COVER SHEET

Title: *Multi-Physics Modeling and Simulation of a Frequency Doubling Antenna Sensor for Passive Wireless Strain Sensing*

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ABSTRACT

This research studies multi-physics simulation of a frequency doubling antenna sensor for wireless strain measurement. The frequency doubling technology allows easy distinguishing of backscattered passive sensor signal (at the doubled frequency $2f$) from environmental reflection (at original reader interrogation frequency f). Upon bonding to a base structure, because strain/deformation causes resonance frequency change of the antenna sensor, the passive wireless antenna sensor can be used to measure strain in the underlying base structure. To accurately model the mechanical and electromagnetic behaviors of the frequency doubling antenna sensor, a multi-physics coupled simulation approach is proposed. For simulating both the matching network performance and the antenna behavior under strain/deformation, two commercial software packages, COMSOL and ADS, are combined to leverage the strength of each package.

INTRODUCTION

In order to monitor the safety conditions of a structure, various sensors can be deployed on the structure, such as strain, displacement, acceleration, humidity, temperature, etc. [1]. Among various measurands needed for structural health monitoring (SHM), strain is one of the most important indicators of stress concentration and damage development. Many types of sensors can measure strain, such as metal foil strain gages, vibrating wire sensors, and fiber optic sensors [2]. Although the performance of these sensors is adequate in many applications, most of the sensors require a cabled system for data acquisition and power supply. However, cabled systems can be costly not only in system installation, but also in long-term system maintenance [3].

Over the past two decades, cost-effective wireless sensors have been developed to reduce system installation and maintenance cost. These wireless sensing devices

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usually contain three main modules: sensing interface (converting analog sensor signal to digital data), computational core (data processing and storage), and wireless communication (data transmitting and receiving) [4-6]. Although these wireless sensing devices significantly reduce the installation time and cost of an SHM system, the devices usually operate on external power such as batteries. Therefore, battery charging and periodic replacement are inevitable for long-term operation.

In recent years, passive (battery-free) RFID (radio frequency identification) antennas have been proposed for wireless strain measurement [7, 8]. Through signal modulation by an economic RFID chip (costing about $0.10), patch antennas demonstrate promising performance for wireless strain/crack sensing. However, the frequency band of the commercial RFID chip is limited to 860-960 MHz, according to EPC Class-2 Generation-2 RFID protocol [9]. Thus, the antenna sensor has a relatively low strain sensitivity. Alternative approaches to operate at a higher frequency band are proposed in order to improve strain sensitivity. In our previous research, the concept of a frequency doubling antenna sensor is introduced. A wireless reader emits a 2.9GHz interrogation signal to a frequency doubling sensor. The sensor then responds with the backscattered signal at a doubled frequency of 5.8GHz. A Schottky diode (SMS7621-079LF) from Skyworks Solutions, Inc. is used to double the interrogation frequency of 2.9GHz to the response frequency of 5.8GHz. The sensor performance is estimated by simulation that linearly scales an antenna shape to mimic strain effect [10]. However, the linear-scaling simulation may not accurately describe mechanical and electromagnetic behaviors of the antenna sensor.

In this paper, a multi-physics coupled simulation approach is proposed. The approach can estimate strain sensing performance of the frequency doubling antenna sensor at a higher accuracy. In order to increase strain sensitivity, high frequency receiving (5.8 GHz) and transmitting (11.6GHz) patch antennas are designed for the sensor. The same Schottky diode is adopted for frequency doubling. A matching network is designed to be integrated with two patch antennas. A SPICE (simulation program with integrated circuit emphasis) model is used to emulate the frequency doubling performance of the Schottky diode. The strain sensing performance of the frequency doubling antenna sensor is estimated using a commercial software package, COMSOL, which supports mechanics-electromagnetics coupled simulation. For simulating the matching network, ADS (Advanced Design System) software package is used to analyze the second harmonic wave from the output side of the Schottky diode. The rest of this paper is organized as follows. First, the strain sensing mechanism of the frequency doubling antenna sensor is described. Then, the design of each component of the frequency doubling antenna sensor is presented. Upon describing the multi-physics coupled (mechanics-electromagnetics) model, simulation results are presented on the strain sensing performance of the frequency doubling antenna sensor. Finally, the paper is summarized with conclusions and future work.

