Adapting Mach-Zehnder Interferometers for Vibration Sensing

HOSSEIN MAHLOOJI, J. STEWART AITCHISON
and FAE AZHARI

ABSTRACT

Silicon photonic sensors are superior alternatives to traditional electromechanical sensors in applications such as vibration monitoring of data center buildings or real-time seismic wave detection at underwater fiber optic network sites. Because they communicate using optical signals, these sensors can be seamlessly integrated into a data center's existing architecture, or underwater fiber optic networks. Their immunity to electromagnetic field interference and ability to withstand harsh environments also contribute to the suitability of these optical sensors for implementation in the nuclear energy industry and power management facilities.

The Mach-Zehnder Interferometer (MZI) is an optical component that operates based on the constructive and destructive interference of light passing through its two arms. This component is usually used for electro-optical modulation in telecommunication. By allowing one of its arms to vibrate freely on a silicon chip, the MZI can also function as an accelerometer. In an MZI accelerometer, the output light power and free spectral range (FSR) correlate with applied vibration. Only, measuring the output power of an MZI at its optical resonance frequencies and/or measuring its FSR in real-time is a challenging task. We propose two modifications to resolve this issue. The first is to create an imbalance to the MZI by increasing the fixed arm length. The resulting MZI responds to applied vibration through changes in the FSR, which can be easily measured using peak-detection. The second modification involves adding a heater as an optical modulator on the fixed arm. A closed loop feedback controller can then be used to apply enough power (heat) to compensate for the vibration of the free-standing arm. The magnitude of applied power correlates with the acceleration. The proposed modifications to the MZI will enable more straightforward and efficient measurement of acceleration using silicon photonic sensors, making them an even more versatile option for a wider range of applications.

Hossein Mahlooji, University of Toronto, Department of Mechanical & Industrial Engineering, Toronto, Ontario, Canada
J. S. Aitchison, University of Toronto, Department of Electrical and Computer Engineering, Toronto, Ontario, Canada
Fae Azhari, University of Toronto, Department of Mechanical & Industrial Engineering, Toronto, Ontario, Canada

INTRODUCTION AND BACKGROUND

Photonic sensors have seen widespread attention from researchers and industry because of their unique capabilities. They are used in a variety of applications from biomedical [1] to gas detection [2]. Since photonic sensors use light waves to detect stimuli, they are immune to electromagnetic fields and dissipate less heat (by at least an order of magnitude) compared to electrical sensors. They are also much faster than electrical sensors and are biocompatible. Among the many types of photonics structures used for sensing purposes, silicon photonics have been investigated the most due to their compatibility with common complementary metal-oxide semiconductor (CMOS) photolithography fabrication procedures [3].

Although much research has been devoted to stationary photonic sensors, only a limited number of successful mechanical photonic sensors have been developed for dynamic monitoring of movements or acceleration. Krause et al. demonstrated that a photonic crystal nanocavity which is monolithically integrated with a nano tethered proof mass is capable of measuring acceleration at different mechanical frequencies [4]. Other groups have also tried photonic crystals with different shapes [5]–[8]. Even though photonic crystal accelerometers show good performance, their fabrication process is not simple. Zandi et al. used a photolithography procedure to fabricate distributed Bragg reflectors (DBRs) at the end of two waveguides connected to a proof mass [9].The DBRs form a Fabry Perot interferometer (FPI) which is sensitive to the proof mass movements. However, real time interrogation of high bandwidth FPIs is not an easy task. Waveguide grating is also used by some researchers as a vibration sensitive element [10]–[12]. A similar interrogation challenge is present when using waveguide Bragg gratings.

Another optical component that can be used for developing a photonic accelerometer is the Mach-Zehnder Interferometer (MZI). MZIs are common interferometers widely used in telecommunications for signal modulation. A number of MZI-based sensors have previously been implemented by researchers. Rochus et al. [13] used a spiral arm MZI attached to a membrane to detect motion. The MZI developed by Thondagere et al. [14] comprises two diaphragms connected to the MZI arms with each arm containing a Bragg grating. Suzuki et al. [15] designed and fabricated an MZI with one free standing arm connected to a cantilever which supports a proof mass. Nonetheless, all the MZI accelerometers proposed so far involve additional parts which not only make the fabrication more challenging but are also not amenable to real-time measurements of the mechanical signal.

