APPLIED PHYSICS LETTERS **95**, 011106 (2009)

Metamaterial-based wireless strain sensors

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(Received 19 February 2009; accepted 10 June 2009; published online 7 July 2009)

We proposed and demonstrated metamaterial-based strain sensors that are highly sensitive to mechanical deformation. Their resonance frequency shift is correlated with the surface strain of our test material and the strain data are reported telemetrically. These metamaterial sensors are better than traditional radio-frequency (rf) structures in sensing for providing resonances with high quality factors and large transmission dips. Using split ring resonators (SRRs), we achieve lower resonance frequencies per unit area compared to other rf structures, allowing for bioimplant sensing in soft tissue (e.g., fracture healing). In 5×5 SRR architecture, our wireless sensors yield high sensitivity (109 kHz/kgf, or 5.148 kHz/microstrain) with low nonlinearity error (<200 microstrain). © *2009 American Institute of Physics*. [DOI: 10.1063/1.3162336]

Measuring and reporting strain in structural components using telemetric methods represents a significant engineering challenge. In many fields, such as civil engineering, this measurement tool would be highly beneficial. For instance, measuring the strain in concrete to discern the temporal course of its strength and flexibility (e.g., before, during, and after an earthquake) would greatly advance our knowledge of concrete's transient structural behavior (in an earthquake).[1,2] Other possible applications include the real-time measurement of the flexural rigidity of aircraft components during service in avionics. Our interest currently lies with using wireless sensing to observe the healing processes of fractured long bones in biomedical engineering.[3] When complicated fractures occur in humans, plates are implanted to impart stability to the fracture site during the acute postoperative period. In order to observe the healing process, wireless measurement of the strain on the plate could be utilized to indicate when healing was proceeding through a normal or aberrant pathway. For this end goal and other possible uses, we propose and demonstrate metamaterial-based wireless radio-frequency (rf) microelectromechanical systems (MEMS) strain sensors that are highly sensitive to mechanical loading. The operating principle of these sensors relies on telemetrically monitoring shifts in their resonance frequencies, which are a function of the strain imparted to the associated circuit in response to externally applied loads. In this letter, we present the design, fabrication, and *in vitro* characterization of these wireless metamaterial strain sensors.

To date, metamaterials have been widely investigated[4–7] and exploited for numerous functions, e.g., to obtain negative refraction,[8–10] cloaking,[11] superlenses,[12] antennas,[13] plasmons with nanowires,[14] laser output facets,[15] and focused light.[16] However, metamaterial architectures have not been studied for sensing till date. In this work, for the purpose of sensing, we employ split ring resonator (SRR) architecture in the fabrication of our rf-MEMS sensors because of their benefits that are unique for the function of telemetric sensing. Among their advantages is the ability to obtain higher quality factors (Q factors), and sharper and deeper dips on resonance in their transmission using SRR compared to traditional rf structures that we previously used (e.g., rectangular and circular coils).[17–19] This makes metamaterials very well suited for telemetric sensing applications. Furthermore, metamaterial architecture enables us to achieve higher resonance frequency shifts, leading to higher sensitivity and better linearity, compared to our previous rf sensor structures. With regard to the aforementioned fracture plate application, by using metamaterials, we also manage to significantly reduce operating resonance frequencies per unit area. This is especially critical for sensing applications that involve transmission through soft tissue (e.g., muscle) because such tissue strongly absorbs electromagnetic waves at otherwise very high operating frequencies.

Previously, we developed high Q factor on-chip resonators at higher operating frequencies.[17,18] Using microwave probes, we demonstrated the proof-of-concept principle of utilizing the resonance frequency shift[19] via on-chip resonators serving as sensors. In this paper, we present the proof-of-concept of fully telemetric resonance frequency shifts using our metamaterial sensors. Specifically, we observe the S parameters of our sensors without using any wires or other connections made to the sensors; our sensors are remotely located away from our external antennas. In characterization, we also externally apply loads to our sensors using a compression apparatus and measure the resulting resonance frequency shifts in response. We also measure the strain using commercially available wired strain gauges and compare the two data sets.

To fabricate our metamaterial sensors, we start with depositing 0.1-μm-thick Si_3N_4 onto our silicon substrate by plasma-enhanced chemical vapor deposition. Subsequently, standard lithography, metal evaporation, and lift-off techniques are utilized to deposit and pattern a 0.1-μm-thick Au film to obtain our SRR structure on the top. Our final geometry is depicted in Fig. 1 (denoted as SRR sensor), with a 2220 μm outer length and a 1500 μm inner length. This

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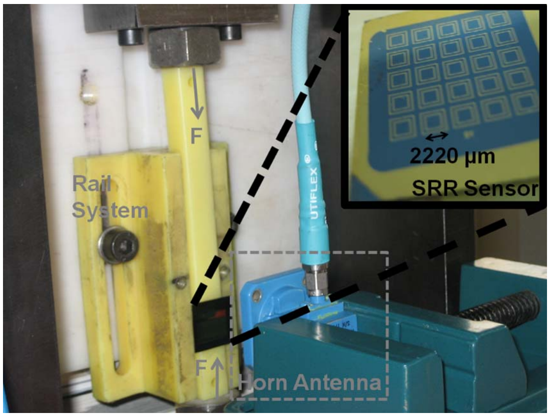

FIG. 1. (Color online) Our microfabricated 5×5 SRR array-based strain sensor under test in the compression apparatus.