OPERATION PRINCIPLE OF THE FREQUENCY DOUBLING ANTENNA SENSOR FOR PASSIVE WIRELESS STRAIN MEASUREMENT

As shown in Fig. 1, the frequency doubling antenna sensor consists of three components, i.e. a receiving patch antenna at resonance frequency f_0, a transmitting patch antenna at the doubled resonance frequency of $2f_0$, and a matching network with a Schottky diode. The diode is a nonlinear circuit device and can generate signal at doubled frequency (a.k.a. the second harmonic wave). During sensor operation, the reader-side transmitting antenna emits the interrogation signal to the sensor at frequency f, which is within a small range around the resonance frequency f_0. The receiving patch antenna at the sensor side captures and transfers interrogation power to the Schottky diode in the matching network. The diode then generates and inputs the second harmonic wave (at the doubled frequency $2f$) to the sensor-side transmitting patch antenna. The output signal with the doubled frequency $2f$ is finally backscattered to the receiving reader antenna for spectrum analysis. In summary, the interrogation signal from the reader has a frequency of f, while the backscattered signal received by the reader (from the sensor) has of frequency of $2f$. Therefore, it is easy for the reader to distinguish backscattered sensor signal at $2f$ from unwanted environmental reflections mostly at original interrogation frequency f. For further size reduction in this study, the antenna sensor adopts a receiving patch antenna $f_0 =$ 5.8GHz and a transmitting patch antenna at $2f = 11.6$GHz.

To achieve wireless strain measurement, the 5.8GHz receiving patch antenna at the sensor side is bonded to a structural surface as the strain sensing component. This patch antenna consists of three layers: top microstrip antenna, dielectric substrate, and bottom metallic ground plane (Fig. 2). The microstrip antenna design aims to optimize radiation performance on a metallic structure. The resonance frequency of a microstrip antenna can be estimated by the following equation.

$$f_0^{\text{Patch}} = \frac{c}{2(L+L')\sqrt{\varepsilon_{\text{reff}}}} \tag{1}$$

where c is the speed of the light; L is the physical length of the antenna copper cladding (as metallic conductor of the antenna); $\varepsilon_{\text{reff}}$ is the effective dielectric constant of the substrate; L' is the additional electrical length due to fringing effect.

When the antenna is under strain, the shifted resonance frequency becomes:

$$f^{\text{Patch}} = \frac{c}{2(1+\varepsilon)(L+L')\sqrt{\varepsilon_{\text{reff}}}} = \frac{f_0^{\text{Patch}}}{1+\varepsilon} \cong f_0^{\text{Patch}}(1-\varepsilon) \tag{2}$$

Eq. (2) shows that when strain ε is small, the relationship between the shifted resonance frequency and strain is approximately linear. Utilizing this relationship, strain experienced by the sensor can be derived by measuring the resonance frequency

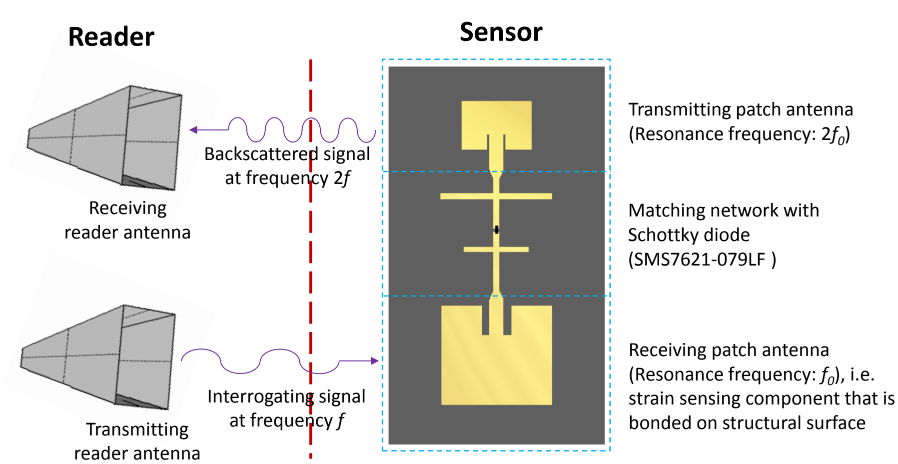
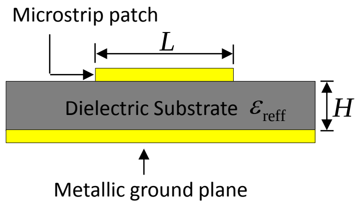
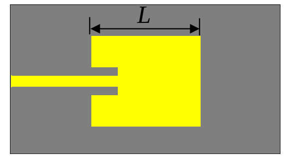


