Flexible coplanar waveguide strain sensor based on printed silver nanocomposites

Shawkat Ali^{1,2} · Arshad Hassan² · Saleem Khan¹ · Amine Bermak¹

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Abstract

This paper presents a robust approach towards the design and fabrication of a stretchable coplanar waveguide monopole strain sensor that measures the tensile strain through a linear shift in the resonance frequency unlike the conventional patch antennas strain sensors. The increment in physical length upon application of stretching force on the sensor results into lowering of the resonance frequency, which is correlated with tensile strain. Being a 2d structure, the sensor can easily be deployed on a planar surface to determine the tensile strain. Sensor parameters are optimized through simulations in high frequency structure simulator software. Silver nanowires (AgNWs) based solution is screen printed using a shadow mask on an elastomeric polydimethylsiloxane substrate. The operating frequency of the sensor is 2.49 GHz at ambient condition and it goes down to 2.31 GHz at 6.1% stretching. The simulated sensitivity of the sensor is 0.072 MHz/ μm and measured sensitivity of 0.076 MHz/ μm has been tested for more than 200 cycles, clearly illustrating the robustness of the proposed approach. These promising results show that this sensor can successfully be implemented for printed wearable applications targeted for monitoring of strain related activities.

Keywords Coplanar waveguide (CPW) · Printed RF strain sensor · Stretchable electronics · Printed electronics

1 Introduction

Printed electronics have evolved as one of the most promising technologies in recent years enabling the design of electronic components on diverse substrates in a much simpler and efficient way [1–4]. Printing involves a single step process for patterned deposition of functional materials as opposed to the costly multi-step fabrication in clean room processes [5]. The printing on-demand and reduced wastage of residual materials after fabrication, makes printing technologies much more cost-efficient as compared to standard microfabrication technologies [6]. Wide range of materials is deposited in the form of micro-droplets or an intact jet controlled by the design software, where materials are patterned on desired location on diverse substrates [7, 8]. The recent developments

in printed electronics are witnessed in almost all fields of electronics including sensing, health monitoring and recently strain sensor applications [9–13].

Ultrathin layers of compliant polymeric materials on flexible substrates overcome the undesired brittleness, however the plastic deformation of these materials is more challenging for stretching and compressing related applications [14, 15]. In this scenario, a new class of engineered materials based on percolation mechanism has attracted significant interest. Conductive nanocomposites based on mixing conductive nanofillers with an elastomer at varying mixing ratios for obtaining acceptable values of electrical and electromechanical properties [12, 13]. In recent years, interest in the fabrication of large area printed electronics on non-conventional substrates has emerged with special interest in cost-effective manufacturing and processing of

✉ Shawkat Ali, shaali@qf.org.qa | ¹College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Doha 5825, Qatar. ²Department of Electrical Engineering, National University of Computer and Emerging Sciences FAST, H 11/4, Islamabad 44000, Pakistan.

a wide range of materials. These conductive nanocomposites behave like piezoresistive transducers, where change in the bulk resistance of conductive network is subject to the application of stress and strain variations [16]. State of the art rigid materials based on metallic or semiconductor strain gauges have several limitations such as low gauge factor, lack of solution processability for cost-effective manufacturing, processing on large areas, noncompliant to nonplanar substrates, non-compressibility and non-stretchability etc. [12, 17]. Therefore, conductive nanocomposites are potential alternatives for addressing the aforementioned challenges for developing piezoresistive sensors.

The moderate electrical conductivities are ideal for piezoresistive based sensors for sensing a detectable change upon actuation, while restoring the original shape after releasing the force. Silicone elastomer i.e. Poly(dimethylsiloxane (PDMS)) is the most widely used base material for mixing conductive nanoparticles [13, 16, 18–21]. PDMS offers attractive features such as, easy processing, efficient moldability, biocompatibility, chemical inertness and stretchability [20]. The piezoresistance mechanism is dependent upon the conductive fillers concentration, geometry, interconnecting conductive channels and tunneling between nanofillers in the polymer matrix, which change the electrical properties upon application of a force (normal/tangential) or structural elongation [16, 22]. Keeping the deformation within the elastic limits, the PDMS restores efficiently after removal of the external stimuli.

The momentary disturbance with the conductive network or the tunneling leads to a change in the bulk resistance of the composite layer. Low mixing ratio of the filler materials is desired to retain a balance between mechanical and electrical properties of the nanocomposites, which are ideal for stretchable interconnection lines and especially strain sensing applications [18]. PDMS properties are well suitable for the high frequency applications such as radiation based transducers including antennas for strain and temperature sensing purposes [23].

