AN ALL OPTICAL SHOCK SENSOR BASED ON
BUCKLED DOUBLY-CLAMPED SILICON BEAM
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ABSTRACT
In this paper, an all optical shock sensor based on a buckled doubly-clamped silicon beam is demonstrated. A buckled silicon beam is in the middle of two ring resonator and it has two stable positions. The silicon beam encounters a snap-through process upon a shock force, which can be monitored by measuring the resonance wavelength of the ring resonators. During experiment, a 0.15 nm wavelength is observed for a > 50 g shock. It has merits such as fast response, low power consumption and immunity to electromagnetic interference. It can be applied to inertial navigation system and automotive industry.

INTRODUCTION
MEMS shock sensor has attracted numerous attentions due to its distinguished advantages such as low cost, small footprint, high sensitivity. However, most of the shock sensors have complicated structures and hardly compatible with standard ICs process [1-3]. With the advance of optical MEMS devices, an all optical shock sensor shows great potential for all optical devices integration and future all optical sensor and actuator systems. Recently, much progress has been made in the development of Nano-optomechanical Systems (NOMS), which provide a new approach for small footprint and low cost all optical devices [4-7]. In this paper, an all optical shock sensor based on a buckled doubly-clamped silicon beam is demonstrated, while the optical sensing is realized via high Q-factor ring resonators. Compared with traditional shock sensor, the proposed all optical shock sensors have merits such as simple structure, fast response, low power consumption and immunity to electromagnetic interference. It has potential applications in inertial navigation system and automotive industry.

DESIGN AND THEORY
The optical shock sensor consists of two ring resonators, a buckled doubly-clamped beam and a bus waveguide, which is shown in Fig. 1(a). Light is coupled into the two ring resonators through bus waveguide. The ring resonators both have a diameter of 50 µm. They are supported by the rib structure to reduce the propagation loss caused by the release window. There is a 40-µm long silicon beam in-between the two ring resonators, which is released from the substrate and anchored at both sides. The doubly clamped silicon beam is buckled and closer to one of the ring resonators due to the residual stress in the silicon structure layer. There are several arcs in the middle of the silicon beam, which works as sensing element and inertial mass. There is a silicon arc structure close to each ring resonator, the gap between the act and ring resonator can

Figure 1: (a) Schematic of optical shock sensor, (b) illustration of the buckled doubly-clamped beam, and (c) spectrum demonstration of the shock sensor.
influence the resonance condition of the ring resonator. The buckled silicon beam has two stable positions, upon a shock occur, the force can switch the silicon beam from one side (“left”) to the other side (“right”) and change the resonance wavelengths of both ring resonators, as shown in Fig. 1(b). The resonance wavelength of the ring resonator shifts due to the gap change. For instance, when the beam bends toward the right ring resonator, it will cause red shift for right ring resonator and blue shift for left ring resonator. Therefore, the shock can be monitored by observing the resonance wavelength shift or the transmission power of a single wavelength laser, as shown in Fig. 1(c).

\[ F_c = 8\pi^4 \frac{EH}{L} \]  

Once the force is large enough (> \( F_c \)), the silicon beam snaps through the middle position and reaches the other stable position. As a result, the shock forces that are larger than the threshold force can switch the silicon beam between the two stable positions. Figure 2(b) shows the simulated snap-through process of the buckled silicon beam using COMSOL and the critical force is around 3.2 pN.

\[ l_c = \frac{\pi t}{E} \frac{E}{3\sigma_0} \]  

where \( t \) is the beam width, \( E \) is the young’s module of silicon, and \( \sigma_0 \) is the compressive internal stress which is in the range of 10–100 MPa for normal SOI wafer. The critical length for an internal stress of 50 MPa is around 20 \( \mu \)m. Consequently, the 40-\( \mu \)m beam is buckled to one side. It is 200 nm in width, 340 nm in height and the central displacement \( h \) is around 100 nm as show in Fig. 2(a).

The buckled silicon beam has two stable positions, which are termed as “left” and “right”. The force required to move the silicon beam form one stable position (“left”) to another position (“right”) can be estimated from the following equation
layer. After etching, a 2-µm SiO₂ layer is deposited on the structure layers to ensure a low optical loss. A 40-nm Al₂O₃ is deposited and patterned, which is used as the protection film to protect those fixed structures and leave the window area open for suspended structures. Finally, HF vapor selectively undercut the layer in the window area so as to release the movable structures. The silicon beam is bended towards one side due to the residual compress stress.

![Buckled Silicon Beam](image1)

![Ring Resonator](image2)

Figure 4: (a) SEM images of the doubly clamped beam and ring resonators, and (b) zoomed view of the sensing element.

EXPERIMENTS AND DISCUSSIONS

Figure 5 shows the transmission spectra of the shock sensor before and after the shock. The silicon beam is closer to ring 2 with resonance wavelength of 1593.25 nm before shock. After a 50-g shock in the y direction, the “snap-through” of buckled beam happens while the beam is switched to the other stable position. Due to the movement of the buckled beam, the resonance wavelength of ring 2 blue shift while resonance wavelength of ring 1 red shift. The resonance shifts for both rings are approximately the same, which is 0.15 nm. Therefore, the shock status can be monitored by observing the wavelength shift or the power change at resonance wavelength.

![Transmission spectra](image3)

Figure 5: Transmission spectra of shock sensor before and after shock

The structure of silicon beam and middle structures can be modified to have different masses, so that the forces required for snap-through can be varied to meet different requirements for shock measurement.

CONCLUSIONS

In conclusion, an all optical shock sensor is designed, fabricated and experimentally demonstrated. Fabricated with CMOS compatible process, this optical shock sensor can be easily integrated with other photonic devices. A > 50 g shock can switch the buckled doubly-clamped beam from one stable position to another and induce a 15 nm wavelength shift. The opto-mechanical shock sensor can be potentially used at hash environment like in oil industry, or military usage in a complex electromagnetic environment. It also has potential applications such as inertial sensor, optical switch and other opto-mechanical devices.

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