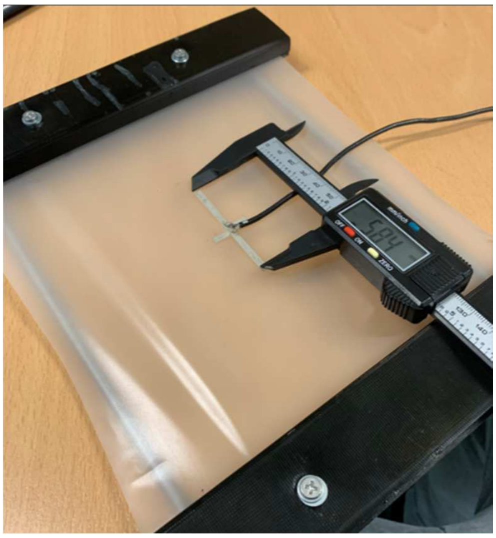


Fig. 9. Antenna sensor being stretched in the Y direction.

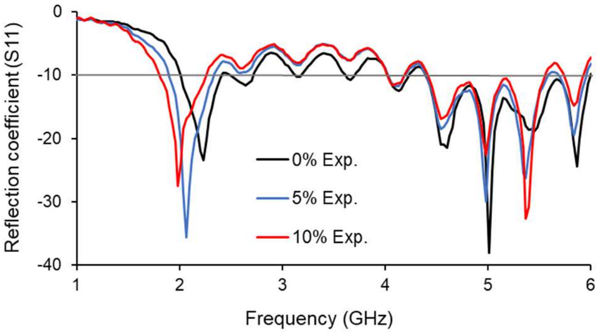


Fig. 10. Measurement S11 when the antenna is stretched in the Y direction.

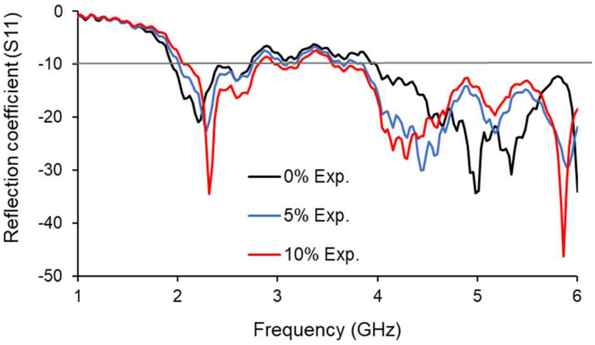


Fig. 11. Measurement S11 when the antenna is stretched in the X direction.

IV. FABRICATION AND MEASUREMENTS

The design was first simulated using CST Microwave Studio™, then the dxf. file was exported for fabrication. The antenna is printed using Voltera V-One PCB printer [7], using stretchable silver conductive ink [8] on a TPU substrate of 200 by 200mm size as in Fig. 7. The standard procedure of fabrication included five steps. First, the board must be aligned in the printer and the printing area of the design must be defined on the board. Next, the printer measures the height profile to compensate for irregularities at different points. Once the printing area and height map is defined, a high precision calibration for the ink deposition is performed to adjust the amount of deposited ink during printing. Then, print the antenna with multiple passes, and finally curing the ink using an oven. The printed antenna is shown in Fig. 8.

For the stretching measurements on the antenna, the custom-built tester shown in Fig. 9 is custom built to apply a controlled amount of stretching to a TPU substrate. The maximum stretch applied to the TPU (200 by 200mm) was 220mm to evaluate the RF performance of the design. The tester's overall frame measured 300x260x30mm, with a clamping area of 220x243mm to accommodate the TPU and its mounting. It featured two opposing clamps: one fixed and one movable, driven by a hand-operated mechanism, allowing elongation up to 20mm (10% stretching). As the apparatus used M6 threaded bars, one full turn (360°) = 1 mm of linear movement down the bar. Therefore, measurements are recorded every 5 full turns (5mm).

Measurements were conducted to analyze the effect of applying mechanical stress along both the x-axis and y-axis. As the stretch level increased from 0% to 10% along the y-axis, the resonant frequency decreased from 2.23 GHz (no stretch) to 1.9 GHz at 10% strain, as shown in Fig. 10. When the design was stretched along the x-axis, the resonant frequency also shifted downward, as illustrated in Fig. 11. The frequency decreased from 5.31 GHz (0%) to 4.46 GHz at 5% strain, and further to 4.3 GHz at 10% strain. However, the measured response under x-axis stretching exhibited some irregularities, including non-monotonic frequency shifts and variations in resonance depth, with multiple resonance notches observed particularly in the 4–6 GHz range (Fig. 11). These issues are likely due to factors such as nonlinear strain distribution, impedance mismatch caused by an unstable measurement setup, or nonlinear changes in the dielectric properties of the TPU substrate during stretching.

V. CONCLUSIONS

This paper has presented the design, simulation, and fabrication of a flexible bidirectional stretch sensor. The sensor operates based on the resonant frequency shift of two half-wavelength dipole antennas, printed using direct ink writing (DIW) technology on a stretchable substrate. The proposed antenna sensor was simulated and experimentally tested under up to 10% strain, showing a dual-band response at 2.4 GHz and 5 GHz in the unstretched condition (0% strain). A strong correlation between simulation and measurement results was observed, demonstrating the reliability and practical feasibility of the design.

Measurements revealed a direct relationship between applied strain and the resonant frequency shift, primarily attributed to mechanical deformation and changes in impedance matching during stretching. This stretch-sensitive antenna design has potential for various applications. For example, it could be integrated into dielectric structures for strain monitoring, where the dielectric properties of the host material would need to be considered during the design process. Additionally, it could be embedded in wearable medical devices for human body motion or strain sensing, offering a dual function of monitoring and wireless communication.

ACKNOWLEDGMENT

The authors would like to thank Antonio Mendoza and Mohammed Al-Dabbagh for their support. This work was funded by the Royal Society - International Exchanges 2019 Cost Share (NSFC) (Ref: IEC\NSFC\191780).

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