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# Split-Ring Resonator-Based Strain Sensor on Flexible Substrates for Glaucoma Detection

**Gizem Ekinci**[1], **Arda Deniz Yalcinkaya**[1,2], **Gunhan Dundar**[1], **Hamdi Torun**[1,2]

[1]*Department of Electrical and Electronics Engineering, Bogazici University, Bebek 34342 Istanbul, Turkey*
[2]*Center for Life Sciences and Technologies, Bogazici University, Kandilli 34684 Istanbul, Turkey*

Corresponding author: hamdi.torun@boun.edu.tr

**Abstract.** This paper presents split-ring resonator-based strain sensors designed and characterized for glaucoma detection application. The geometry of the sensor is optimized such that it can be embedded in a contact lens. Silver conductive paint is to form the sensors realized on flexible substrates made of cellulose acetate and latex rubber. The devices are excited and interrogated using a pair of monopole antennas and the characteristics of devices with different curvature profiles are obtained. The sensitivity of the device, i.e. the change in resonant frequency for a unit change in radius of curvature, on acetate film is calculated as -4.73 MHz/mm and the sensitivity of the device on latex is 33.2 MHz/mm. The results indicate that the demonstrated device is suitable for glaucoma diagnosis.

## 1. Introduction

Metamaterials exhibit electromagnetic properties, which are not present in ordinary materials, such as negative values of electric permittivity and magnetic permeability, simultaneously [1]. The unique properties bring metamaterials into consideration for sensing applications. One of the most popular structures of metamaterials is split-ring resonators (SRRs). A conventional SRR is simply a ring with a split, which is made of a preferably high-conductivity metal, and is fabricated on a dielectric substrate. In addition to their favorable electromagnetic characteristics, the SRR devices can be realized in a simple and cost-effective manner.

Wireless strain measurement attracts attention of many researchers and finds application in numerous fields when it comes to material characterization. In civil engineering, the sensors of the sort are used to ensure maintenance in infrastructure, by measuring the strain on the structure and take precaution in case of any abnormal strain [2]. In biomedical engineering, these sensors are utilized by observation of the healing process of a fractured bone [3]. Moreover, in aerospace industry, wireless strain measurement comes into prominence in crack or abnormal strain detection on metal surfaces [4]. SRR-based sensors have been demonstrated for wireless strain measurement previously [3,4]. The resonant frequency of the device strongly depends on the geometry of the ring and any deviation in geometry due to external strain applied to the device results in change in resonant frequency of the resonator. This enables strain measurement through the observation of the shift in resonant frequency.

Glaucoma is an eye disease, which may damage the optic nerves and leads to vision loss. Even though it might be caused by different factors, in most of the patients, it is caused by the increase of intraocular pressure and might eventually cause irreversible blindness. Today, there are several

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different methods to detect the symptoms of glaucoma, such as measuring central corneal thickness, measuring peripheral vision, examining the optic nerve and measuring the eyeball pressure [5]. It was demonstrated that the radius of curvature of the sclera is well correlated with the intraocular pressure, while the radius of the curvature of the cornea is insensitive to the changes in intraocular pressure [6]. Noninvasive monitoring of the intraocular pressure has been demonstrated using piezoresistive [7] and capacitive [8] sensors embedded on soft contact lenses. It is possible to monitor the progress of the disease in noninvasive and continuous manner using this approach. However these sensors are electrically active and require application of electrical signals in the contact lens during operation. In addition, the system on the contact lens also includes a transmission circuitry to send the signals to an external unit.

Here, we describe an electrically passive, wireless and low cost sensor to measure intraocular pressure by placing an SRR on top of contact lenses. The sensor on the lens does not require any electrical signal to operate and are interrogated by external antennas that can be located away from the contact lens. We use silver conductive paint to define the rings on flexible substrates. We realized two different SRR-based strain sensors and characterized them experimentally to evaluate their potential for wireless strain sensing. This study suggests that SRR-based sensors are promising for the diagnosis of glaucoma.

## 2. Design and Fabrication of the SRR-based Sensors

SRRs behave like RLC circuits but in most cases the material is chosen so that the resistance value is negligible. Hence the structure might be reduced to LC resonator and the resonant frequency might be calculated by Eq.1.

$$f_o = \frac{1}{2\Pi\sqrt{LC}} \tag{1}$$

The inductance of the ring is expressed in equation 2 as a function of geometrical parameters [9].

$$L = \mu_0 R_m \left( \log \frac{8R_m}{h+w} - \frac{1}{2} \right) \tag{2}$$

where $\mu_0$ is the free-space permeability, $R_m$ is the effective radius of the ring, $w$ and $h$ are the width and the height of the ring, respectively.