Fig. 1. Operation mechanism of a frequency doubling antenna sensor system



(a) Side view



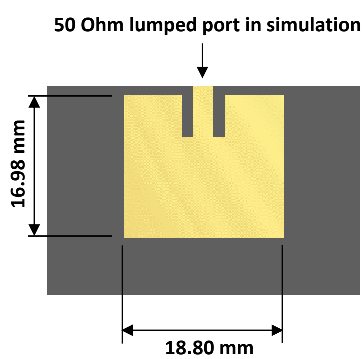
(b) Top view

Fig. 2. Microstrip patch antenna

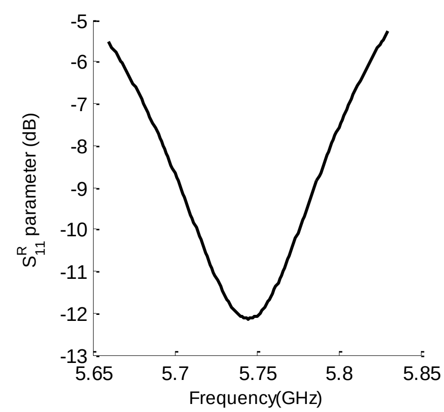
shift through wireless interrogation. Therefore, if the sensor-side receiving patch antenna is bonded to a structural surface that is under strain, the patch antenna length changes and resonance frequency shifts from f_0^{Patch} to f^{Patch}. The diode-integrated matching network doubles the signal frequency to $2f^{\mathrm{Patch}}$ and response signal from the sensor-side transmitting patch antenna is backscattered to the reader-side receiving antenna. In short, the basic sensing mechanism of the frequency doubling antenna sensor relies upon the relationship between strain ε and the resonance frequency shift of the signal received by the reader.

FREQUENCY DOUBLING ANTENNA SENSOR DESIGN

The substrate adopted in the sensor design is the Rogers RT/duriod®5880 material, a glass micro-fiber reinforced PTFE. The material has a low dielectric constant ($\varepsilon_r = 2.2$) and a low tangent loss (0.0009) that help to improve interrogation distance and signal-to-noise ratio. The thickness of the substrate is chosen as 31mil (0.7874 mm), a trade-off between antenna gain and strain transfer ratio. In the preliminary design, the resonance frequency of the receiving patch antenna is $f_0 = 5.8$GHz, while $2f_0 = 11.6$GHz is set as the resonance frequency of the transmitting patch antenna. Dimension of the receiving antenna is 18.80mm × 16.98mm (Fig. 3(a)). Because scattering parameter (S_{11}) represents antenna radiation efficiency at certain electromagnetic frequency, S_{11} is utilized to determine the resonance frequency of an antenna. The parameter S_{11}, which shows the lowest magnitude at the antenna's resonance frequency, is calculated as:



(a) Dimensions of the 5.8GHz receiving antenna



(b) Simulated S_{11}^{R} parameter

Fig. 3. Sensor-side receiving antenna design

$$S_{11} = \frac{V_{\text{out}}}{V_{\text{in}}} \tag{3}$$

where V_{in} and V_{out} are input (incident) and output (reflected) voltage at the 50 Ohm lumped port.

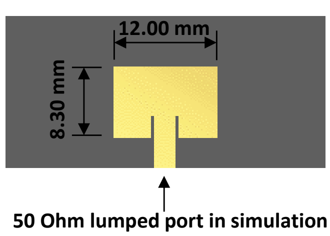
If the output (reflected) voltage is small at certain frequency, most of the input energy is radiated into the air, which means the antenna has a higher radiation efficiency at that frequency. Therefore, the frequency corresponding to the minimum value of $|S_{11}|$ is regarded as the resonance frequency of the antenna. In Fig. 3(b), scattering parameter of the receiving patch antenna, S_{11}^{R}, shows around –12dB return loss at 5.8GHz. This is lower than the required –10dB return loss threshold of a typical antenna, indicating high radiation efficiency. In addition, the 11.6GHz transmitting patch antenna (12.00mm $\times$ 8.30mm) is as shown in Fig. 4(a). The simulated scattering parameter of the transmitted antenna, S_{11}^{T}, is –25dB at around the doubled frequency of 11.6GHz (Fig. 4(b)).

