# EXPERIMENTAL AND NUMERICAL STUDY OF HIGHLY SENSITIVE DISPLACEMENT SENSORS BASED ON PHOTONIC CRYSTALS AT MICROWAVE BAND

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**ABSTRACT:** *Structures composed of two photonic crystal slabs are fabricated, measured, and simulated around 13.5 GHz. Experimental and simulated results are in good agreement. The transmission spectrum is highly sensitive to the distance between the two slabs, which demonstrates that the structures under investigation can be used to achieve displacement sensors.*  Microwave Opt Technol Lett 54:432–434, 2012; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.26558

**Key words:** *displacement sensor; photonic crystal; microwave; anechoic chamber; finite-difference-time-domain*

## 1. INTRODUCTION

Photonic crystal structure constitutes a nice candidate to achieve displacement sensors with compactness, high sensitivity, and low loss [1]. Specifically, when two photonic crystal slabs are placed close to each other, the coupling between their individual resonances is highly sensitive to the relative displacement between the two slabs [2, 3]. As a result, displacement can be precisely determined via measuring the reflection or transmission spectrum. Although there has been extensive theoretical/numerical investigation on reflection/transmission characteristics of two photonic crystal slabs [1–7], little experimental study has been reported, largely because of practical difficulties related to fabricating and testing the double-slab structures. To the best of the authors' knowledge, Ref. 8 is the only published literature that presents measurement results on the reflectivity spectrum from two photonic crystal slabs in wavelength range around 1200 nm; nevertheless, the impact of displacement on the reflectivity spectrum is not inspected in Ref. 8. In Ref. 9, two photonic crystal slabs are measured at THz band; but, the focus of Ref. 9 is on group-velocity anomaly rather than displacement sensing. In this letter, structures made of two photonic crystal slabs are studied comprehensively at microwave band. Photonic crystal slabs are fabricated with guided resonant frequencies around 13.5 GHz; transmission spectra through double-slab structures are measured using a compact range in the anechoic chamber. The major benefit of scaling up photonic crystal structures to microwave regime is the ease pertinent to fabrication and measurement. Thanks to the long wavelength (>1 cm), the photonic crystal patterns can be fabricated reliably by traditional machining and the displacement between the two slabs can be controlled accurately. Our measurement data show excellent agreement with numerical results obtained from a simulator based on finite-difference-time-domain method. Both the experimental and numerical studies demonstrate that the configuration under investigation (i.e., double photonic crystal slabs) can be exploited to accomplish highly sensitive displacement sensors: when the distance between the two slabs is tuned in a small range (smaller than one wavelength), the transmission spectrum exhibits substantial variation. To be specific, when the distance is smaller than one wavelength, coupling between the two slabs creates two stop-bands, and moreover, the separation between the two stop-bands varies significantly with slight change of distance.

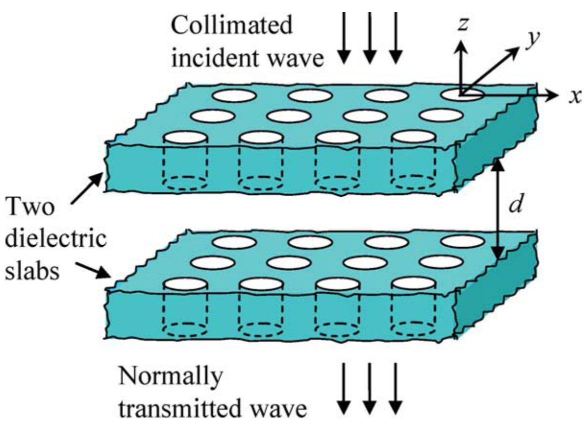


**Figure 1** Illustration of two photonic crystal slabs as displacement sensor. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

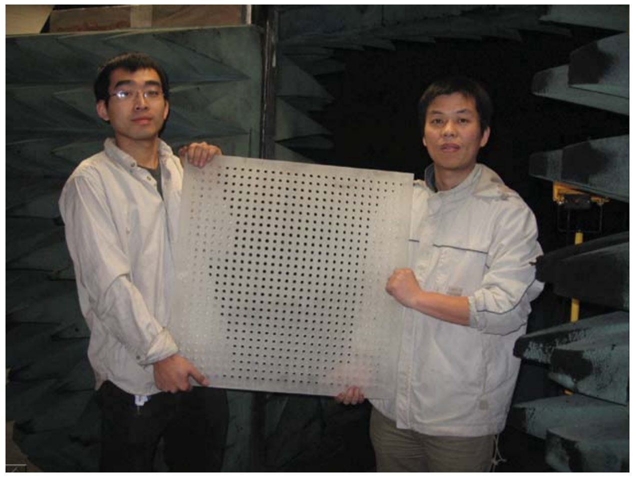

**Figure 2** Photo of a fabricated photonic crystal slab at microwave band. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

The rest of this letter is organized as follows. Section 2 describes our experimental and numerical methods. Some results are presented in Section 3. And finally, Section 4 relates to our conclusions and future work.