In this work, two simple modifications are proposed for vibration measurement. The first is to fabricate an imbalanced MZI with a free-standing arm. Imbalanced MZIs have free spectral range (FSR) in their output spectra. Vibration is correlated with the FSR in the spectrum and can be measured by any peak-detection-based interrogator. The second method of interrogation involves incorporating a heater on the fixed arm of the MZI and measuring vibration by modulating the heater's power to compensate for the motion.

MZI-BASED VIBRATION SENSORS

In an MZI, incoming light power at the input port is divided into two equal intensities at the first Y-branch. Each output then passes through a straight waveguide and finally both light powers combine at the second Y-branch. If the two arms (waveguides) have exactly equal lengths and similar properties (such as refractive index), the light signals at the end of the two arms will be in phase and make a constructive interference at the Y-branch. Constructive interference means adding up two equally divided power and transmitting a power equal to the input power. However, any change in the attributes of one arm can cause a phase shift in the traveling light inside the waveguide. This phase shift leads to a partial or complete destructive interference at the Y-branch and consequently lower (or potentially zero) power at the output port. A well-known method of imposing this phase shift is to change the length of one of the MZI arms. Modifying the waveguide length changes the number of full wavelengths it can accommodate and results in a phase difference between the two arms. This effect can be harnessed to make the MZI sensitive to mechanical motion by removing the bottom oxide (BOX) layer of the chip and making one arm free to vibrate. Figure 1 shows a schematic of the proposed MZI vibration sensor.

Mechanical Simulation

A finite element model was prepared using ANSYS to study the behavior of the sensor under different mechanical excitation conditions (Figure 2). The simulation predicts the resonance frequencies of the sensor and the maximum deflection of the free-standing waveguide. Four different MZI arm lengths of 2 mm, 4 mm, 6 mm, and 8 mm were considered to cover a wider range of sensitivity to different mechanical frequencies. The waveguide width and height are 500nm and 220nm respectively. Shorter MZI arm lengths were expected to be more sensitive to higher frequencies whereas longer lengths cover lower vibration frequencies. The waveguide elongation was also calculated to determine the phase shift in response to vibration-induced deformations.

Optical Simulation

Modal analyses and finite-deference time-domain (FDTD) analyses were used for the design of waveguides and Y-branches, respectively. MZIs with a directional coupler instead of the Y-branch at the output were also simulated. This configuration adds redundancy to the system by adding an extra output port. ANSY-Lumerical software was used for the optical simulation and design of the sensor. Figure 3 Illustrates the