The role of the matching network is to match input and output impedance to 50 Ohm for receiving and transmitting antennas. The diode in the matching network, which is a two-terminal semiconductor device, has a nonlinear relationship between excitation voltage and current. This nonlinearity is exploited for frequency doubling, as the output terminal of the diode produces second harmonic waves. A Schottky diode has relatively low junction capacitance, allowing operation at the high frequency needed in this research [11]. In particular, the SMS7621-079LF Schottky (Skywork Solution, Inc.) diode model is adopted.

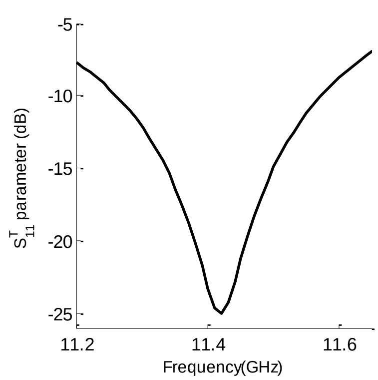
The matching network consists of input and output matching stubs, integrated with the diode (Fig. 5(a)). The overall size of the matching network is 36.80mm $\times$ 22.00mm. The goal of the matching network design is to maximize output power upon frequency doubling. A commercial circuit simulation software package, advanced design system (ADS) is used in the harmonic-balance simulation of the matching network, by adopting a SPICE model of the diode. Conversion gain of frequency doubling is defined as the following equation.

$$G_C = \frac{P_2}{P_1} \tag{4}$$

where P_1 is input power with frequency f to Port 1; P_2 is output power with doubled frequency $2f$ from Port 2.

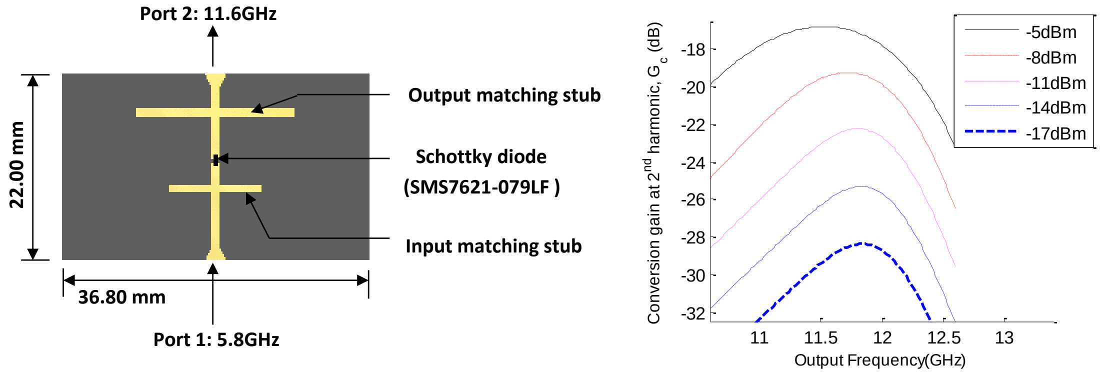


(a) Dimensions of the 11.6 GHz transmitting antenna



(b) Simulated S_{11}^{T} parameter

Fig. 4. Sensor-side transmitting antenna design



(a) Dimensions of the matching network

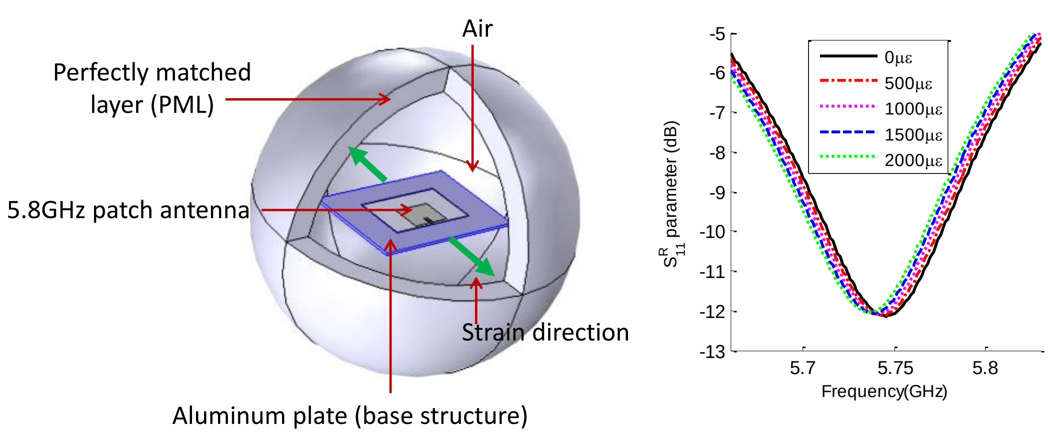
(b) Simulated conversion gain at the 2nd harmonic, G_c with different input power levels

