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Integration and Control of a MEMS Optical Phased Array Scanner

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Abstract – The paper presents an integration and control of a surface micromachined optical phased array (OPA) system based on tightly spaced and narrow piston-motion micromirrors. The individually actuated micromirrors are made of polysilicon and metal thin films to realize an electrostatic actuation and a high optical reflectivity. This configuration enables the realization of an electrostatic parallel plate actuator for each gold-coated micromirror (pixel) where the micromirror beam is suspended by actuating springs at both sides. An electrical interconnect line is made of the first polysilicon layer fixed to the substrate through an insulating nitride layer and is routed underneath the corresponding micromirror to fit a tight pitch of the array. The die carrying the OPA device is then connected to a suitable MEMS package through a standard wire bonding process. A test fixture is designed for the OPA device package. This approach allows to obtain a relatively wide field of view, to operate the device at a low actuation voltage, and to reduce complexity of the system design, fabrication, and integration.

***Keywords*:** electrostatic actuation, MEMS packaging, optical phased array, remote sensing, silicon micromirrors.

1. Introduction

The general design goals for remote sensing systems such as LiDAR sensors are to reduce their costs, sizes, weights, and power requirements so that they can be conveniently mounted on autonomous vehicles, without sacrificing the main benefits they can offer. The major limitations of the motorized optomechanical scanners and microelectromechanical systems (MEMS) scanning mirrors lead to the emergence of new technology - optical phased array (OPA) systems [1]. The OPA based scanners can deflect and steer the wavefront of the output laser beam while requiring no or minimum mechanical motions of the reflective elements. Thus, the OPA technology can lead to fast, reliable, compact, and low-cost optical beam steering. Designing an OPA for visible or infrared light wavelengths (usually 532-1550 nm) demands a miniaturized system that consists of phase shifting elements with sizes in the wavelength scale. The limitations are low signal-to-noise ratio (SNR) and control complexity. A silicon MEMS based OPA system consisting of 160 × 160 gratings was recently reported but could not operate all the phase shifters simultaneously due to the pin number limitation of the printed circuit board (PCB) used [2]. The limitations offer both challenges and new opportunities for the development of OPA based scanners capable of wide scan angle, high operating speed, and high scanning resolution for automotive or UAV-borne LiDAR systems.

This paper describes an integration and control technique for an array of electrostatic micro-actuators used in a one-dimensional (1-D) OPA system. A standard wire bonding process is implemented for the individual micro-actuators in order to integrate the OPA device with a suitable package for electrical connectivity. A custom-made test fixture is designed and built for the OPA prototype consisting of individually actuated multiple micromirrors (pixels) in order to establish its individual mirror-pin connectivity. An electrical circuit is introduced for the test fixture to drive the OPA pixels. An experimental assessment of the OPA prototype operated using the electrical interface is described.

2. Materials and Methods

The proposed design utilizes an array of piston-type micromirrors which are made of polysilicon thin-films for optical phase modulation. In order to activate or deactivate the 0th order and 1st order diffracted light beams, the OPA reflective elements are usually required to have an optical path difference (OPD) along the out of the plane to realize an optical phase shift through delaying or advancing the phase of the reflected light waves relative to that of the reflected light waves from their neighbouring unmoved elements (see Figure 1(a)). The out of plane displacements are usually in the sub-wavelength range (<1 μm). Since the light waves from the displaced mirrors travel a total additional distance of 2δ as compared to the other light waves from the adjacent mirror surfaces, the relative phase shift ($\Delta\phi$) of the waves is $(2\pi.2\delta)/\lambda$ [3]. As a result, the relative displacement must be equal to quarter of the laser wavelength ($\delta = \lambda/4$) to make the pairing reflected light waves (traveling normal to the mirror surfaces) to be exactly out of phase (when $\Delta\phi = \pi$ radian or 180º) and cancel each other along the 0th order diffracted beam. At the same time, the same relative phase shift results in the pairing light waves along the 1st order diffracted beam to be in phase. Thus, the relative phase shift leads to activation of the 1st order diffracted beam which can be then used for optical beam steering (see Figure 1(b)).

