A two-dimensional $f$-$\theta$ micro optical lens scanner with electrostatic comb-drive XY-stage

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Abstract: We report the design, fabrication and electromechanical performance of a newly developed micro electromechanical XY-scanner for micro-optical spatial light modulation using the silicon micromachining technology. A two-dimensional stage is integrated with a silicon micro lens to scan a transmitting infrared light of 1.55-micron-wavelength by the mechanism of the $f$-$\theta$ lens scanner. Mechanical displacement of up to $\pm$10 microns (optical angle of $\pm$0.57 degrees) was obtained with a drive voltage of 30 V; optical simulation has suggested that the scanner can be used to construct a free-space optical crossconnect of 9-input by 9-output port counts.

Keywords: MEMS, 2D optical scanner, micro lens, electrostatic micro actuator, double gimbal XY-stage

Classification: Micro- or nano-electromechanical systems

References

1 Introduction

Microelectromechanical system (MEMS) is an enabling technology to develop advanced devices for optical fiber telecommunication network. Optical cross-connect (OXC) based upon the micromechanical-optics such as mechanically movable mirrors cannot be operated at fast switching speed but usually in the millisecond range; however, it has advantage in terms of extremely high data transmission to enjoy the full bandwidth of optical fibers, because light signals in such system are rerouted in the optical domain without experiencing the bottleneck of the opto-electro or electro-opto conversions. In addition to this, optical MEMS approach in OXC can deliver low optical insertion loss, large inter-channel isolation, and large number of port counts for input and output.

Most MEMS OXC proposed today use micro mirrors for spatially light modulation [1, 2]. Light beams of infrared wavelength are emitted from an optical fiber array, and each of them is collimated through a collimator lens before projected onto a MEMS element, where the beam is spatially scanned. A serious drawback of this optical system is the sub-micron deviation of the fiber position with respect to the collimator position due to the manufacturing error of the fiber arrays. The deviation makes the lateral offset in the collimator optics that causes the angular offset of the traveling light, resulting in the degradation of the entire optics such as extra insertion loss. Therefore, the optics in an OXC cannot be assembled by passive alignment but with the micromanipulator mechanisms of multi-degrees-of-freedom at the penalty of increased module cost.
To propose a cost-effective and agile optical alignment system, we have developed a position adjustable silicon micro lens collimator integrated with a silicon-micromachined XY-stage [3, 4]. The lens can be driven along the XY plane in the lateral directions only (see Figure 1 (a)), such that the optical axis can be finely adjusted to the incoming light. Furthermore, the transmitting light beam can also be spatially scanned for optical switching by the relatively large displacement of the lens, by which a simple architecture of OXC can be designed with smaller number of optical components. Compared with the previously reported models, the latest device in this paper could be operated with lower drive voltage to produce larger mechanical displacement, i.e. larger optical scan angle, thanks to the major upgrade of the electromechanical design.

In this paper, we report the micro mechanical structure, fabrication process, and experimentally obtained electromechanical performance of the newly developed two-dimensional (2D) micro lens scanner.

2 MEMS XY-stage with comb-drive mechanism

Figure 1 (a) illustrates a schematic view of the 2D lens scanner. A plano-convex silicon micro lens is suspended to the inner stage (Stage-A) by the folded-beam suspensions; the stage is driven bi-laterally along the X-direction by the integrated electrostatic comb-drive mechanism [5], which is also made of silicon. The inner stage is suspended by yet another set of folded-beam suspensions, and is driven along the Y-direction by the similar comb-drive mechanism. By placing an optical fiber facet at the focal length of the micro lens, the transmitting infrared beam is first collimated by the lens, and then two-dimensionally scanned in the free-space by the $f\cdot\theta$ lens scanner mechanism. The identical mechanism can be used to receive a collimated beam and to guide into the optical fiber core after adjusting the coupling position of the lens.

The whole movable elements including the lens, the suspensions, and the comb-drive electrodes are made of doped-device silicon of a 30-micron-thick silicon-on-insulator (SOI) wafer, and the back-plate of Stage-A is made in the handle-wafer of the SOI. Electrical isolation between the drive electrodes is made by the insulting buried oxide (BOX) layer of the SOI wafer.

