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An Optical Accelerometer Based on Wavelength Modulation of Light

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Abstract-*In this paper, we propose an ultrasensitive optical Micro-Electro-Mechanical-System (MEMS) accelerometer based on wavelength modulation, using one dimensional photonic crystal (PC). An air-dielectric multi-layer Photonic Band Gap (PBG) material, a typical Laser diode (LD) light source, a Photo Diode and integrated optical waveguides build up the optical sensing system of the proposed device. Functional characteristics of the proposed accelerometer are as follows: a mechanical sensitivity of* $3.18 nm/g$, *an optical sensitivity of* $1.17 nm/g$ *and a linear measurement range of* -22 to $+22g$. *Regarding to the mentioned characteristics, the proposed MOEMS accelerometer is suitable for a wide range of applications such as inertial navigation, consumer electronics, automotive, etc.*

Keywords: *Micro-electro-mechanical systems (MEMS), accelerometer, wavelength modulation, PC, sensitivity.*

1 Introduction

Over the last decades, high performance inertial MEMS sensors have been developed dramatically. One of the most popular inertial sensors is accelerometer which can measure the acceleration along one, two or three axes. Core part of the accelerometer is a displacement sensing system which is based on displacement of a suspended mass relative to the body frame. This displacement can be measured by using various methods such as capacitive [1, 2], piezo-resistive [3], piezoelectric [4], optical [5-7], and so on. Among these, optical detection techniques provide several advantages such as higher thermal stability, better performance, more sensitivity and better resolution compared to the other detection approaches.

During the past three decades, several contributions have been presented on optical acceleration sensors. Most of them are based on modulation of light wave features such as photo elastic effect [5], wavelength modulation [6], intensity modulation [7], etc. In contrast with intensity modulation sensing mechanisms, sensitivity of the wavelength modulation based methods is independent of light source fluctuations which make it very reliable.

In this paper, a novel topology for a MOEMS accelerometer based on wavelength modulation is presented by using a one dimensional PC filter. The presented micro-device can be used in a wide range of applications from consumer electronics to inertial navigation.

The remainder of this paper is organized as follows: In section 2, operation principle of the proposed accelerometer is presented. In section 3, mechanical structure of the proposed sensor is modelled by a two degree of freedom mechanical resonator. In addition, design and analysis of the mechanical and optical parts are carried out. At the end of the paper, section 4, conclusions and perspectives are derived.

2 Operation principle of the accelerometer

The proposed MOEMS accelerometer (Figure 1) relies on wavelength modulation of light. This wavelength modulation is performed by lateral moving of the defect layer inside of the PC.

The operating principle of the device is as follows: The light generated by the LD is coupled to the input waveguide through a conventional optical fiber. Passing through the PC, the generated light enters the output waveguide and then sent into a Photo Detector (PD) through an optical fiber. Finally, by monitoring the output signal of the PD one can estimate the applied external acceleration. In the proposed mechanical structure, the mass is suspended by four serpentine springs and a thin silicon finger is attached to it. While an external acceleration is applied, silicon finger attached to the proof mass moves inside of the PC along sensing axis (y), which results in changes of the output defect mode central wavelength of the PC. Magnitude and direction of the external applied acceleration can be then calculated by detecting the central wavelength shifts of the output optical mode.

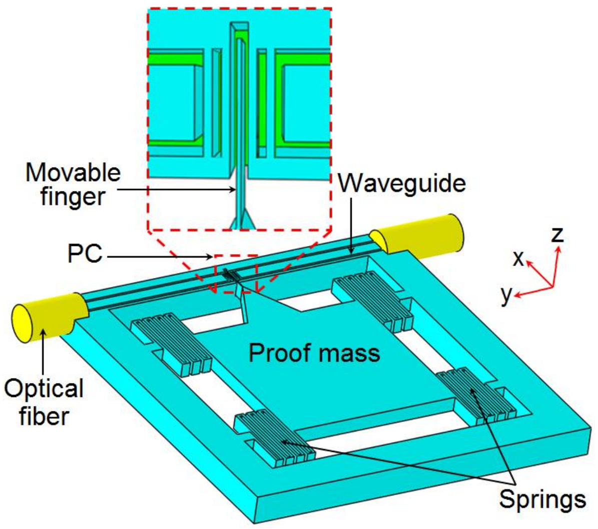

Figure 1: 3D model of the proposed PC based MOEMS accelerometer.

3 Design and Analysis

3.1 Design and analysis of mechanical structure

An accelerometer can be modelled mechanically as a two degree of freedom mass-spring-damper system. The dynamic behaviour of such a system can be described by a second order differential equation [8].

Physical and geometrical parameters of the mechanical part are effective on the performance of the device. Hence, these parameters should be chosen carefully. Physical and geometrical parameters of the proposed accelerometer are listed in **Error! Reference source not found.**.

