

Advances in Development of MOEMS Devices: A Review

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Abstract

Micro-Opto-Electro-Mechanical Systems (MOEMS) are the combination of Micro-Electro-Mechanical Systems (MEMS) merged with Micro-optics. The precision workings of MEMS, its optical functionality, and fabrication techniques make possible a broad variety of movable and tunable mirrors, filters, and other optical structures. Micro-optics has new features that are widely used in many applications than the classical optics. MOEMS contain movable components that have an effect on an optical signal that is pointed towards the surface of this optical component. In this paper, the focus is on MOEMS mirrors, filters, switches and few applications. Additionally, the emphasis is on finding the important and key issues for identification of scope for further work.

Keywords

Micro-optics, MEMS, MOEMS, Micro-Mirror, Tunable Filters.

Introduction

Recent development in micromachining approaches and processing techniques based on integrated circuits (IC) facilitate the manufacturing of IC-based complex opto-electronic and micro-electromechanical devices. Miniaturization of devices or mechanical elements is an important aspect in development of new technology. In 1993, for the first time, Dr. M. Edward Motamedi officially introduced MOEMS. In early 1990s, a contribution toward development in micro-optics technology was carried out by Rockwell Science Center in association with various research lab and government agencies. In 1992, system were developed with applied micro-optics for industrial applications, optical coupling enhancement using micro lens array [1], development of binary optics micro lens arrays [2], binary optics processing applied to a silicon substrate [3], integration of binary optics micro lens [4,5], beam steering device for communication system [6], coupling of laser to optical fibre [7], and fabrication of Micro lens array in various infrared material using ion milling processing [8].

A micro-opto-electro-mechanical system (MOEMS) is a miniaturized device that measures and manipulates optical signals on actuation of mechanical signals. Over the last decade, it has gained importance for industrial application in terms of sensors or actuators. Recent advances in MOEMS technologies have made optical system more robust and allowed simpler designing. Now-a-days, micro-electro-mechanical systems (MEMS) and MOEMS are applications in consumer, industrial, automotive, avionic, and biomedical fields [9]. MOEMS are optoelectronic nano size devices for generating, modulating, guiding, switching, and detecting optical radiation. The development in new technology will pave way for wider applications of MOEMS devices in the future.

MOEMS devices are array of micro mirrors for image processing, optical switches and tunable filters for optical communication and micro optics (micro lenses). MOEMS based devices have a wide range of industrial applications like sensors, telecommunications, micro-switches, imaging, cameras, and medical devices. MOEMS are fabricated on compact size silicon wafers. They are reliable and stable in operations and have recently shown immense potential and growth. Advantages of optical MEMS are miniaturization, integration and mass production, which create a lot of potential for future research. This paper presents a brief review of literature on the technological development of MOEMS based devices and their applications such as micro-optics, micro mirrors, tunable filters, and micro switches.

Micro Mirrors

Micro mirrors are designed for optical beam scanning and with actuation voltage it results in rotation of mirrors. Repeatability and reliability are important parameters for micro mirrors. It is possible to operate micro mirrors in different modes such as quasi-static (point-to-point), resonant, one axis in quasi and other in resonant.

Light valve (mirror-matrix tube) was specifically developed for projection display and for producing quality images. [10]. Since then significant improvements have been carried out in the area of micro mirrors by introducing new designs and technology. Digital Micro Mirror Devices (DMD) was first introduced by Texas Instruments in 1987, followed by its use in NASA's next generation space telescope with 4M micro mirror developed by Sandia National

Laboratory. Tortschanoff A. et.al. [11] have proposed a compact device for MOEMS mirrors with microcontroller-based driver for position sensing. Characteristics of this device were determined by experimentation, theoretical consideration, and optical simulation. They concluded that close loop control for accurate position feedback could increase the performance of MOEMS mirrors. Viswanatha A. et. al. [12] designed and developed MOEMS based mirror steering of beam system on small size for quick tracking and accurate pointing of transceivers. The authors also focused on turbulent atmospheric conditions using an optical turbulence generator (OTG) chamber where experiments were carried out at varied temperatures and atmospheric conditions. They concluded that a developed system has low frequency response and MOEMS mirrors demonstrate high settling time after a large swing, which can be minimized but it will increase the execution time.

Ciubotariu D. A. [13] focuses on study of Lead Magnesium Niobate – Lead Titanate (PMN-PT) based MOEMS micro mirror actuator. This actuator is used as Reconfigurable Free Space – Micro Optical Bench (RFS-MOB) for controlling the displacement of micro-mirrors. Further finite element simulation is carried out to study the effect of actuator shape on displacement and validates it through experiments. Lenzhofer M. et. al. [14] carried out experimentation to analyze the performance of analog driver circuits for controlling resonant and quasistatic MOEMS mirrors. They concluded that control circuits are better for synchronizing more mirrors and can provide substantial impact in application MOEMS mirrors like compact projection devices.