The capacitance of the ring has two components, the gap capacitance and surface capacitance. The gap capacitance is calculated as follows [9]:

$$C_{gap} = \varepsilon_0 \frac{hw}{g} + C_0 \tag{3}$$

where $\varepsilon_0$ is the free-space permittivity. $C_0$ is the capacitance caused by the fringing fields and can be calculated as $C_0 = \varepsilon_0 (h + w + g)$ [9]. Equation 3 assumes that the ring is in free-space. If the ring is placed on or embedded into a dielectric substrate, then the effective permittivity of the medium should be considered in this equation.

The geometry of the SRR structure is determined so that it can be placed around the boundary between cornea and sclera where the change in intraocular pressure can be measured effectively to diagnose glaucoma [6]. In addition, the sensor is optimized for S-band (2-4 GHz) of the electromagnetic band. Fig. 1(a) shows a photograph of a sensor placed on a flexible substrate made of cellulose acetate. We extended the gap region to increase the gap capacitance and to keep the resonant frequency of the device in S-band. We applied silver conductive paint (SCP, Electrolube, United Kingdom) to define the ring using a hard mask on the substrate. The thickness of the ring is 50 $\mu$m and the other relevant geometrical parameters are shown in Fig. 1(a). We prepared another type of sensor on a spherically deformed substrate made of latex rubber with a thickness of 50 $\mu$m. Using a hard mask on a spherical substrate is not possible, so we painted the ring on the second substrate.

We simulated the device using commercially available electromagnetic simulation software (CST Microwave Studio, Darmstadt, Germany) to obtain its scattering parameters. We performed the simulations in time domain. Fig. 1(b) shows the surface current density along the conductor path at the resonant frequency observed at 2.54 GHz. The magnetic field is perpendicular to the surface of the device for the simulation that supports the circulating current at resonance. Fig. 1(c) shows the s21 spectrum of the device with these settings.