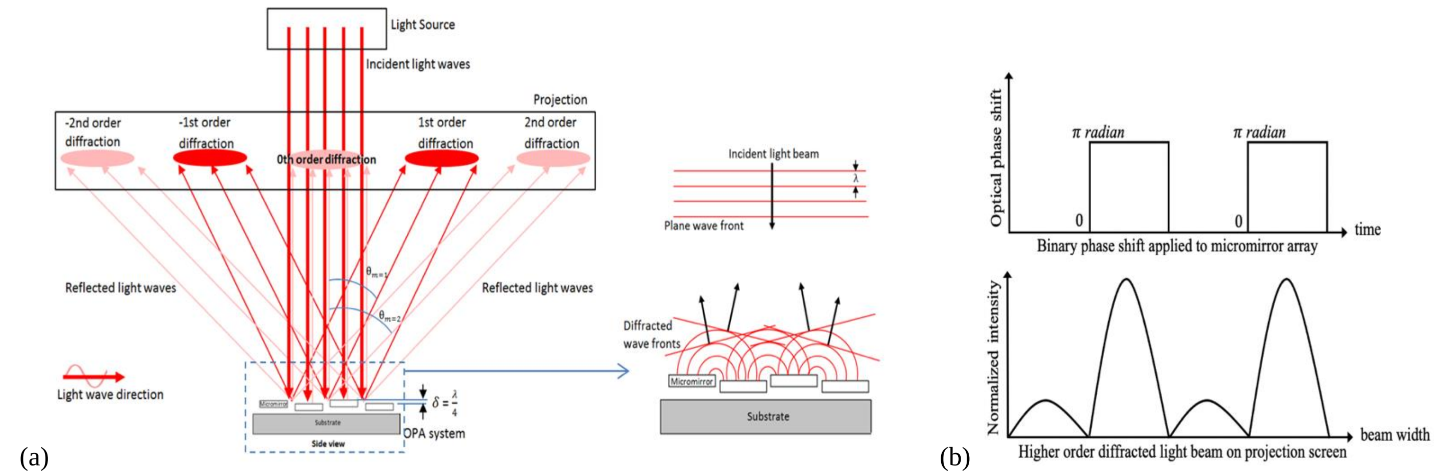


Fig. 1: Schematics of (a) illuminated OPA micromirrors to change the reflective light wave front by setting up interference fields; (b) binary phase shift applied to the OPA micromirrors results in light intensity modulations along a higher order diffracted light beam.

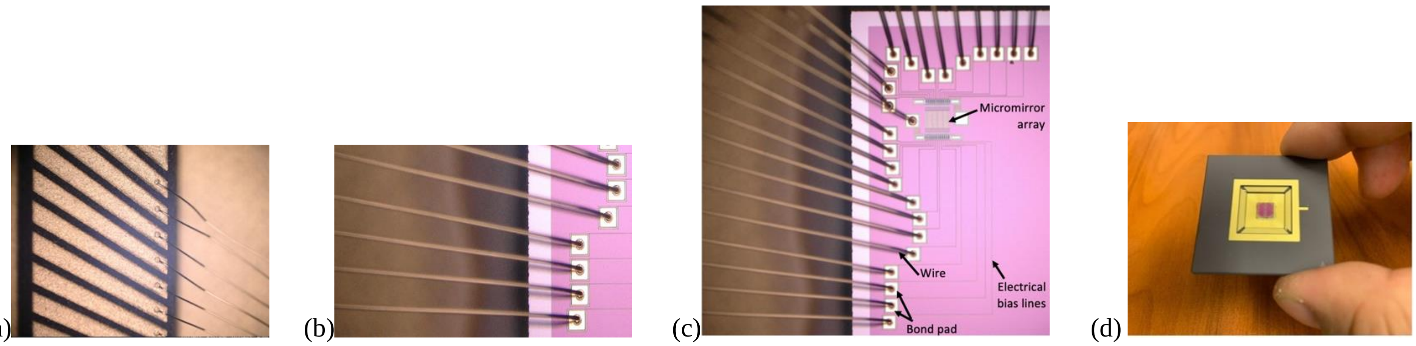
2.1. Design and Fabrication of Micromirror Based Phase Shifters

The diffraction angle of the output laser beam can be defined by Bragg's law [4]. According to the formula, the diffraction angle can be changed by adjusting the laser wavelength and the pitch (average distance between the centres of two neighbouring elements). The width of the planar OPA micromirrors is required to be narrow (4.5 μm) in order to obtain a fine pitch (8 μm) of the array. The mechanical spring width of the suspended micromirrors are also required to be proportionally narrow. For LiDAR applications, a monochromatic laser beam steering is required. Therefore, the laser wavelength cannot be actively modulated. For a given pitch, the scan angle can be modulated by creating various phase shift patterns along the array. By rapidly changing the number of mirrors used per phase shift pattern, the diffraction angle can be changed [5]. A high fill factor (ratio of reflective area to total area) of a micromirror array leads to a high-power output diffracted beam (main lobe) and suppression of unwanted side-lodes [5].