## 2. EXPERIMENTAL AND NUMERICAL METHODS

The structure investigated in this letter is composed of two photonic crystal slabs, as depicted in Figure 1. Two dielectric slabs are separated with a distance $d$ along $z$ direction. Square lattice of air holes is fabricated over each slab; the two lattice patterns are aligned along $x$ and $y$ directions. The two slabs are excited by a normally incident wave with electric field polarized along $x$, and the normally transmitted wave is detected. In our experimental implementation, Rexolite 1422 sheets, with 2.54-cm thickness and dielectric constant of 2.53, are used for the two

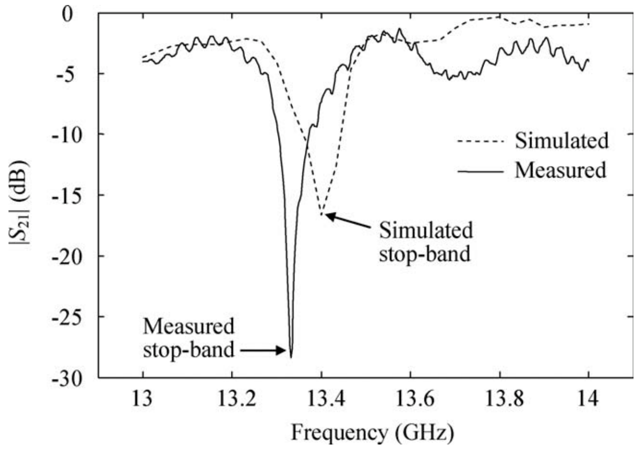


**Figure 3** Measured and simulated transmission spectra for a single slab

slabs; the air holes have diameter 0.95 cm; lattice period is 2.1 cm. One of the fabricated photonic crystal slabs, with 28 by 28 holes, is shown in Figure 2. Incident collimated wave is generated by a Ku-band side-fed parabolic reflector antenna, which results in a quiet zone with size about 60 × 60 $cm^2$. The normally transmitted wave is received by a standard probe horn antenna. The parabolic and horn antennas are connected to an HP8510C network analyzer. All the measurements are carried out in the anechoic chamber at the University of Texas at Arlington. In experiments, the two slabs are surrounded by absorbers. Two forward transmission coefficients are measured by the network analyzer: one with the presence of photonic crystal slabs, and the other without the slabs (i.e., there is only air between the transmitting and receiving antennas). The ratio between these two measured coefficients is defined as the transmission coefficient $S_{21}$ associated with the two photonic crystal slabs.

To verify our experimental data, the configuration in Figure 1 is analyzed by a simulator we developed recently, which is based on finite-difference-time-domain algorithm [10]. Furthermore, our simulator is implemented on parallel cluster computers at Texas Advanced Computing Center such that it is capable of analyzing the large-scale problems in this letter.

### 3. EXPERIMENTAL AND NUMERICAL RESULTS

In Figure 3, measured and simulated transmission spectra for a single photonic crystal slab are plotted. A stop-band (transmission coefficient below −10 dB) is identified in both the measurement and simulation. Measured and simulated center frequencies of the stop-band (13.34 and 13.4 GHz, respectively) agree very well with each other. The discrepancy between the measurement and simulation is mainly because the excitation wave generated by the parabolic antenna in the quiet zone is not an ideal plane wave used in the simulation.

Measured and simulated transmission spectra for double photonic crystal slabs are presented in Figures 4 and 5, respectively. Both the experimental and numerical results demonstrate that the transmission spectra exhibit substantial variation when $d$ is tuned in a small range (smaller than one wavelength). In both Figures 4 and 5, results for three $d$ values are plotted. To facilitate our discussion, $f_0 = 13.5$ GHz is used to denote the center frequency in the band of our concern, and $\lambda_0 = 2.22$ cm is the corresponding free-space wavelength. Both Figures 4 and 5 reveal that, when $d$ is greater than $\lambda_0$, there is only one stop-band as the coupling between the two slabs is weak. On the other hand, when $d$ is less than $\lambda_0$, strong coupling leads to two stop-bands, and the separation between the two stop-bands increases with the reduction of $d$. Specifically in Figure 4, when $d$ changes from 1.14 cm ($\cong 0.51\lambda_0$) to 0.48 cm ($\cong 0.21\lambda_0$), the separation between the two stop-bands increases from 155 MHz ($\cong 0.011 f_0$) to 445 MHz ($\cong 0.033 f_0$). It is therefore concluded that the displacement in Figure 1 can be sensitively detected via measuring the transmission spectrum.

