A Stretchable RF Antenna With Silver Nanowires

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***Abstract*— A stretchable, flexible antenna fabricated with silver nanowires (AgNW) and polydimethylsiloxane (PDMS) is presented. Highly conductive AgNWs coupled with mechanically flexibility and durable PDMS are shown to produce promising results for RF sensing. The RF antenna is designed as a 1.5-GHz microstrip patch antenna using the transmission-line model. The resonance frequency of the antenna shifts in response to the applied force/strain, making the configuration suitable for wireless sensing applications.**

***Index Terms*— Flexible, patch antenna, RF antenna, strain sensor, stretchable.**

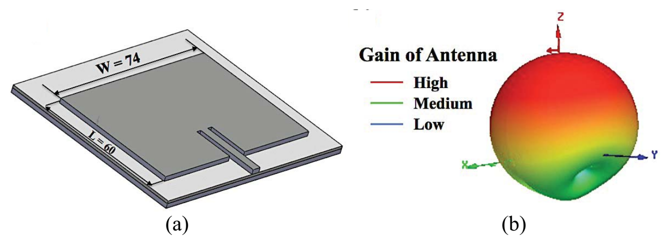

Fig. 1. (a) Design and dimensions of the antenna. (b) Simulated radiation pattern of the nonstretched antenna using Ansoft HFSSS.

I. Introduction

FLEXIBLE electronics technology has generated a lot of interest in recent years [1]. This technology can be employed to fabricate lightweight, stretchable, biocompatible, and flexible devices and systems. These unique qualities have led to many advancements in technologies that were not otherwise possible including wearable electronics which is a fast growing field as it integrates practical functions and features by incorporating computer and advanced electronic technologies [2]. Wearable electronics have the potential for many applications such as detecting different types of human motion including movement, typing, breathing, and speech [2].

Various types of highly conductive stretchable strain sensors have been developed for applications such as human motion detection [3] and tactile sensing [4] most of which have features that are very complex or detailed in nature and can be expensive to fabricate such as the microfluidic channels of a tactile sensor [4]. In this letter, we present a low-cost, durable, and flexible antenna with strain sensing capabilities based on a simple design of a microstrip patch antenna. This gauge can sense an applied strain stronger than 10 N.

Reversible stretchable, flexible antennas have recently demonstrated promising results for tunable RF devices where the frequency response can be controlled by changing the dimensions of the structure [5]. This capacity of an antenna could be used for strain sensing applications specifically for wearable electronics among other applications.

Among all the different materials used for flexible antennas, silver nanowires (AgNWs) have an advantage as they are not only conductive and flexible but also demonstrate an ease of application on any substrate via depositing or embedding methods [6]–[8]. There has been previous research using copper and polydimethylsiloxane (PDMS) for flexible RF antennas [9] but this structure does not have the extensive mechanical flexibility required for many printed electronic applications. Similarly, microfluidic technologies have definitely been of interest in terms of flexible RF applications [10]–[13] and have proven effective but are costly for mass production. AgNWs have been used for flexible circuitry due to their low-cost fabrication and simple application [14].

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II. Experimental Design

A. Material and Design

Highly conductive AgNWs were used as the conductive element and the PDMS was used as the dielectric substrate for the fabrication of the monopole patch antenna.

The microstrip patch antenna demonstrated in Fig. 1(a) follows the transmission-line model of the rectangular microstrip patch antenna. A dielectric substrate separates the ground plane from the transmission line and patch antenna on either of its sides. The patch antenna receives signals transmitted over the microstrip line which creates "fringing fields" with the ground plane and causes the radiation of the electromagnetic waves. Fig. 1(b) shows the radiation pattern of the non-stretched patch antenna and demonstrates that the maximum strength of the signal, as expected, is in front of the top face.