Fig. 5. Matching network design

Because of the diode nonlinearity, conversion gain G_c, has different magnitudes based on the input power, which is plotted in Fig. 5(b).

STRAIN SENSING PERFORMANCE ESTIMATIED BY MULTI-PHYSICS SIMULATION

As previously mentioned, the role of the 5.8 GHz sensor-side receiving antenna is not only to receive interrogation power from the reader, but also to serve as the strain sensing component. Therefore, the 5.8GHz antenna is fully bonded to structural surface. Meanwhile, all other parts of the sensor, including the matching network and the 11.6 GHz transmitting antenna, are strain free. Therefore, the mechanics-electromagnetics coupled simulation for the 5.8GHz receiving patch antenna is first conducted as illustrated. As shown in Fig. 6(a), an air sphere describes the electromagnetic simulation domain. The outer surface of the air sphere is matched by PML (perfectly matched layer) which absorbs radiation energy and mimics performance in infinite space. Inside the air sphere, the aluminum plate is modeled as a base structure where strain occurs. The 5.8GHz receiving antenna is bonded on top of the aluminum plate. Key parameters for mechanical and electromagnetic properties



(a) Multi-physics simulation model of the 5.8GHz receiving antenna

(b) Simulated S_{11}^R parameter under strain

Fig. 6. Multi-physics modeling and simulation for the receiving (5.8GHz) patch antenna

Table 1. Key materials properties of the receiving 5.8GHz patch antenna

	Substrate	Copper cladding	Aluminum
Material type	Glass microfiber reinforced PTFE	Copper	6061 Aluminum alloy
Relative permittivity ($\varepsilon_{\mathrm{reff}}$)	2.2	-	-
Conductivity (S/m)	0.5×10^{-9}	PEC	PEC
Young's modulus (GPa)	1.07	110	69

of the materials are summarized in Table 1. To investigate strain sensing performance, five strain levels are applied from zero to 2,000με, with 500με strain change per step. Fig. 6(b) shows the simulated S_{11} parameter under different strain levels. S_{11}^{R} curves clearly shift from right to left as strain increases.

COMSOL provides multi-physics functionality to more accurately model the electromagnetic performance of the antenna sensor under mechanical strain. However, electromagnetic analysis in COMSOL is not capable of nonlinear circuit simulation for the diode, such as harmonic balance analysis. In order to accomplish the simulation for the entire sensor, three stepped-simulation is proposed: (i) mechanics-electromagnetics coupled simulation of the 5.8 GHz receiving antenna in COMSOL, (ii) harmonic balance simulation of the diode-integrated matching network in ADS, and (iii) electromagnetic simulation of the 11.6 GHz transmitting antenna in COMSOL.

The input power P_0 is set to -5dBm, based on experimental testing results and power P_1 to Port 1 of the matching network at each strain level is calculated based on scattering parameter, S_{11}^{R} (Fig. 7). Then the harmonic balance simulation is conducted in ADS and the output power P_2 of the doubled frequency is evaluated at the Port 2. The 11.6GHz transmitting antenna is simulated in COMSOL to obtain scattering parameter, S_{11}^{T}. In this simulation, a total number of 99,203 triangular, 14,500 prism, 10,604 triangle, 900 quadrilateral elements are used. Finally, the overall power P of the overall response signal backscattered to the reader can be estimated as [11]:

$$P = (1 - [S_{11}^{T}]^2)P_2 \tag{5}$$

where P_2 is the output power from Port 2 of the matching network.