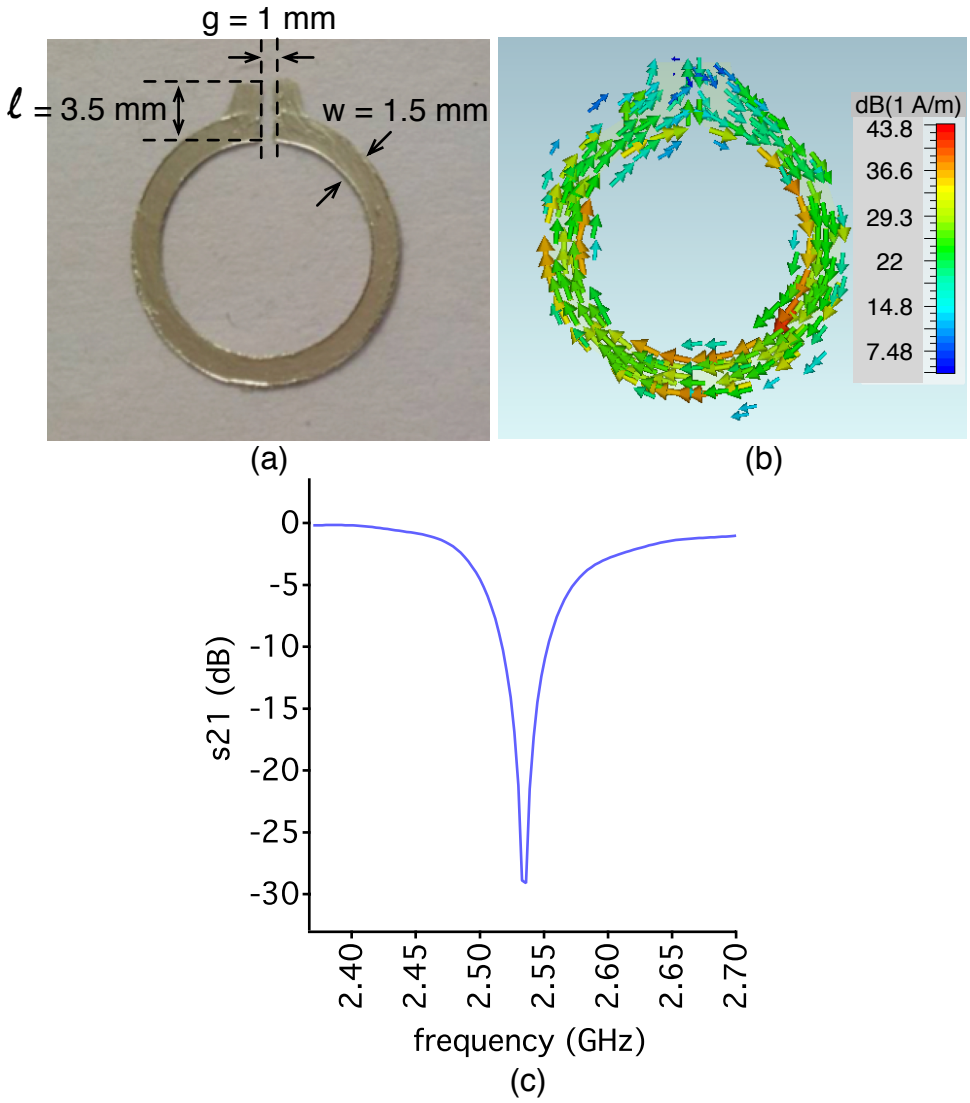


Figure 1.(a) A photograph of a realized device on a substrate made of cellulose acetate, (b) Simulated distribution of surface current density for the device at resonance, (c) Simulated s21 spectrum of the device.

## 3. Experimental Characterization

We characterized the SRR-based strain sensors using a vector network analyzer (ZVB4, Rohde & Schwarz, Munich, Germany) by measuring their scattering parameters. We conducted the experiments using two different setups. We placed the SRR sensor realized on the substrate of cellulose acetate in the first setup shown in Fig. 2(a). The device was placed on an adjustable frame to introduce controllable bending between two monopole antennas. We adjusted the radius of curvature while measuring the s21 spectrum of the resonator. The nominal resonant frequency of the device was

measured as 2.49 GHz, which is in good agreement with our simulations. Fig. 2(b) shows how the s21 spectrum changes with increasing curvature (1/ρ). As the curvature increases, the resonance frequency increases monotonically as shown in Fig. 2(c). The change in resonant frequency linearly depends on curvature for the selected range of curvature. We repeated the bending experiment six times and report the standard error mean of the measurements with the error bars of Fig. 2(c). The gap size of the device does not change significantly with curvature. However, the projected area of the bended device on the plane of antennas decreases with curvature. This results in a decrease in surface capacitance, so the resonant frequency of the device increases.