The operation of the presented wireless sensor is based on the change in the length of the antenna due to an applied strain. The resonant frequency of a microstrip patch antenna is calculated using (1) [15] which shows an inverse relationship between the frequency and the length

$$f_r = \frac{c}{2L}\sqrt{\epsilon_\gamma} \quad (1)$$

where C is the free-space velocity of light and L is the length of the antenna. Therefore, increasing the length of the antenna should decrease its resonant frequency. The target resonance

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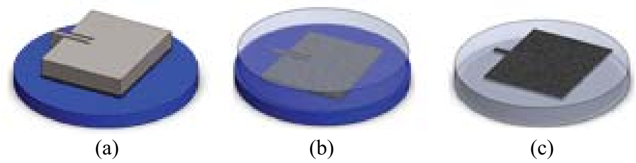

Fig. 2. Fabrication process for embedding AgNWs. (a) AgNWs were deposited on a silicon wafer and etched using a mask. (b) Liquid PDMS was poured on the silicon wafer after removing the mask. (c) After peeling off the PDMS, the embedded AgNWs were revealed.

frequency (f_γ) for the patch antenna is 1.5 GHz. The PDMS dielectric constant (ϵ_γ) is 2.65.

The dimensions of the antenna play a key role in determining its operational frequency. The width was determined using

$$W = \frac{c}{2f_\gamma}\sqrt{\frac{2}{\epsilon_\gamma + 1}} \tag{2}$$

and the length is determined using

$$L = \frac{c}{2f_\gamma\sqrt{\epsilon_\gamma}}. \tag{3}$$

The resulting length L and width W of the patch antenna are 61 and 74 mm, respectively. The microstrip transmission line width W_c is 3 mm for a characteristic impedance (Z_c) of 50 Ω.

In order to avoid mismatching between the transmission line and the antenna, and incurring a lossy signal transmission, the feed point must be inset at 19 mm from the end of the patch antenna with an input resistance of 50 Ω according to the transmission-line model [15].

B. Fabrication Procedure

To fabricate the antenna, AgNWs were synthesized via a copper (II) chloride ($CuCl_2$)-mediated polyol [16] process and are deposited onto a silicon wafer using drop casting deposition method. Resulting AgNWs were dispersed in a 10wt% isopropyl alcohol solution prior to application. The pattern was then etched out of the AgNWs using an antenna mask. The stencil mask was created using the laser cutter and Corel Draw software and was made out of polyethylene terephthalate (PET). Once the nanowires dried, uncured liquid PDMS was poured onto the substrate and cured at 200 °C for 2 h. The cured PDMS was then peeled off the substrate to reveal AgNWs embedded onto the PDMS surface. Fig. 2 illustrates the fabrication process for embedding the AgNWs in PDMS.

Both the ground plane and the antenna were embedded using the same process. Once both sides are prepared, they were bonded together using a thin layer of PDMS. The final device thickness was 3 mm and the resistivity of the embedded AgNWs was found to be < 5 Ω/sq.

III. Results and Discussion

A. Transmission-Line Model

A precursor study was also conducted to prove the ability of AgNWs as a transmission line. The fabrication method of the transmission line was the same as shown previously for the embedded AgNWs' patch antenna. SubMiniature version A (SMA) connectors were sealed onto the PDMS substrate via the cured PDMS and connection between the line and the SMA center pin was established using silver paint (SPI supplies).

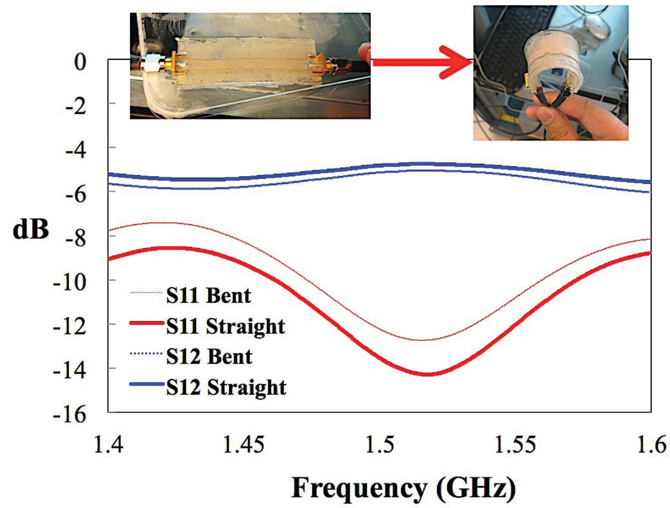

Fig. 3. Transmission-line model displaying the behavior of the S_{11} (red) and S_{12} (black) parameters when the transmission line is straight (inset left) and bent with a 10-mm bending radius (inset right).