Lenzhofer M. et. al. [15] developed a high voltage driver box to control six MOEMS mirrors with resonant and quasistatic axes. They also compared the simulation results with real system output and concluded that MOEMS mirrors show robust driving performance. TienN.C. et.al. [16] designed and fabricated movable micro mirrors with on-chip beam-steering devices for positioning and off-chip laser-beam scanning. They observed that micro mirrors are stable under temperature change and vibration. They concluded that this technology can be used for variety of applications such as interferometers, lasers, scanning-laser systems for displays, printers, and bar-code readers. Larry J. Hombeck [17] discussed the current status of the CRT, LCD, and DMD technologies in terms of performance and reliability. The author introduced and tested a new hidden hinge DMD structure where the test results showed a higher optical efficiency and improved contrast ratio.

Micro-optics

New micro optics devices have been developed with the development in technology of micro fabrication processes and new material. Friese C. et.al. [18] in their review elaborated on tunability of micro-optics devices and emphasized on better functionality for the new applications in optical microsystems. They discussed the characteristics of various devices such as Deformable Micro mirrors (overview, structure, material, design, fabrication and performance), Scanning Mirrors (overview, structure, fabrication and performance; Membrane), Micro lenses: Overview, structure, material, fabrication and performance; Liquid Lenses: Overview, Basic requirements, System design, fabrication and performance; Tunable Bragg Mirrors: Principle, Structure, material, fabrication and performance. They look forward to a rapid growth in field of tunable micro-optics and suggest its further exploration.

Hans Zappe [19] in his tutorial focuses on micro-optics materials and fabrication process. He studied materials such as glass, semiconductors, polymers, liquids, dielectrics, and other for micro-optics. He discussed microfabrication technology for micro-optics; photoresist reflow, micro contact printing, and replication. Further, he elaborated on refractive, diffractive, and reflective components. Finally, he briefly discussed about the advances in micro-optics technology, tunable micro-optics, Optofluidics and Nano-optics.

Tunable Filters

Tunable filters are an important type of optical device. Various factors affect the performance of tunable filters such as material, working environment, thermal, and mechanical properties. Boutami S. [20] demonstrated Photonic crystal membrane (PCM) reflectors as a compact, high speed, and low actuation voltage device. He found that the tunable filter has shown a quality factor of resonance up to 1000 (FWHM of 1.5nm around 1.55um), relatively comparable with tunable filters based on two 3-periods-InP/air Bragg stacks. The device was tuned over a 20nm-wavelength range, keeping a FWHM (full-width at half maximum) below 2.5nm. He concluded that the difference between the experimental (1.5nm) and the theoretical (0.5nm) FWHM is due to the bending stresses in PC membrane. Spisser A. [21] designed and developed micromachining techniques for InP/air-gap-based Fabry-Perot filter used for InP-based MOEMS for application in telecommunication. The fabricated filter recorded a FWHM resonant dip close to 0.4 nm, that matched with the wavelength-division-multiplexing (WDM) requirement and tuning range of 62 nm that was achieved with an electrostatic actuation voltage of 14 V. The FWHM is kept below 1 nm over a 40-nm tuning range.

Weidong S. [22] carried out the numerical analysis based on transfer matrix method and deduced effect of phase shift dispersion on reflection near the central wavelength of dielectric reflectors as it is important for the resonant wavelength determination in MEMS-based F-P tunable filter. He concluded that tuning properties of tunable filters is important and significantly depends on optical parameters of reflectors and coating refractive index. He also found that for low interference order, phase shift is considered and for high it can be ignored. Huibing M [23] investigated photonic crystal defects and three different structures were studied for tunable filters. He found that if the structure has two discrete tuning regions then it is not suitable for tunable filter and if the tuning regions are coalescent then it provides better optical tuning linearity for narrow photonic band gap (FWHM is about 2 nm). Simple suspended membrane, an asymmetric Fabry-Perot optical tuning structure is built on photonic crystal. Such structures are able to fabricate by the surface micro machined technique and are driven by the static force.

Unamuno A [24] carried out experimentation evaluation and performance of hybrid optical MEMS-based electro thermally actuated tunable filter for FBG with tuning range of over 870 pm (operating around 1560.61 nm). He observed that the strain and temperature sensitivities for a FBG sensor operating at a 1550-nm wavelength are $1.2/\mu\epsilon$ pm and at $13/0C$ pm it is possible to measure over $725\mu\epsilon$ and $670C$ variations of the FBG. He suggested that it is possible to differentiate Bragg grating sensors of similar central wavelength using time-division multiplexing (TDM). Chee J [25] designed and fabricated MOEMS Fabry-Perot interferometer filter (FPF) devices for Focal plane array (FPA) are for providing hyper spectral filtering for 320×256 $30\text{-}\mu\text{m}$ pitch FPA. He analyzed the behavior of membrane and tested small FPFs devices by providing electrostatic transduction method. He found that membrane validates the maximum deflection of $3 \mu\text{m}$ at 100 V with step increment of tens of nanometer. He suggested few modifications in beam design, manufacturing and assembly of FPF chip to achieve more effective filtering area.