Table 1: Physical and Geometrical Parameters of the Accelerometer.

	Parameter	Value
1	Young's modulus of silicon	$169 Gpa$
2	Density of silicon	$2330 kg/m^3$
3	Poisson ratio of silicon	0.23
5	Length & width of the seismic mass	$250\mu m \times 250\mu m$
6	Thickness of the seismic mass	$20\mu m$
7	Effective proof mass	$3.0607\mu gr$

ANSYS modal solution can be used to calculate the resonance modes of the mechanical resonator and the response of the proposed accelerometer to the excitations with these frequencies. Figure 2 shows four first mechanical mode shapes of the proposed accelerometer under the applied acceleration along sensing axis.

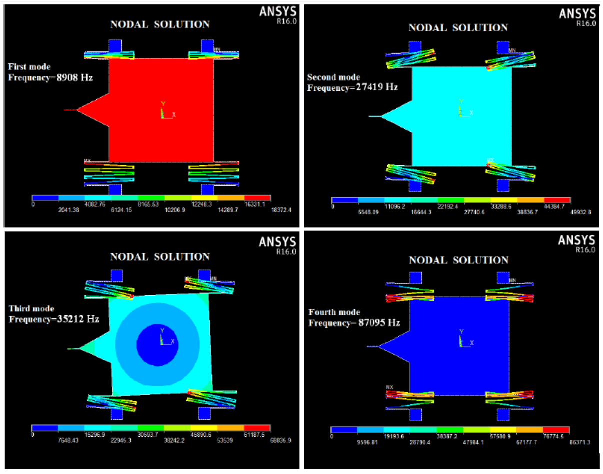

Figure 2: Simulation of the four first resonance modes of the proposed accelerometer with ANSYS.

As shown in Figure 2, first resonance mode of the mechanical resonator is corresponded to displacement of the proof mass in the sensing direction (f_r=8908Hz). Also, Second (f_r=27419Hz) and third (f_r=35212Hz) modes cause the proof mass to rotationally displaced which may lead the device to work in undesired states. Results show that the higher order mechanical resonance frequencies are far from first resonance frequency, considering bandwidth, these mode shapes are not excited on the operating bandwidth of the accelerometer. Thus, in the operating bandwidth of the device the cross axis sensitivity is very small.

Serpentine springs used in the suspension system realize small spring constant with relatively little occupied area and provide more linear mechanical behaviour compared to the simple beam springs [9].

Based on the desired application and chosen physical and geometrical parameters, functional characteristics of the mechanical part of the proposed accelerometer can be derived. Functional characteristics of the mechanical resonator used in this accelerometer are listed in Table 2:.

Table 2: Functional characteristics of the accelerometer.

	Parameter	Simulated with ANSYS
1	Spring constant along sensing axis (y)	$10N/m$

2	Mechanical sensitivity along (y) axis	$3.18nm/g$
3	Spring constant along x axis	$168N/m$
6	Measurement range	$\pm 22g$

3.2 Design and analysis of optical sensing system

The displacement sensing system is the most important component of an accelerometer. Sensing system of the proposed device consists of a tunable one-dimensional PC structure composed of alternating layers of silicon and air with a movable silicon finger attached to the proof mass which can displaced inside of the PC. As shown in Figure 3, a defect introduces in to the structure of this PC which leads to appear a transmitted optical defect mode in the photonic band gap of the PC. In such a structure, small displacements of the movable finger with respect to the fixed grating can significantly shift the transmittance spectrum of the PC as well as the optical defect mode. In Figure 4 transmittance spectra of the PC used in the proposed sensor is shown for five different applied accelerations.

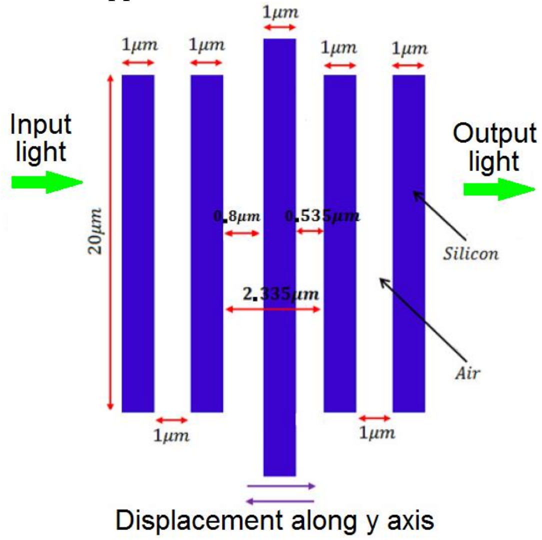

Figure 3: Schematic of the PhC structure used in the proposed device.