This letter showed conclusively that the embedded AgNWs are adequate for signal transmission. As part of the testing, the transmission line was put under a bending strain configuration (Fig. 3). S-parameters S_{11} and S_{12} were collected using the Rohde & Schwarz ZVB4 Vector Network Analyzer. The results show that within the desired frequency, the line's capability is not compromised due to its physical configuration.

B. Monopole Patch Antenna

S_{11} was measured to find the reflection coefficient and the resonant frequency of the antenna using the Rohde & Schwarz ZVB4 Vector Network Analyzer within the frequency range of 1–3 GHz. Before carrying out the experiment, the Short, Open, Load, Thru calibrations were performed.

We used a custom-made rectangular platform to hold the antenna that clamped two sides of the antenna rigidly in place and also suspended the antenna a few centimeters above the table. The connection to the vector analyzer was made by attaching an SMA connector to the transmission line of the antenna.

Mechanical tests were then performed by applying pressure to the center of the antennas surface using a force gauge. Force was incrementally increased in intensity from 0 to 10 N. As shown in Fig. 4, a shift in resonant frequency was observed. The nonstretched antenna showed a resonant frequency of 2.37 GHz and as the intensity of the pressure increased, the resonant frequency decreased.

The antenna was then tested by applying and slowly increasing the pressure. Similarly, it showed a notable shift to the left in the resonant frequency. The antenna was also subjected to mechanical tests to examine its durability and robustness. It showed no signs of any physical damage after stretching, twisting, and folding it multiple times.

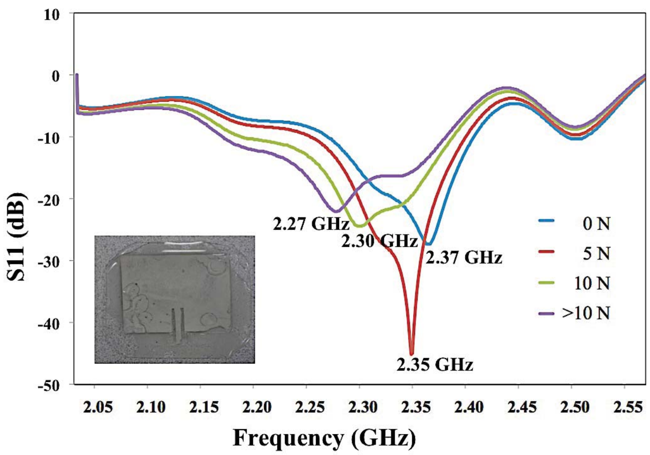

Fig. 4. Resonant frequency of the RF antenna. There is a notable shift to the left as the force applied increases. Inset: the antenna prototype tested.

The original antenna was designed to be operated at 1.5 GHz resonant frequency but due to the issue of homogenous distribution of the AgNWs on the antenna, the effective length turned out to be shorter ($L = 50$ mm) than designed ($L = 60$ mm). Consequently, it increased the resonant frequency to around 2 GHz.

Further experiments are planned to be perfected with noise reduction techniques; it could advance this stretchable antenna technology into communications applications for wearable electronics, RFID, or WLAN.

IV. Conclusion

We demonstrated a reversibly flexible and stretchable antenna which can sense force higher than 10 N. This mechanically durable and robust antenna was fabricated by embedding AgNWs onto the surface of PDMS. The antenna has strain sensing abilities shown by the resonant frequency shift triggered by pressure. This technology could have many applications in the wearable electronics and tactile sensing as it is light and stretchable, and can conform to any shape.

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