Recently antenna based sensors are developed especially for strain related transductions. Patch antennas are used for such measurements, however they are restricted to only planar surfaces and produce nonlinear response due to their geometry of patch [23–26]. The non-uniform deformation results in non-linear frequency shift [25]. Therefore, coplanar waveguide antennas are the most suitable candidates for strain sensing applications on non-planar surfaces. The applied force produces uniform change in length of co-planar waveguide, producing a linear shift in the frequency response. Coplanar waveguide on PDMS substrate for the strain sensing has not been reported. Coplanar waveguides enable simplified structures. In this

paper we present a coplanar waveguide strain sensor together with its fabrication process as well as experimental test and characterization. The sensor is designed and simulated in HFSS software. The popular screen printing process for the deposition of AgNWs on a preprocessed PDMS substrate is explored within this research for the fabrication of strain sensor. The resonance frequency is inversely proportional to the physical length of the sensing coplanar waveguide. The operating frequency is 2.5 GHz at and it goes down to 2.31 GHz at maximum safe stretching. This change in resonance frequency is correlated with tensile strain. The maximum change in length of the sensor is 6.1% of its total. The sensitivity of the sensor is calculated by using Eq. 1. S is sensitivity, Δf is change in the frequency at maximum stretching and ΔL is change in the length of the radiating patch at maximum safe stretching. In our case the maximum change in resonance frequency was 180 MHz and change in the length was 2.5 mm which is 6.1% of the total length of the radiating patch.

From these values the sensitivity is calculated as 72 kHz/ μm simulated and measured 0.076 that has been repeatedly tested for more than 200 endurance cycles.

$$S = \frac{\Delta f}{\Delta L} = \frac{f_{0\%} - f_{6.1\%}}{L_{0\%} - L_{6.1\%}} \quad (1)$$

2 Working principle of the sensor

Percolation mechanism play significant role in developing strain sensor, which allow the substrate to stretch while maintain the electrical properties in acceptable ranges for sensing [12, 21]. Percolation involves mixing of different conductive fillers with a base elastomer material, where conductive network is established randomly after polymerization [21]. In this work, the sensor design is based on a coplanar waveguide with operating frequency of 2.5 GHz. It is consisted of a coplanar waveguide structure as radiating element and ground plane on the PDMS substrate as shown in Fig. 1a. The strain sensing mechanism is based on deformation of the radiating patch such as by apply longitudinal force, the length increases and the resonance frequency decreases. This phenomenon enable the sensor to measure the strain with high sensitivity because the operating frequency is in GHz where a small change in physical length of the radiating patch results in a prominent change in the resonance frequency shift. Under tensile strain, a small change in the physical length creates a resonance frequency shift in the input reflection coefficient of the sensor i.e. S_{11} . The working principle is illustrated in Fig. 1b as the sensor is subjected to tensile strain, the physical length of the coplanar waveguide increases and results in lowering the resonance frequency proportionally as

Fig. 1 **a** Geometry of the proposed coplanar waveguide sensor, **b** principle of the coplanar waveguide strain sensor: **b** stretching the physical length of planer patch, **c** trade-off between the physical length and resonance frequency

shown in Fig. 1c. The resonance frequency varies according to following Eq. 2.

$$f_r = \frac{c_0}{2(L + \Delta L_o) \sqrt{\epsilon_r}} \quad (2)$$

where c_0 is the speed of light, L is the length of resonance element and ΔL_o is the change in length due to tensile strain. The change in the resonance frequency is inversely proportional to the physical length of the resonance element and the relation between them is linear. The relation between ΔL and Δf is linear because the radiating patch is simple planar element and during the tensile strain the only effect is increment in the length. The increment in the physical length therefore linearly decreases the resonance frequency and gives a linear relationship. As the operating frequency is in the GHz range, hence the sensitivity is very high and produce prominent shift in the resonance frequency at micrometer change in the physical length.