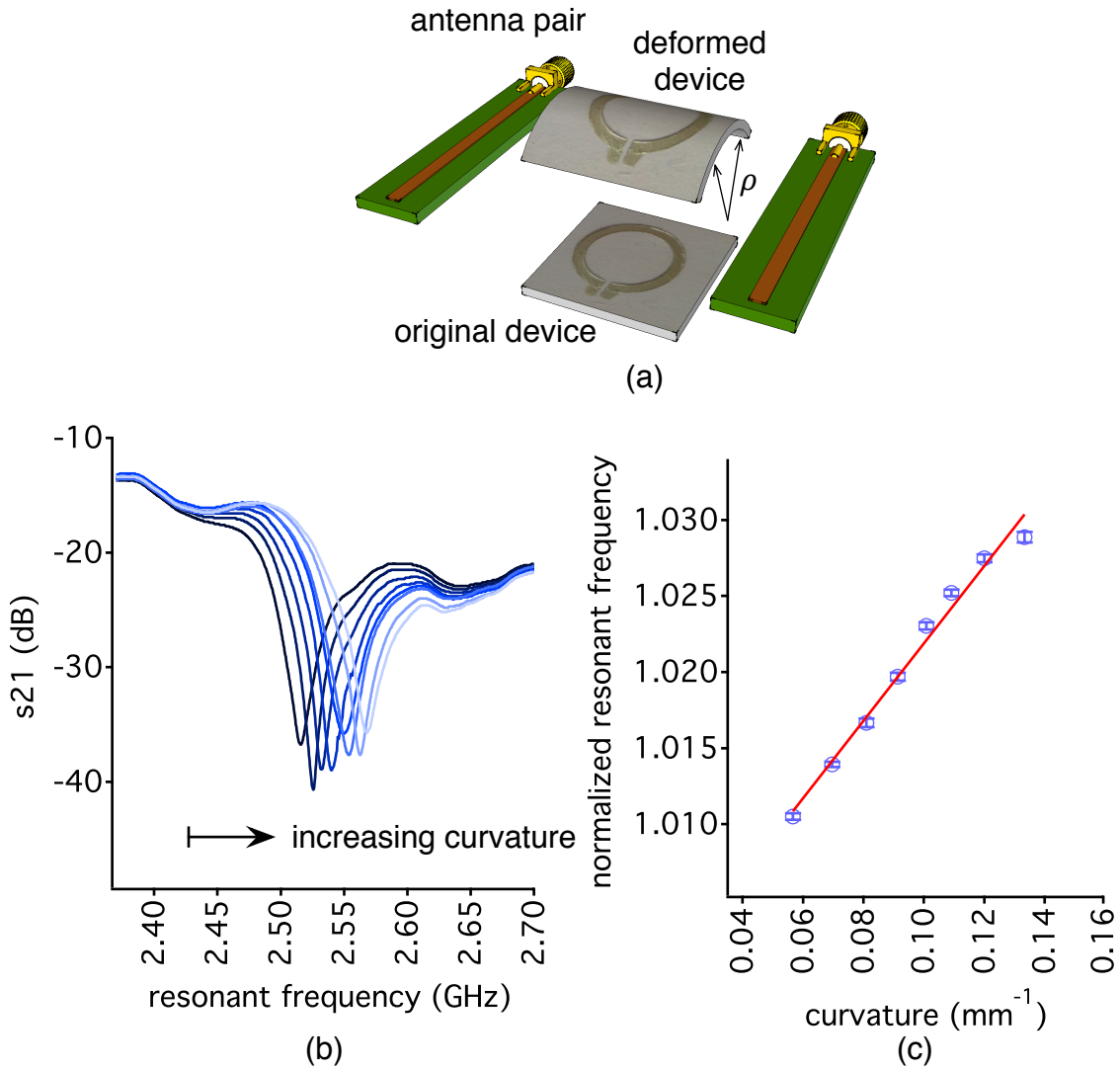


Figure 2.(a) Three-dimensional drawing of the experimental setup for the SRR sensor realized on cellulose acetate, (b) s21 spectra of the device as the curvature (1/ρ) increases, (c) Variation of the resonant frequency as a function of curvature.

We used the second setup to characterize the SRR sensor realized on the substrate of latex rubber. Fig. 3(a) shows the experimental setup where the substrate is stretched on top of a cylindrical injection syringe with a diameter of 9 mm. The syringe is used to pump air in and out of the device. First, we pumped air so that the radius of the curvature of the substrate becomes 13 mm. Then, we paint the SRR structure on the surface and obtained its s21 spectrum using the vector network analyzer. We continued the following measurements by evacuating 0.2 ml air at each step and obtaining the s21 spectrum of the device. The inflated device shrinks with decreasing air volume so does the radius of

the curvature. Fig.3 (b) shows how the s21 spectrum of the device changes with decreasing radius of curvature. The gap of the SRR structure decreases as the radius of the curvature decreases. This results in an increase in the capacitance of the resonator, so the resonant frequency decreases as shown in Fig. 3(c). We repeated this experiment six times with different SRR structures painted on the substrate each time separately after we pumped air such that the radius of the curvature became 13 mm. Fig.3(c) shows the mean values and the standard error mean values of the measured resonant frequencies normalized to the value we measured for the radius of curvature of 13 mm. The range of the change in radius of the curvature is physiologically relevant to the diagnosis of glaucoma. The result of an experiment conducted with 16 fresh porcine eyes, by applying five consecutive incremental 100µl injections, suggests that with each incremental injection of fluid, intraocular pressure and radius of curvature of the sclera increases linearly from 9mm to 13mm [6].