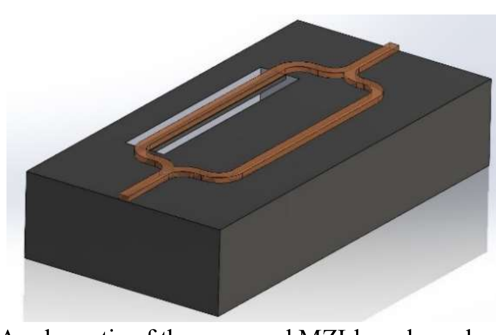

Figure 1. A schematic of the proposed MZI-based accelerometer

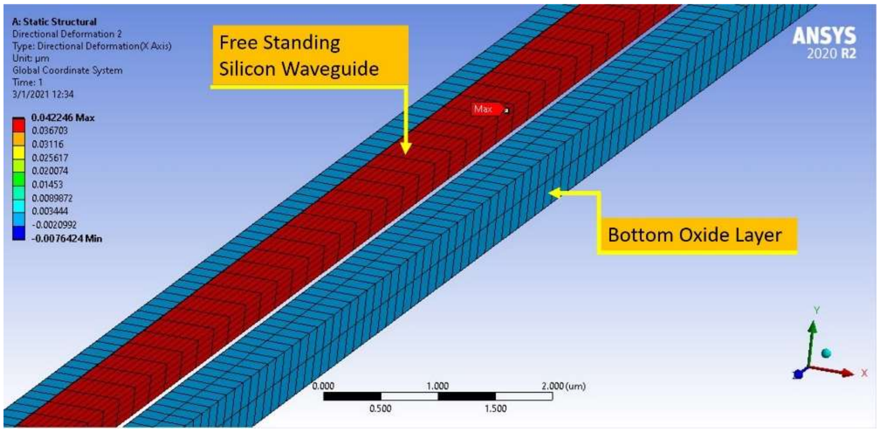

Figure 2. Mechanical FEA model of the free-standing waveguide

power propagation calculated with the FDTD method for a Y-branch and directional coupler. The multimode interferometer part of the Y-branch is optimized using a particle swarm algorithm. The imbalance which is seen in the Y-branch helps to compensate for refractive index changes caused by removing the BOX beneath the free-standing waveguide.

OPTO-ELECTRICAL INTERROGATION OF MZI ACCELEROMETERS

As mentioned earlier, real-time interrogation of optical sensors is a challenging task. The most common technique is to monitor the output power at a certain wavelength. This method requires a tunable laser source which provides a light wave with a single frequency (wavelength). However, tunable light sources are expensive and heavy, and therefore difficult to use in real industrial applications. In this work, we suggest two different methods of interrogation to resolve this issue.

The first method involves using an ordinary peak detection interrogator to measure the FSR of the output spectra of the MZI. The output spectrum does not have FSR in the steady state condition when the two arms are in balance. As vibration is applied and one arm experiences deformation, the resulting imbalance varies the FSR. This variation is demonstrated in Figure 4 for different levels of acceleration. Nevertheless, measuring these spectra and comparing them to determine the acceleration amplitude in real-time is not possible since the fastest available optical spectrum analyzer requires a multiple-second sweep through the entire spectrum. Our solution is to create an imbalance in the MZI by increasing the fixed arm length (Figure 5). The resulting MZI has an FSR at steady state. When we apply vibration, the unbalance between the two arms changes, which results in a different FSR value. Implementing this method makes it practical to measure vibration by monitoring the distance between two peaks (FSR) using a peak-