Such fine features and complex structures are realized by using the PolyMUMPs surface micromachining process consisting of three polysilicon thin films. The critical dimension of the process determines the minimum allowable clearance (3.5 μm) and width (4.5 μm) of the micromirror structure in the array. The electrical connections (bias lines) are made of POLY0 layer for the individual micro-actuators. To achieve the electrical connectivity, the standard bond pad configuration commonly used in PolyMUMPs is utilized. The top of the individual bond pads is metal coated to increase the electrical conductivity and the footprint size is 100 μm × 100 μm. Since the POLY0 is used for routing, the ANCHOR1 holes are not enclosed by POLY1 layout in the bond pad configuration. This is to avoid a dissection of the POLY0 line during the POLY1 etch. The Nitride layer between the substrate and the polysilicon interconnect lines acts as an electrical insulation plane. The mirror beams are made of both POLY1 and POLY2 layers stacked together. The mirror springs are made of POLY2 layer. The metal (gold) layer is used to realize a high optical reflectivity of the mirrors. When all the steps are complete, the die consisting of the released structure is cut away from the wafer through dicing.

2.2. Wire Bonding for OPA Micro-actuators

The thermo-sonic ball-stitch bonding process has been utilized for the integration of the free-standing OPA microstructure. Also, the reverse loop shape is implemented to maintain a compact size of the OPA device package (see Figure 2(a). A standard ceramic PGA 144 pin 15×15 has been selected because it consists of a large number of connection pins arranged in a configuration that would be particularly suitable for the OPA prototype with individually actuated multiple micromirrors. In the OPA prototype, all the twenty-four (24) micromirrors are actuated by corresponding separate parallel plate electrostatic micro-actuators. As a result, 24 corresponding electrical interconnect lines are originated from the individual bottom electrodes of the micromirrors, then routed through the individual tunnels and finally connected to the separate large-scale bond pads which are located away from the micromirrors (see Figure 2(b)).

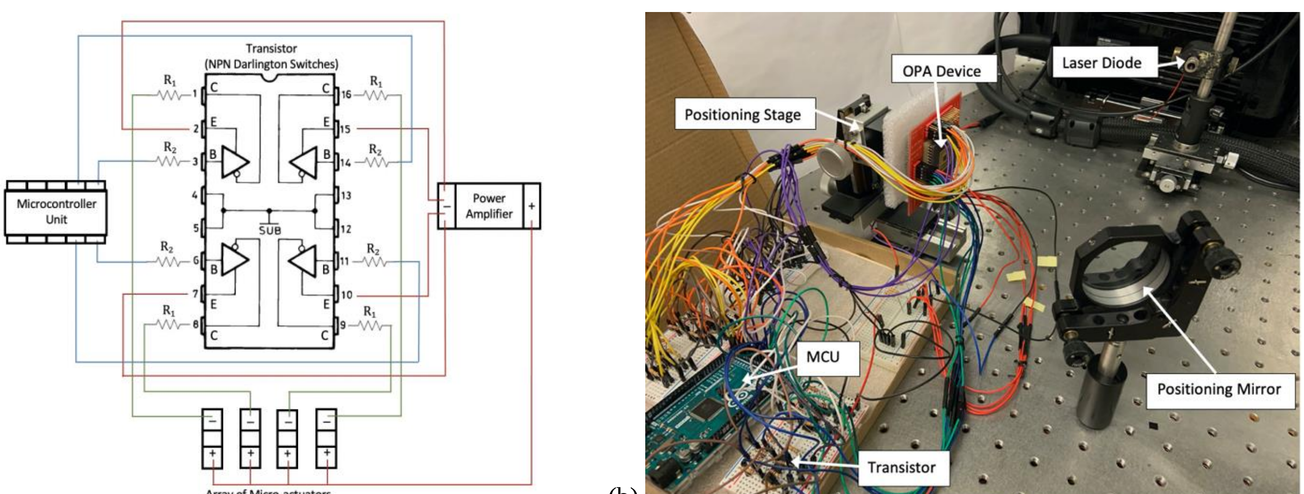


(a) (b) (c) (d)

Fig. 2. Microscopic images of (a) reverse loop wire bonding between the OPA bond pad and the package pad; (b) ball-stitch wire bonding used for bond pads in the OPA; (c) entire OPA device where all micro-actuators are wire-bonded; (d) OPA package.