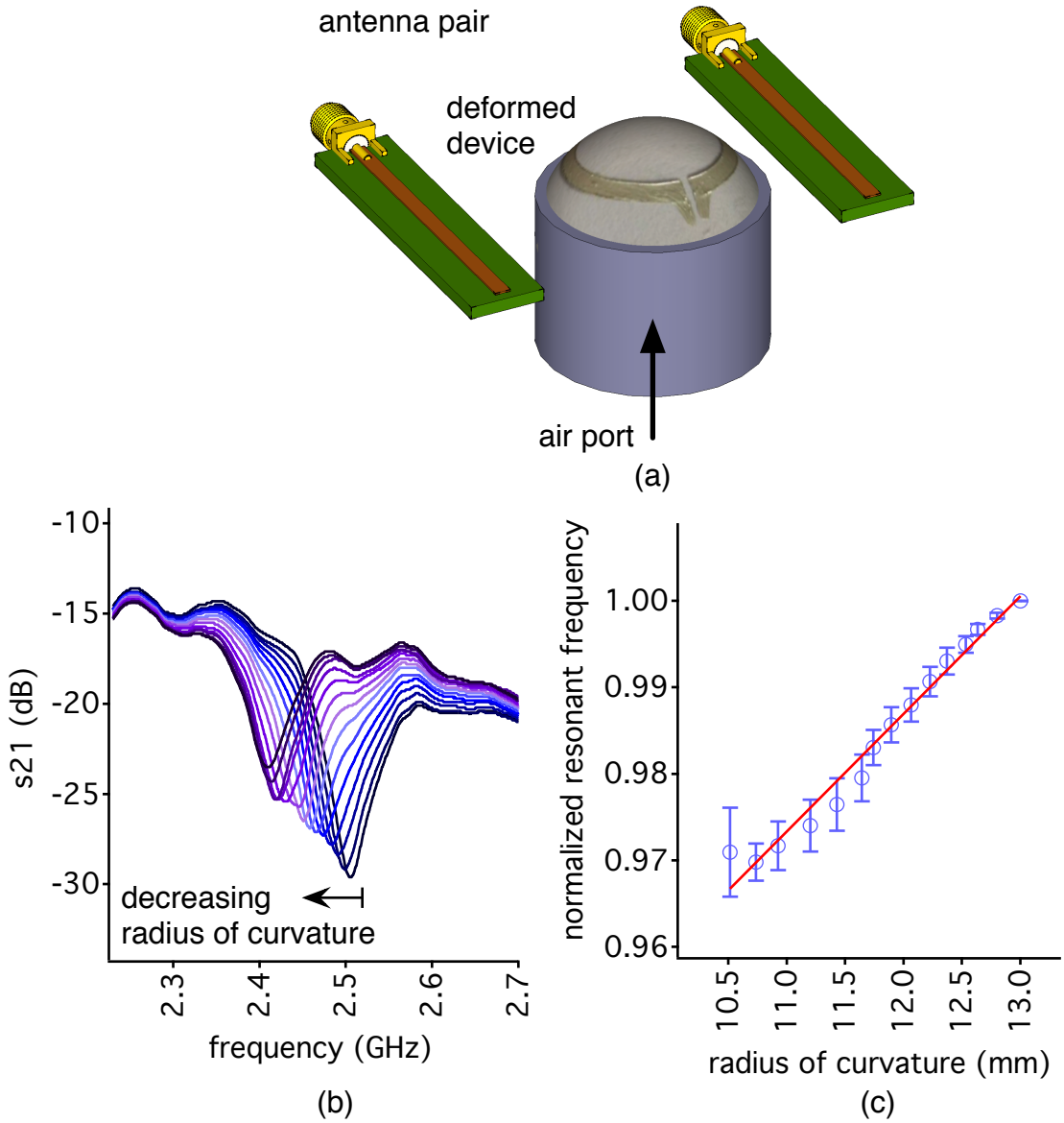


Figure 3.(a) Three-dimensional drawing of the experimental setup for the SRR sensor realized on latex rubber, (b) s21 spectra of the device as the curvature (1/ρ) increases, (c) Variation of the resonant frequency as a function of radius of curvature.

## 4. Conclusion

Split-ring resonator-based strain sensors enable realization of wireless strain sensors that are electrically passive. In this study, we demonstrate the feasibility of detecting glaucoma using SRR sensors realized on flexible substrates that can be integrated to contact lenses. We present two devices with different substrates that are suitable for distinct curvature profiles. The resonant frequencies of the devices depend on the curvature and the devices exhibit monotonic variation with respect to change in radius of curvature.

The first device, depicted in Fig.2, has a sensitivity of -4.73 MHz/mm. We measure the quality factor of the resonators on the order of 500. This corresponds to a frequency resolution of 5 MHz. Given the sensitivity values, the change in radius of curvature of the first SRR sensor can be measured with a resolution of 1.1 mm. The sensitivity of the second device, illustrated in Fig.3, is obtained as 33.2 MHz/mm and the measurement resolution for the radius of curvature corresponds to 150 $\mu$m. The demonstrated device is promising towards a novel method for glaucoma diagnosis.

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