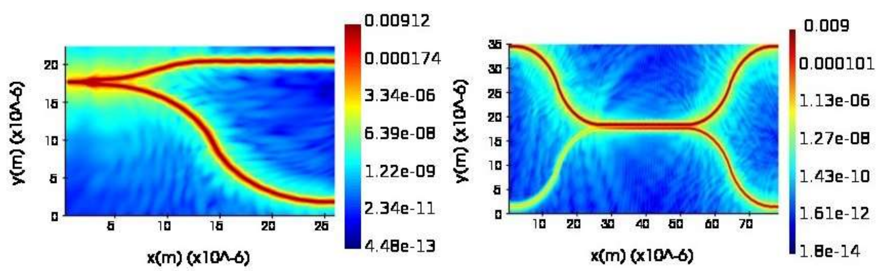

Figure 3. FDTD analyses of Y-branch and directional coupler, intensity of light

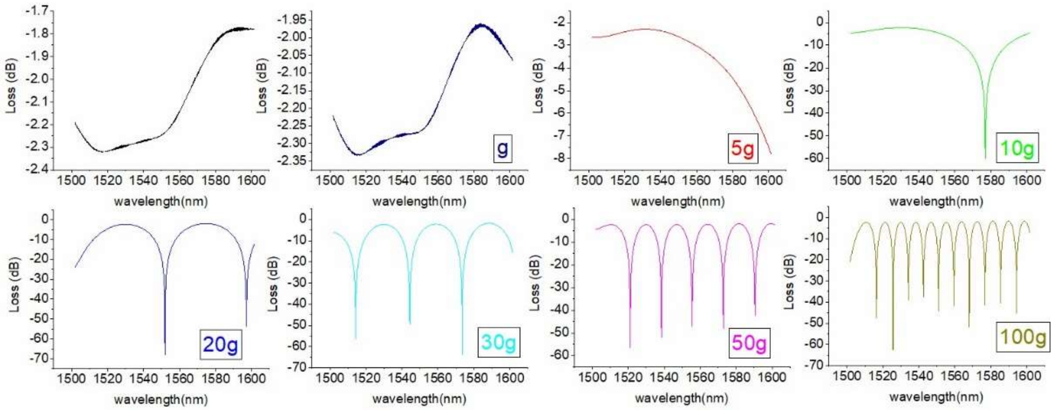

Figure 4. MZI output spectra at different acceleration levels

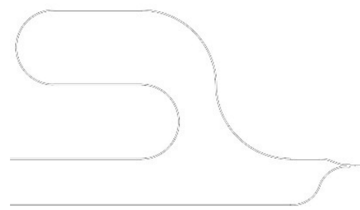
Figure 5. An imbalanced MZI

detection-based interrogator.

The second suggested interrogation method involves adding a thermo-optical modulator on the fixed arm and using a feedback loop controller to keep the output power constant while vibration is applied. In this technique, a photodiode measures the MZI's output power with a high sampling rate. A controller unit, which could be a simple microcontroller, detects and calculates any changes in the power. Then it generates enough voltage to excite the heater which in turn changes the refractive index of the fixed arm to compensate for the deformation in the suspended arm. The compensation takes place in real time at a relatively high speed. The heater voltage is proportional to the deformation of the free-standing arm and can be recorded as a measure of acceleration. Figure 6 depicts a schematic of the proposed interrogation method. Note that the heater must not necessarily be placed on the same chip; it can be implemented on a separate chip at the interrogation station.

SIMULATION RESULTS

Figure 7 shows the mechanical frequency response of a 2 mm arm MZI. The three first fundamental resonance frequencies of this particular sensing element are 50 Hz, 140 Hz, and 550 Hz. Resonance can damage the sensor structure due to excessive

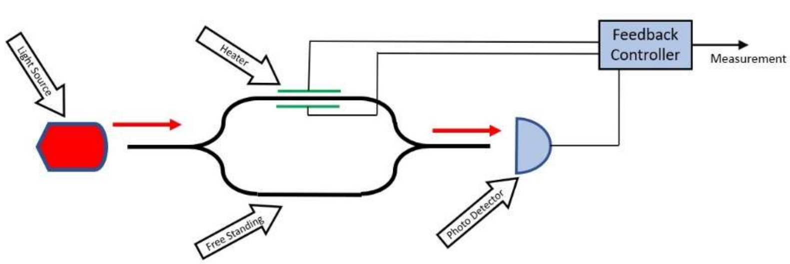

Figure 6. An MZI modified using a heater and feedback controller

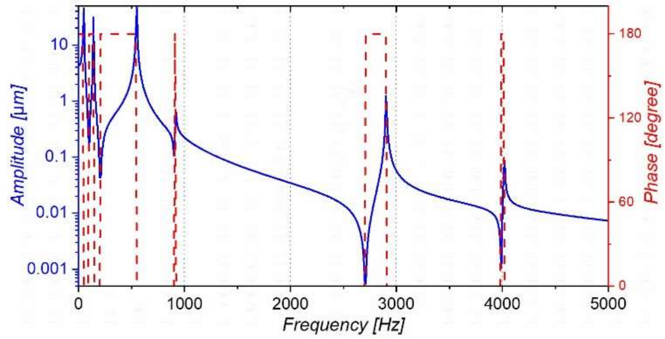

Figure 7. Mechanical frequency response of a 2 mm waveguide

deformation and can cause the sensor to respond nonlinearly. Therefore, the sensor dimensions must be designed in such a way that the first resonance frequencies are avoided. This design procedure paves the way of designing a sensor for any application with specific performance requirement just by tailoring the length of the MZI arm.

FEA was also used to determine the maximum deformations of the suspended waveguide under different levels of acceleration (presented in TABLE I). The total elongation was then used in the optical calculation. As acceleration increases, the waveguide experiences larger deformations, which in turn leads to a larger difference between the lengths of the two arms and a higher change in the MZI's output spectrum used for vibration measurements.