The suspensions are designed to provide mechanical support as well as electrical interconnection to the drive electrodes on the internal stage. The internal comb-drive actuators requires three different electrical levels, namely the earth GND, voltage for the $+X$ electrode, and that for $-X$, while the stage has two sets of folded suspensions on the left- and the right-hand sides. Therefore, one of the suspensions is electrically separated into two parts to provide different voltage levels but mechanically connected on Stage-C, which moves with the suspension, as shown in Figure 1 (b) [6,7].

The benefit of the new design with the nested comb-drive actuators is the extended displacement with low drive voltage. In our previous report [4], we used a silicon suspension in the shape of an “H” with a lens at the
center part, in which the suspension was directly attracted by the nearby electrostatic electrode. However, the displacement was limited to almost 1/3 of the initial electrostatic gap, for the mechanism was governed by the pull-in limit of the parallel-plate actuator. The design also suffered from the trade-off of a parallel-plate electrostatic actuator, where larger displacement implied higher drive voltage. On the other hand, the new design in Figure 1 (a) is free from the trade-off, and is designed to be in a smaller footprint under given conditions such as maximum voltage and expected output displacement [8].

Figure 2 (a) shows the SEM image of the microfabricated 2D lens scanner. The inner stage has a thin silicon lens of a 3.4-micron-sag and a 260-micron-diameter (focal length of 1.0 mm) with four pairs of folded-beam suspensions of 2 microns wide, 500 microns long and 30 microns high. The silicon lens profile was transferred by the isotropic reactive ion etching (RIE) from a thermally reflowed photoresist pattern [4, 9]. The microactuator patterns were made in the SOI layer by the high aspect-ratio DRIE, after which the handle wafer was etched from the backside to make the internal stages. Figure 2 (b) is a close-up view of the electrostatic comb-drive electrodes; each comb finger
Fig. 2. (a) SEM view of 2D micro lens scanner by using double-gimbal comb drive actuator. (b) Close-up view of the comb finger.

is 40 microns long and 1.4 microns wide with a 2.4-micron-gap.

3 Experimental results

Figure 3 (a) plots the micro lens displacement \( x \) as a function of applied voltage \( V \). We also used the same figure to read the scan angle \( \theta \) calculated by using \( \theta = \frac{x}{f} \), where \( f \) is the focal length, 1 mm. A 10-µm-displacement (which was needed for optical switching to the nearest neighborhood fiber coupled over a distance of 20 cm) was obtained within 40 V in both the X and the Y directions; the voltage was almost 1/10 of that of the previously reported device of the same device footprint [4]. The mechanical resonant frequency at the fundamental mode in the X-direction (1.40 kHz) was higher than that in the Y-direction (0.55 kHz), which was thought to be acceptable for OXC applications. We used an infrared camera (Hamamatsu Photonics C2741-03) to observe the beam spot after the silicon lens. The far field beam diameter at a 10 cm distance from the lens was measured to be 0.7 mm.

Figure 3 (b) is a movie showing the micro XY-stage in electrostatic motion. For optical transparency, the device was not metallized but was used as of bare silicon. We used an infrared light of 1.55-micron-wavelength and observed the beam spatially scanned by maximum 1.52 degrees.

4 Conclusions

We have reported electrostatic micro XY-stage mechanism using comb drive actuator to drive micro lens scanner. Thanks to the newly developed double-gimbal structure, we achieved a 10-µm-displacement with an applied voltage of 30 V; this voltage was 1/10 of that of the previously reported device of the same device footprint. In addition, we obtained maximum 26.5-µm-displacement or optical scan angle of 1.52 degrees. Optical simulation suggested that an OXC of \( 3^2 \)-inputs by \( 3^2 \)-outputs could be designed by the current scanner capability. Optical test as an OXC is under investigation now and is to be reported elsewhere.
Fig. 3. (a) Typical electrostatic displacement curve as a function of applied voltage. (b) Movie attached to show the lens in XY-motion.

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