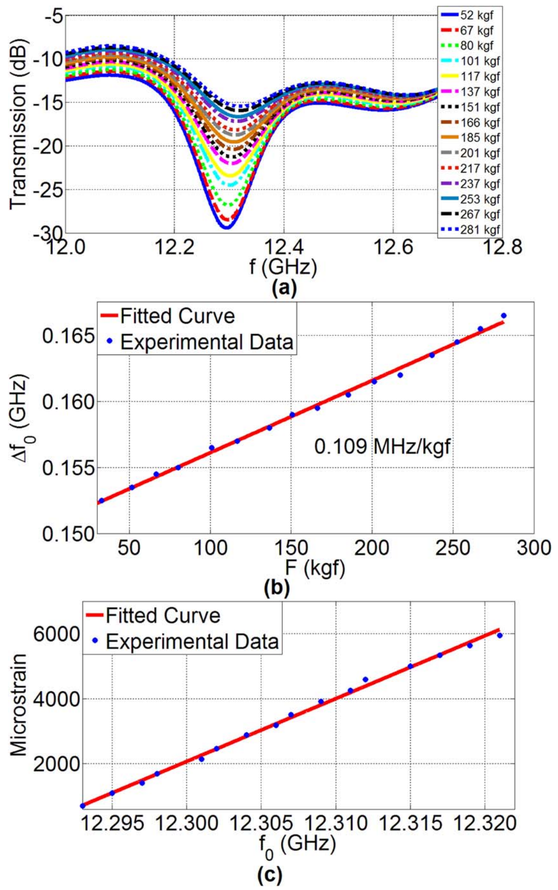

FIG. 2. (Color online) (a) Transmission spectra of our metamaterial strain sensor parameterized with respect to the external force, (b) its resonance frequency shift vs the applied force, and (c) the microstrain vs resonance frequency.

design also has an 80 μm inner width and an 80 μm outer width, with a 280 μm inner spacing and a 280 μm outer spacing, respectively. The unit cell length of one SRR structure is 2780 μm. We have a 5×5 array of these SRR unit cells incorporated in the sensor, resulting in a total of 1.5 cm^2 chip size. Our sensor is fixed to the test material via hard epoxy. A cast polyamide stick is employed as the test material. The apparatus applies compressive loads to the cast polyamide stick from 0 to 300 kgf. Our sensor returns the strain on the cast polyamide stick. One antenna acts as the transmitter and one antenna as the receiver, where standard gain horn antennas are used as shown in Fig. 1.

In operation, the sensor is mechanically deformed under stress and this shifts the operating resonance frequency. For example, in compression, the dielectric area and capacitance (dielectric capacitance) are decreased, the spacing between the metals is increased, and the capacitance between metals is decreased. These changes result in an overall increase in the resonance frequency. The theoretical rationale of the design has been previously presented in detail for conventional spiral coil architecture.[19] Transmission through the metamaterial sensor is shown as a function of the frequency parameterized with respect to the applied load in Fig. 2(a). There is a definite trend of increasing resonance frequency with increased applied load shown in Fig. 2(a). Here in the transmission spectra, the dip represents the second harmonic of our structure's resonance frequency within our characterization range. This characterization demonstrates that we can use further lower resonance frequencies for sensing purposes. The device size is much smaller than the operating wavelength. This is particularly important for measuring the strain of instrumented and implanted sticks under soft tissue conditions. In Fig. 2(b), we obtain the strain measured telemetrically from the resonance frequency shift and depict the microstrain versus the resonance frequency. From this measurement, we obtain a sensitivity level of 109 kHz/kgf, which corresponds to 5.148 kHz/microstrain. The wireless sensor is observed to have a nonlinearity error of less than 200 microstrain in this telemetric strain measuring experiment using the resonance frequency shift data. This shows us that we can accurately read the strain wirelessly with metamaterials. For comparison, we also measure the stress versus microstrain of a semiconductor-based wired strain gauge (Tokyo Sokki Kenkyujo Co., Ltd. strain gauges with a gauge factor of 2.1). Here we observe that the wired strain gauge also exhibits a nonlinearity error of less than 600 microstrain. Therefore, both the commercial wired gauge and our wireless strain sensor return equivalent results, with the difference that the wireless sensor provides an additional benefit of remote readout.

For comparison of this current work against our previous work, we are able to take fully telemetric data by using SRR structure in this work instead of using spiral coil structure with a pair of microwave probes in full contact with the coil as in our previous work. In our previous work, we took on-chip data and we did not use any external antennas. Here we use only external antennas and do not use any probes or any other wired connection, and we therefore measure the strain wirelessly in this work.