TABLE I. ELONGATION OF THE SUSPENDED WAVEGUIDE

Max. Acceleration [g]	**Deflection [µm]**	**Elongation [µm]**
1	2.543	0.0064
2	5.086	0.0258
5	12.715	0.1616
10	25.43	0.6465
50	127.15	16.1023
100	254.3	63.6554

The outputs of the mechanical FEA model were plugged into ANSYS Lumerical Interconnect to study the optical spectral variation of the MZI due to the applied acceleration. Figure 8 shows the block diagram of the simulated MZI and the resulting spectra at different lengths. Each blue contour in the spectrum shows a peak in the output power of the MZI. As the length of the suspended arm increases due to vibration, more peaks appear in the output spectra. A higher number of peaks means lower FSR. Consequently, when applied acceleration increases the length of the free-standing arm, a lower FSR is observed in the output spectra of the MZI. The results show that, save for frequencies in the vicinity of resonance, the relation between the amplitude of applied vibration and FSR is perfectly linear.

CONCLUSIONS AND FUTURE WORK

The optical component Mach-Zehnder Interferometer (MZI) can function as an accelerometer if one of its arms is allowed to vibrate freely on a silicon chip. In an MZI

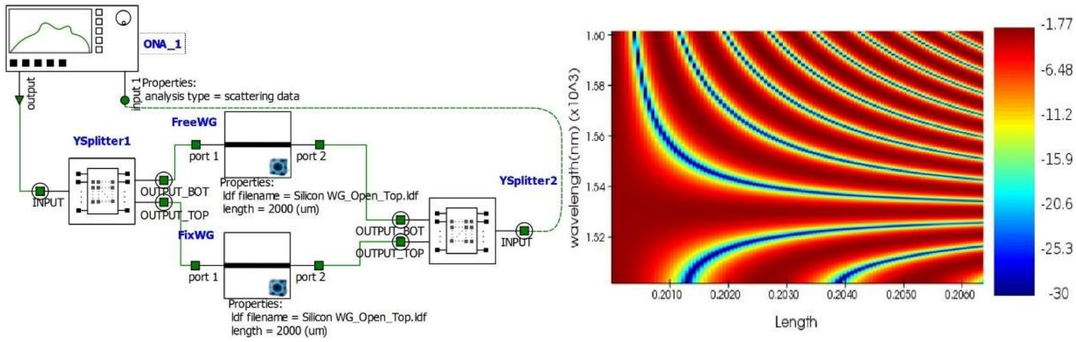

Figure 8. Block diagram of the simulated MZI (left) and the output optical spectrum at different free arm lengths (right)

accelerometer, the output light power and free spectral range (FSR) correlate with applied vibration. The challenge, however, is to measure output power at the MZI's optical resonance frequencies and to determine FSR in real-time. In this work, we proposed two solutions. The first was to increase the length of the fixed arm, effectively creating an imbalanced MZI. Vibration-induced changes in the FSR of the resulting MZI can be measured using peak-detection. The second solution was to modify the MZI by adding a heater on the fixed arm such that a closed loop feedback controller can be used to measure applied vibration based on the power (heat) required to compensate for the vibration of the free-standing arm. The proposed modifications to the MZI were examined numerically. Future research will aim to fabricate MZI-based silicon photonic accelerometers and evaluate their performance in response to a wide range of vibration frequencies.

REFERENCES

[1] C. Dhote, A. Singh, and S. Kumar, "Silicon Photonics Sensors for Biophotonic Applications - A Review," *IEEE Sensors Journal*, vol. 22, no. 19. Institute of Electrical and Electronics Engineers Inc., pp. 18228–18239, Oct. 01, 2022. doi: 10.1109/JSEN.2022.3199663.

[2] D. K. T. Ng *et al.*, "Considerations for an 8-inch Wafer-Level CMOS Compatible AlN Pyroelectric 5-14 μm Wavelength IR Detector towards Miniature Integrated Photonics Gas Sensors," *Journal of Microelectromechanical Systems*, vol. 29, no. 5, pp. 1199–1207, Oct. 2020, doi: 10.1109/JMEMS.2020.3015378.