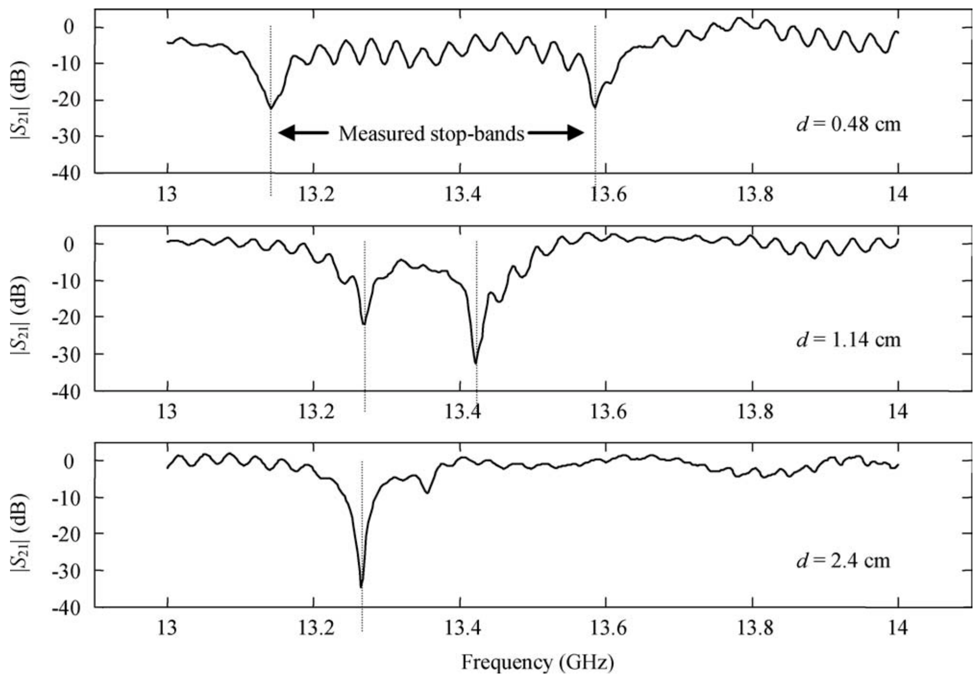


**Figure 4** Measured results for double slabs with three vertical displacements

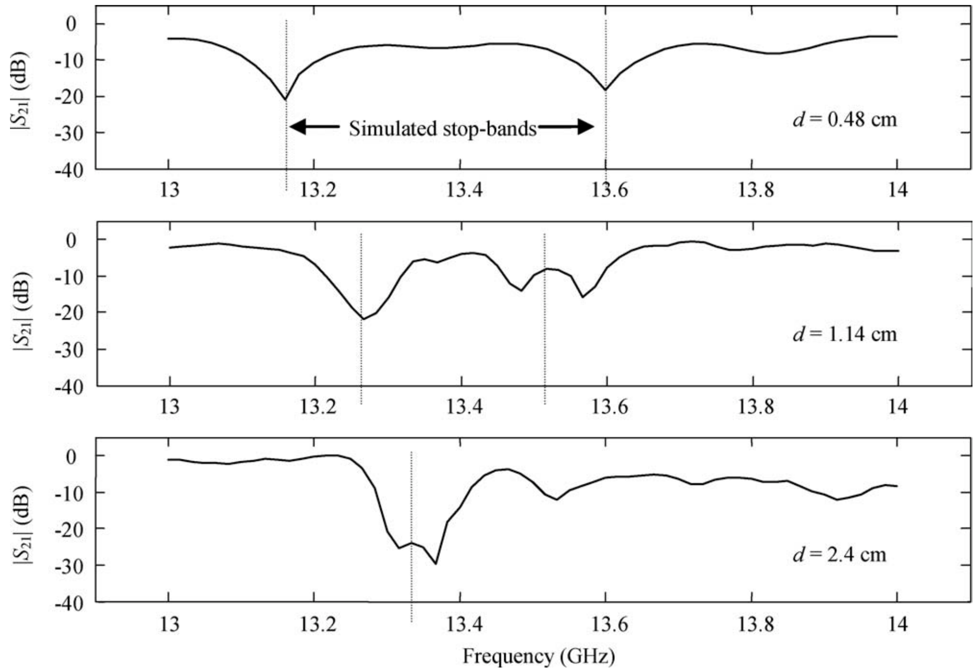


**Figure 5** Simulated results for double slabs with three vertical displacements

## 4. CONCLUSIONS

In this letter, experimental and numerical studies are conducted for coupling between two photonic crystal slabs at microwave band. Measurement and simulation results match each other very well. The transmission spectrum is shown highly sensitive to the distance between the two slabs, which in turn demonstrates the feasibility of applying the structure in this letter to accomplish highly sensitive displacement sensors. Our ongoing research includes investigating the impact of horizontal displacement between the two slabs on transmission/reflection spectrum [9].


## ACKNOWLEDGMENTS

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# DESIGN OF A NOVEL COMPACT BROADBAND PATCH ANTENNA USING BINARY PSO


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**ABSTRACT:** *In this article, a C-Band broadband patch antenna is designed. The binary particle swarm optimization (BPSO) combining with IE3D software is adopted to broaden the bandwidth of the patch antenna automatically. Characteristics of the antenna are calculated using the well-known Zeland IE3D software package while the bandwidth characteristic of the antenna is optimized using BPSO technique. The comparison results show that the 3.2% impedance bandwidth (4.63–4.78 GHz) of the patch antenna is upgrade to 10.4% (4.47–4.96 GHz) through the BPSO-IE3D method. The antenna gain is stable and the radiation patterns are similar in configuration over the whole operating frequencies to that of a conventional patch antenna. A prototype of the optimized antenna has been fabricated and important*