In this work, the SRR geometry is more sensitive compared to the spiral case because of their additional gaps in their SRR structure. These gaps produce additional capacitance, which is changed when the load is applied. Hence, it makes SRR more sensitive than the spiral coil geometry. In addition, the electric field density is much higher in the gaps so these gaps are important to have strong resonances. When the load is applied, these gaps change and hence the resonance frequency changes. This leads to higher sensitivity in SRRs compared to spiral coil structure.

Also, as a result of these gaps, SRRs yield higher dips and higher Q factors compared to the spiral structure. This enables us to measure telemetrically and observe the resonance frequency relatively more easily. As a result, a SRR sensor is more linear than a spiral coil sensor. Also, because of these gaps, we can lower resonance frequencies per unit area, which we need for our bioimplant applications. Therefore, because of the gaps in SRR structure, we obtain higher Q factors, higher dips, higher sensitivities, better linearity, and lower resonance frequency per unit area compared to spiral coil structure.

In spite of being fully wireless in this work, our sensor exhibits a very good level of sensitivity (109 kHz/kgf, or 5.148 kHz/microstrain) with a low nonlinearity error of less than 6% while the wired sensor in our previous work has a sensitivity level of 400 kHz/kgf with an error of 12%.

In conclusion, this work proposes and demonstrates the implementation of metamaterials in wireless rf-MEMS strain sensors. By using metamaterials, we can obtain high Q factors, high transmission dips on resonance, high resonance frequency shifts, high sensitivities, and very good linearity. These are highly desirable properties of an accurate wireless sensor. Furthermore, we achieve significantly lower resonance frequencies per unit area with sharper dips by using metamaterials, which is very useful particularly for sensing applications involving soft tissue. Specifically, a sensitivity level of 109 kHz/kgf (corresponding to 5.148 kHz/microstrain) with a nonlinearity error of less than 200 microstrain in the strain reading is shown in the telemetric measurements. Our wireless sensor's strain readouts that are obtained telemetrically are found to be comparable to those obtained using commercially available wired strain sensors that are used in electrical contact.

This work is supported by Turkish National Academy of Sciences Distinguished Young Scientist Award (TÜBA GEBİP), European Science Foundation European Young Investigator Award (ESF-EURYI), and TÜBİTAK EEEAG Grant Nos. 105E066, 105E065, 109E002, 104E114, 106E020, 107E088, and 107E297, and EU MOON Grant No. 021391. We acknowledge Dr. Z. Dilli and Dr. I. Bulu for valuable discussions.

[1] R. Park and T. Paulay, *Reinforced Concrete Structures* (Wiley, New York, 1975).

[2] A. Ghali and R. Favre, *Concrete Structures: Stresses and Deformations* (E & FN Spon, London, 1994).

[3] K. Stoffel, K. Klaue, and S. M. Perren, Injury **31**, 37 (2000).

[4] W. E. Kock, Proc. IRE **34**, 828 (1946).

[5] V. G. Veselago, Usp. Fiziol. Nauk **92**, 517 (1967).

[6] J. B. Pendry, A. J. Holden, W. J. Stewan, and I. Younes, Phys. Rev. Lett. **76**, 4773 (1996).

[7] R. M. Walser, *Introduction to Complex Mediums for Electromagnetics and Optics* (SPIE, Bellingham, 2003).

[8] D. R. Smith, Phys. World **16**, 23 (2003).

[9] D. R. Smith, J. B. Pendry, and M. C. K. Wiltshire, Science **305**, 788 (2004).

[10] U. K. Chettiar, S. Xiao, A. V. Kildishev, W. Cai, H.-K. Yuan, V. P. Drachev, and V. M. Shalaev, MRS Bull. **33**, 921 (2008).

[11] W. Cai, U. K. Chettiar, A. V. Kildishev, and V. M. Shalaev, Nat. Photonics **1**, 224 (2007).

[12] D. R. Smith, Science **308**, 502 (2005).

[13] K. B. Alici and E. Ozbay, J. Appl. Phys. **101**, 083104 (2007).

[14] V. A. Podolskiy, A. K. Sarychev, and V. M. Shalaev, J. Nonlinear Opt. Phys. Mater. **11**, 65 (2002).

[15] M. S. Rill, C. Plet, M. Thiel, I. Staude, G. von Freymann, S. Linden, and M. Wegener, Nature Mater. **7**, 543 (2008).

[16] J. B. Pendry and S. A. Ramakrishna, J. Phys.: Condens. Matter **15**, 6345 (2003).

[17] R. Melik, N. K. Perkgoz, E. Unal, Z. Dilli, and H. V. Demir, IEEE Trans. Electron Devices **55**, 3459 (2008).

[18] R. Melik and H. V. Demir, Microwave Opt. Technol. Lett. **51**, 497 (2009).

[19] R. Melik, N. K. Perkgoz, E. Unal, C. Puttlitz, and H. V. Demir, J. Micromech. Microeng. **18**, 115017 (2008).