2.3. Electrical Interface of OPA Device

Wire-bond pads along the left side of the OPA correspond to even-numbered pixels, and wire-bond pads on the top side correspond to odd-numbered pixels (see Figure 2(c)). The size of a single OPA device based on the piston-motion micromirrors including all the electrical bias lines and bond pads is approximately 1.0 mm × 2.0 mm. Since the individual OPA device size is much smaller than the overall die size (4.5 mm × 4.5 mm), a total of four (4) OPA prototypes are fabricated on the same die. Each OPA operates as a stand-alone chip, with independent supply voltages and ground. The OPA package (see Figure 2(d)) is then integrated to a pin adapter and an electrical circuitry to control the mirror (out of plane) positions. The package has a total of 225 pins whereas the single OPA device consists of twenty-five (25) electrical bias lines. Therefore, all the four devices on the same package can be operated simultaneously.



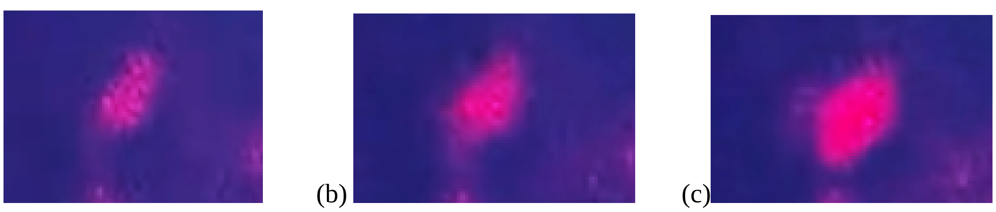
(a) (b)

Fig. 3. (a) Diagram of electrical circuit for controlling the OPA device through MCU and power amplifier or supply; (b) Experimental setup used to generate laser scanning.

A microcontroller unit (MCU) is used to control the OPA micromirrors and to create various binary phase shift patterns. The MCU provides an output voltage of 5V through its output pins. However, the micro-actuators require an input voltage of up to 60V in order to generate a desired range of the mirror motion. The power amplifier does not have enough number of channels to individually drive all the actuators in the OPA prototype. The transistor has four (4) NPN Darlington switches and a single isolated Darlington pinout for each switch. Therefore, at least six (6) transistors are required to individually actuate all the 24 micromirrors in the OPA prototype. The MCU outputs are connected to the transistor base (B) pins (see Figure 3(a)). The collector (C) pins are for load to the individual micro-actuators. The emitter (E) pins are connected to negative end of the power amplifier. The positive end from the power amplifier goes into the positive ends of the actuators whereas the negative ends of the corresponding actuators return into the corresponding pins which are basically the collectors for the isolated switches. Therefore, the load is in between the amplifier and one of the collector pins. Upon the reception of a signal from the MCU, each base pin conducts the corresponding actuator through the collector and then goes out of the emitter to ground. Thus, the amplifier would energize the corresponding actuator load when its respective base is activated and the MCU controls the transistor.

3. Experimental Results

Figure 3(b) shows the experimental setup for evaluating the optical performance by the OPA device. A laser diode is used to project a laser beam with a wavelength of 650 nm. The positioning mirror is used to locate and re-direct the incident laser beam on the reflective surface of the OPA device in the package. Figure 4 shows a variation in the light intensity along a higher order diffracted light beam on the projection due to the phase shift performed by the micromirror motion. Figure 4(a) shows the initial diffracted beam spot or main lobe in an unactuated state of the OPA device. Figure 4(c) shows an increase of light intensity along that diffracted beam spot or lobe during an actuated state where a dc bias voltage of 56 V is applied to every other micromirror. When the amplitude of the micromirror displacement would be equal to a quarter of the laser wavelength, the light intensity becomes maximum along that direction. This is because of the constructive interference occurring between the pairing light waves along the higher order diffraction caused by the optical path difference among the mirrors which would agree with the concept shown in Figure 1(b).



(a) (b) (c)

Fig. 4. Far-field images of (a) higher order diffracted light beam spot from the OPA during unactuated state; (b) the diffracted light with an increased intensity on the same spot during transition in actuated state; (c) the diffracted light with maximum intensity on the same spot due to the actuation.

4. Conclusion

A MEMS based OPA device in silicon is wire-bonded to a ceramic package in order to control it dynamically for laser beam steering. The low power requirement by the OPA prototype allows to use conventional thin wires for the densely packed active phase shifters. The OPA photonic and electrical components are designed to fit within a narrow channel width. The released OPA device is integrated into a standard package through a highly reliable and low-cost wire bonding process. The piston-motion micromirror based OPA device is capable of providing an accurate phase shift to activate the 1st order diffracted light beams.

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