3 Simulations

The device was designed and simulated in Ansoft high frequency structure simulator (HFSS). The waveguide coplanar antenna was designed as shown in Fig. 2a. This design is based on a micro strip coplanar waveguide, where the ground patches are also on the same PDMS

substrate. The relative permittivity and loss tangent of the PDMS substrate are 2.5–3.0 and 0.01–0.05, respectively under the frequency range of 0.5–3.0 GHz. Figure 2b shows simulations results of the sensor at 0–8% length increment. As the physical length increases, the resonance frequency decreases from 2.5 to 2.31 GHz. The radiation pattern and gain plots are shown in Fig. 3, in normal condition the gain is 2.95 dB at 0 mm stretching. When stretching force is applied and the physical length of the radiating patch is increased by 1.48 mm the gain reduced to 2.72 dB and at 1.5 mm stretching the gain is further reduced to 2.58 dB. The gain reduction is due to the shift in the resonance frequency. This change in frequency shift can successfully be harvested for the strain sensing applications, which is the core theme of this research work. The azimuth and the elevation radiation patterns are not much affected with the stretching. The 3d radiation pattern shows that radiation will remain the same under various stretching intensities. Hence, it indicates robustness under various conditions. Gain is affected under stretching as it decreases from 2.98 to 2.58 dB against the strain from 0 to 6.1%. The impedance of the strain sensor is changed because of applied longitudinal tensile strain. The impedance variations affect the efficiency of the sensor and hence, the gain is decreased as shown in Fig. 3. Similar trend is shown in Fig. 2b, where the plot of S_{11} shows that when the tensile longitudinal strain increases the value of S_{11} increases. Hence,

Fig. 2 **a** Geometry of the proposed RF strain sensor, **b** frequency sweep S11 response

indicating poor impedance matching which affects the efficiency.

4 Fabrication

PDMS with two parts i.e. liquid base and curing agents (Sylgard 184 Purchased from Dow Corning) were mixed with 10:1 wt% and stirred for 15 min. Degasification carried out in a vacuum desiccator for 30 min to remove air bubbles from the PDMS mixture. The PDMS substrate was prepared by casting the solution in a petri dish and cured inside an oven at 90 °C for 45 min and ramped down slowly to room temperature. The cured PDMS substrate was cut into 50 × 22 mm² size and then ultra-violet (UV) ozone treated for 10 min using UV cleaner. All fabrication steps of the proposed RF strain sensor are shown in Fig. 4a. AgNWs ink was used without any further processing as purchased from Sigma Aldrich. The prepared PDMS substrate was masked according to the dimensions of coplanar waveguide sensor design as shown in Fig. 2b. The prepared ink solution of AgNWs was casted over the PDMS

substrate by using a pipette tip. Screen printed AgNWs film on masked PDMS substrate is shown in Fig. 4b. The long wires have good sensing capability as compared to small wires because these cannot break on stretching easily. Afterward the film was cured for 120 min at 100 °C in furnace. The cured sample was unmasked as shown in Fig. 4b. The average thickness of the Ag film was 50–70 μm. For feeding the input signal, a 3.5 mm subminiature version A (SMA) connector is attached to the coplanar waveguide feed line by using silver nanoparticle conductive epoxy paste and sintered for 30 min at 100 °C in furnace. The fabricated RF strain sensor is shown in Fig. 5.

Figure 5a shows the scanning electron microscopy SEM image of the AgNWs film deposited on PDMS substrate. This image is taken from the coplanar waveguide at 0% strain. The inset of Fig. 5a shows the fabricated sensor. This SEM image confirms the higher density of AgNWs, which is ideal for the increases in electrical conductivity of the deposited film. Figure 5b shows results of the cracks in the conductive film when over-stretched beyond the elastic limit i.e. 6.1%. Due to the breakage of film on the substrate, the operating frequency shifts from the desired operating range of the sensor.

5 Results and discussions

The electrical characterization of the device under test (DUT) was done at frequency range of 1–3 GHz using calibrated two port HP RF vector network analyzer. Figure 6a, shows the DUT connected to HPD1875 using 50 Ω transmission line and 50 Ω RF SMA Connector. The performance of the fabricated strain sensor was analyzed under various cyclic tensile strains.