[3] S. Org/Books, Y. Su, and Y. Zhang, "Passive Silicon Photonic Devices Design, Fabrication, and Testing." [Online]. Available: http://pubs.aip.org/books/book-pdf/9018159/9780735424319.pdf

[4] A. G. Krause, M. Winger, T. D. Blasius, Q. Lin, and O. Painter, "A high-resolution microchip optomechanical accelerometer," *Nat Photonics*, vol. 6, no. 11, pp. 768–772, Nov. 2012, doi: 10.1038/nphoton.2012.245.

[5] E. Soltanian, K. Jafari, and K. Abedi, "A novel differential optical MEMS accelerometer based on intensity modulation, using an optical power splitter," *IEEE Sens J*, vol. 19, no. 24, pp. 12024–12030, Dec. 2019, doi: 10.1109/JSEN.2019.2936752.

[6] X. Lu, J. Y. Lee, and Q. Lin, "Silicon carbide zipper photonic crystal optomechanical cavities," *Appl Phys Lett*, vol. 116, no. 22, p. 221104, Jun. 2020, doi: 10.1063/5.0010078.

[7] M. Hosseinzadeh Sani, H. Saghaei, M. A. Mehranpour, and A. Asgariyan Tabrizi, "A Novel All-Optical Sensor Design Based on a Tunable Resonant Nanocavity in Photonic Crystal Microstructure Applicable in MEMS Accelerometers," *Photonic Sensors*, vol. 11, no. 4, pp. 457–471, Dec. 2021, doi: 10.1007/s13320-020-0607-0.

[8] O. E. Orsel, M. Erdil, and S. Kocaman, "A 2D Slotted Rod Type PhC Cavity Inertial Sensor Design for Impact Sensing," *IEEE J Quantum Electron*, vol. 56, no. 1, Feb. 2020, doi: 10.1109/JQE.2019.2960134.

[9] K. Zandi, J. A. Belanger, and Y. A. Peter, "Design and demonstration of an in-plane silicon-on-insulator optical MEMS fabry-pérot-based accelerometer integrated with channel waveguides," *Journal of Microelectromechanical Systems*, vol. 21, no. 6, pp. 1464–1470, 2012, doi: 10.1109/JMEMS.2012.2211577.

[10] B. Yao, L. Feng, X. Wang, M. Liu, Z. Zhou, and W. Liu, "Design of out-of-plane MOEMS accelerometer with subwavelength gratings," *IEEE Photonics Technology Letters*, vol. 26, no. 10, pp. 1027–1030, May 2014, doi: 10.1109/LPT.2014.2312796.

[11] Q. Lu, J. Bai, K. Wang, P. Chen, W. Fang, and C. Wang, "Single chip-based nano-optomechanical accelerometer based on subwavelength grating pair and rotated serpentine springs," *Sensors (Switzerland)*, vol. 18, no. 7, Jul. 2018, doi: 10.3390/s18072036.

[12] B. Malayappan, N. Krishnaswamy, and P. K. Pattnaik, "Novel high-resolution lateral dual-axis quad-beam optical MEMS accelerometer using waveguide bragg gratings," *Photonics*, vol. 7, no. 3, 2020, doi: 10.3390/PHOTONICS7030049.

[13] IEEE Electronics Packaging Society and Institute of Electrical and Electronics Engineers, *2019 20th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE)*.

[14] C. Thondagere, A. Kaushalram, T. Srinivas, and G. Hegde, "Mathematical modeling of optical MEMS differential pressure sensor using waveguide Bragg gratings embedded in Mach Zehnder interferometer," *Journal of Optics (United Kingdom)*, vol. 20, no. 8, Jul. 2018, doi: 10.1088/2040-8986/aacf2a.

[15] M. Suzuki, T. Takahashi, S. Aoyagi, Y. Amemiya, M. Fukuyama, and S. Yokoyama, "A study of mach-zehnder interferometer type optical modulator applicable to an accelerometer," *Jpn J Appl Phys*, vol. 50, no. 4 PART 2, Apr. 2011, doi: 10.1143/JJAP.50.04DG14.