While there is not any applied acceleration, the movable finger is placed in the position shown in Figure 3 and thus, the output defect mode appears at the wavelength of $1598.7nm$ (Figure 4, solid line with triangle markers). While an external acceleration is applied along the sensing axis with positive direction $(+y)$, silicon finger attached to the proof mass displaces laterally in the opposite direction $(-y)$ inside of the PC, because of the inertial forces. This can shift the grating transmittance spectrum and its defect mode towards smaller wavelengths (Figure 4, solid curve and solid curve with circle markers). In the other hand, for an applied acceleration along the sensing axis with negative direction $(-y)$, movable finger displaces in the opposite direction $(+y)$ which shift the defect mode towards larger wavelengths (Figure 4, dashed curve and solid curve with square markers). The Magnitude and direction of the external applied acceleration can be then measured by detecting the central wavelength changes of the output defect mode.

Figure 5 shows the FDTD simulation results of the central wavelength of the Transmitted defect mode versus the changes of applied acceleration. It is clear from the Figure 5 that the wavelength shift of the transmitted defect mode is a linear function of the applied external acceleration in the range of -22 to $+22g$. This range can be considered as the operational linear measurement range of the accelerometer.

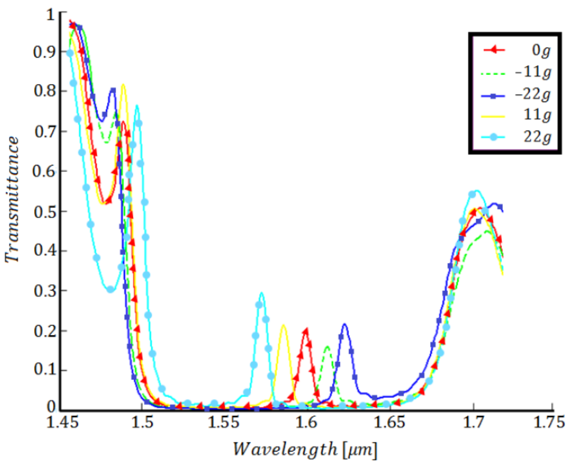

Figure 4: Transmittance of the output defect mode as a function of wavelength for five different values of external applied accelerations.

Note that quality of the proposed sensor can be determined by define a parameter which is called optical sensitivity $(\Delta\lambda/\Delta\alpha)$. This parameter indicates the central wavelength changes of transmitted output defect mode against external applied acceleration. Simulation results show that this so-called optical sensitivity is about $1.17nm/g$ for our proposed accelerometer. As shown in Figure 5, the proposed sensor behaves linearly in the whole measurement range.

4 Conclusion

In this paper, an integrated optical MEMS accelerometer has been proposed. The present sensor, using a one dimensional PC, is based on a wavelength modulation approach. The sensing system of the micro-device includes an air-dielectric multilayer Photonic Band Gap (PBG) material, a typical LD as light source, a photo-diode and integrated optical waveguides. The behaviour of the mechanical structure and optical sensing system has been studied by Finite Element Analysis (FEA) and FDTD simulations.

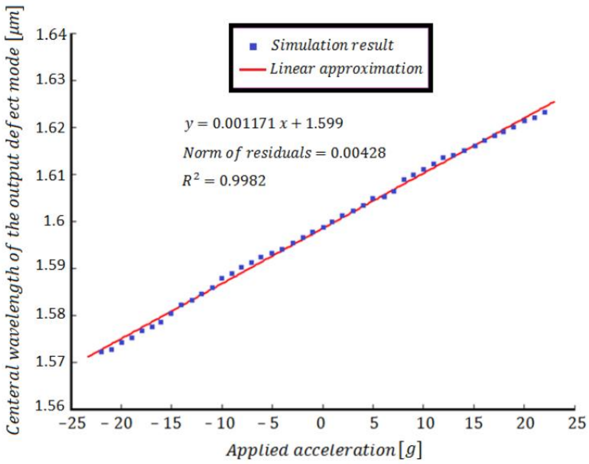

Figure 5: The wavelength variations of the transmitted output defect mode versus the changes of external applied acceleration in the linear measurement range of the sensor ($\pm 22g$).

Simulation results show that the presented accelerometer provides mechanical sensitivity of $3.18nm/g$, an optical sensitivity of $1.17nm/g$, a linear measurement range of -22 to $+22g$ and a resonance frequency of $8908Hz$ and negligible non-linearity in the whole measurement range. The proposed device can be used in various applications such as inertial navigation, thanks to the mentioned functional characteristics.

Fabrication of the proposed MOEMS accelerometer by using Deep Reactive Ion Etching (DRIE) is an ongoing work which can be the subject of a wholly different paper. A low-cost Built-In-Self-Test (BIST) method based on parameter estimation approaches such as those presented in [9], [10], can be also implemented as a future work.

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