To investigate the amount of power loss, in the input signal, the reflection coefficient (S_{11}) or return loss was measured. The reflection coefficient in decibels (dB) can be represented by

$$RL \text{ (dB)} = 10 \log_{10} \frac{P_r}{P_i} \quad (3)$$

where P_r and P_i represents the reflected and incident power. Figure 6b shows the reflection coefficient curves for the DUT at various tensile strains. To analyze the reflection coefficient at the resonant frequency, the bottom line is –15 dB. This value corresponds to 96.84% of the transmitted power, which means the RF strain sensor can radiate or receive the RF signal effectively. The fabricated sensor was placed at lab-made stretching machine as shown in Fig. 6a. A 50 Ω coaxial cable was used to connect the sensor with spectrum analyzer. The reflection coefficient was measured at various tensile strains. From the graph

Fig. 3 Sensor stretching versus gain simulation, sensor is stretched from 0 to 1.5 mm and gain changes from 2.95 to 2.58 dB

shown in Fig. 6b, it can be seen that at zero tensile strain the AgNWs based RF strain sensor exhibited low return loss of -30 dB at the resonant frequency of 2.5 GHz and it has a bandwidth of 350 MHz which is suitable for most of the practical applications. Here bandwidth means, the

frequency range over which the reflection coefficient is less than -10 dB value.

Figure 6b shows results of the fabricated device. The measured resonant frequency of the device is 2.49 GHz and it decreased to 2.31 GHz fewer than 6.1% tensile strain. Hence, it is very sensitive to the tensile strain as showed

Fig. 4 **a** Fabrication steps of the proposed device through screen printing, **b** images of the device fabrication process

Fig. 5 **a** SEM image of the AgNWs film on the PDMS substrate, **b** SEM image of the AgNWs film when stretched beyond 6.1%

460 MHz difference in resonant frequency. The device shows a close match and similar trend with the simulation results performed using high frequency structure simulator (HFSS) software, the resonant frequency decreased when the tensile strain increased. Figure 6c shows change in length of the coplanar versus change in the resonance frequency. As the physical length changes under tensile strain, the resonance frequency changes inversely. When the physical

length is increased by 6.1%, the resonance frequency lowers to 2.31 GHz from 2.49 GHz. Figure 6d shows the endurance cycle test, the DUT was tested for 200 cycles and data was recorded. It was found that there is no significant change in the frequency when device was released from stretched position to the normal and back to the stretched position.

The sensor was analyzed for its thermal stability analysis; the sensor was connected to spectrum analyzer through

Fig. 6 **a** Test setup for the RF sensor: sensor is placed on a lab-made stretching machine and connected to spectrum analyzer through coaxial cable, **b** measured and simulated results of the sensor

against stretching, **c** sensitivity of the RF sensor change in physical length and frequency variation, **d** endurance cycles analysis of the sensor

coaxial cable 50 Ω . The sensor was measured at 0% stretching and 6% stretching in order to see the effect of temperature on both the extreme cases of temperatures. Sensor was placed inside the furnace at room temperature *i.e.* 25 $^{\circ}\text{C}$ and measure the reflection coefficient at 0% stretching. The furnace was then heated at 100 $^{\circ}\text{C}$ and the reflection coefficient was measured at the same 0% strain. The sensor was then stretched at 6% of its length and put in the furnace and measured the reflection coefficient at 25 $^{\circ}\text{C}$ and 100 $^{\circ}\text{C}$. The results of the reflection coefficients for both the temperatures and stretching percentage are shown in Fig. 7. We believe that, the slight shift in the frequency at 100 $^{\circ}\text{C}$ is due to the expansion of the patch against temperature. Due to temperature, the physical size of the patch is increased the resonance frequency of the sensor is decreased accordingly on both stretching %. From measurement and simulation results, we can conclude that the flexible strain sensor has a great potential for printed electronics applications as it is

Fig. 7 Frequency response of the sensor stretching at 0% and 6% at temperature 25 $^{\circ}\text{C}$ and 100 $^{\circ}\text{C}$

very sensitive against strain and also it is cost effective as fabricated by using screen printing technique.

6 Conclusion

In this paper we proposed an innovative approach for the design of flexible strain sensors using coplanar waveguide RF devices. AgNWs are printed on thin film of PDMS substrate through screen printing technology. The sensor is designed and simulated in the HFSS software. The change in physical length of the coplanar RF sensor upon stretching, resonance frequency is recorded to be decreased upon increase in the length. The proposed sensor is observed to be stretched about 6.1% of its original length. The operating frequency of the sensor is 2.5 GHz at 0% strain and went down to 2.31 GHz at 6.1% tensile strain, clearly illustrating frequency correlation with the sensed tensile strain. Simulated sensitivity of the sensor was 0.072 MHz/ μm and measured sensitivity of 0.076 MHz/ μm which show a linear shift in frequency. Simulated and measured results showed good agreement. The simple fabrication process combined with cost-effectiveness, improved sensitivity and precise sensing results makes this sensor an excellent candidate for wearable electronics applications.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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