The output power from the frequency doubling antenna sensor at different strain levels is plotted in Fig. 8(a). The resonance frequency of the sensor response signal clearly shifts from right to left as strain increases. The resonance frequency at each strain level is then extracted from the output power plot. Linear regression is performed to plot the relationship between strain and resonance frequency (Fig. 8(b)). The strain sensitivity is –5,537 Hz/με, the magnitude of which is around 7.5 times higher than that of the RFID antenna sensor. In addition, the coefficient of determination is found to be 0.9999, which indicates a good linearity.

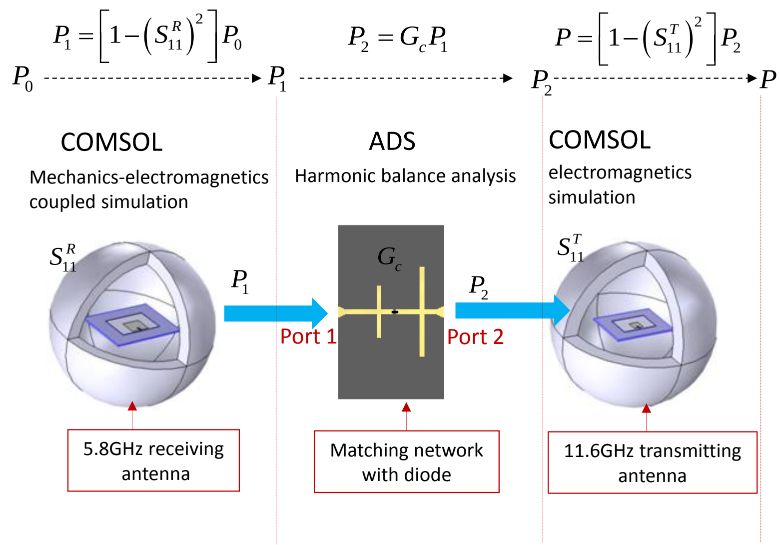


Fig. 7. Flow chart illustration of the multi-physics coupled simulation for the entire sensor

SUMMARY AND CONCLUSIONS

In this research, a frequency doubling technique is proposed for wireless strain measurement. A passive (battery-free) 5.8 to 11.6 GHz frequency doubling antenna sensor is designed. In order to accurately estimate wireless strain sensing performance, multi-physics modeling and simulation for the frequency doubling antenna sensor are performed. Future studies will adopt systematic optimization procedures to improve the sensor performance for strain sensing. In addition, extensive experiments will be conducted to validate the sensor performance, and to iteratively improve the design.

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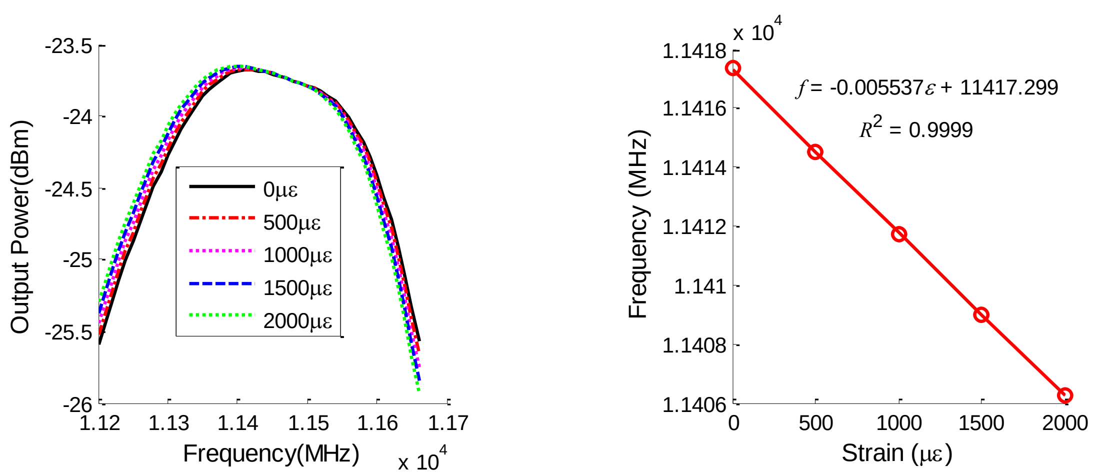

(a) Output power P vs. frequency (b) Resonance frequency change under strain ε

Fig. 8. Multi-physics simulation result

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