Garrigues M [26] fabricated Fabry-Pérot tunable filters based on a multi-air-gap/InP suspended structure in order to reduce the lateral losses of the cavity without curving the membranes. He observed that the bandwidth (BW) of the experimental response degraded by 20% from the targeted value. Also, the drawback of indirect tuning mechanism of the air cavity length was overcome by a symmetric actuation of both sides of the cavity (using a four-diode doping scheme and an intermediate ohmic contact onto the cavity layer). The tunability was improved considerably by reducing the thicknesses of the InP quarter-wave membranes.

Micro Switches

The MOEMS switches and waveguides are made together on a single crystal silicon wafer. Such on-chip integration avoids complex alignment, cost and space issues associated with manufacturing. Schrenk B. [27] presented fully passive electro-optic 2×2 switches dynamic engine for flexible metro-access network nodes. Experimentation was performed to demonstrate latching MOEMS technology paired with energy scavenging for avoiding the space switching, WDM crosstalk and optical return loss, which in turn provided a way for optical node technology. They demonstrated circuit reconfigurability and latching at feeding levels of 6 dBm and fast consecutive switching within 120 ms. Paterson A. [28] demonstrated simultaneous Q-switching and wavelength tuning of an end-pumped Yb: KGW laser through actuation of a single MOEMS mirror. They achieved wavelength tuning range of 15.4 nm with laser pulse durations between 460 ns and 740 ns at a repetition rate of 2.06 kHz. He concluded that with developments in MOEMS design and optical coating, such laser can be used in applications like range finding, target tracking, and optical gas sensing.

Paterson A. [29] experimentally demonstrated wavelength tunable end-pumped Yb: KGW laser with simultaneous Q-switching using a single MOEMS mirror. He found that continuous tuning range of 22 nm and 15.3 nm was achieved under continuous-wave (CW) and Q-switched operation respectively for an end-pumped Yb: KGW laser. Also, for the range of laser wavelengths a pulse repetition rate of 2.06 kHz was found with pulse widths varying between 460 ns and 740 ns. This technique is applicable in the $2 \mu\text{m}$ range or in the mid-infrared using suitable gain media and coatings on the bulk laser cavity optics.

Applications of MOEMS

The future advancement and areas of application areas are medical, automotive, industrial maintenance and control, Demotic, Space and astronomy, and Environmental monitoring. Hortschitz W. et.al. [30] developed a set up for MOEMS vibration sensors to operate under low frequencies at ambient air without close loop feedback. They suggested that the sensitivity of the sensor can be increased by adjusting stiffness and mass and simultaneously decreasing the resonance frequency to get more bandwidth for displacement sensing. Kainz A. et.al. [31] studied the organic light-emitting diode (OLED) and organic photodiode (OPD) based device with MOEMS chips for vibration sensing and recorded the frequency response. They concluded that the organic optoelectronic can be used in future low-cost fabrication and suggested that reliability and sensitivity are technical issues to be taken care of.

Balasubramanian M. et.al. [32] proposed and simulated the waveguide based SOI MOEMS accelerometer. The change in strain due to acceleration caused period shift of waveguide grating. They also measured sensitivity and resolution and found that Bragg wavelength varies linearly with acceleration.

Challenges

There are several challenges in development of MOEMS devices. Achieving high reflectivity and resolution images from micro mirrors surface is a big challenge. Integration of MOEMS devices with other circuits and CMOS [33] is an additional challenge. Selection of manufacturing process and Packaging is important issue to achieve reliability and stability of MOEMS devices.

Result

This review focused on the identification of various key and important issues related with the MOEMS devices in view of identification of research gap and area of research in related area. Various issues discussed in literature are performance, stability, improvement of efficiency of optical devices and other factors affecting related with time response of MOEMS device. This review particularly aims at mitigating the issues related with above mentioned issues and provide a feasible solution to address these issues. Following are the proposed approach to carry out further research in this area to find the solution.

In medical applications and in seismology as well, High sensitive low frequency MOEMS plays vital role. The feature of working in multiple directions and axis can be utilized in MOEMS accelerometer sensor which helps to improve operating range of sensor. Higher sensitivity feature in MOEMS vibration sensors can be worked out by adjusting the stiffness and mass i.e. mechanical parameters. Moreover it can also gain more bandwidth by decreasing the response frequency which is helpful in displacement sensing. With regards to improved reproducibility and tunability, it is observed that there is an enough scope for development of new materials.

Conclusion

The review presented in this paper focuses on MOEMS devices and few sensor applications. Additionally, the emphasis is also on finding the important and key issues for identification of further scope for research. Followings are the few issues identified after reviewing the literature:

1. The performance of MOEMS mirrors can be enhanced by close loop control for accurate position feedback. It will improve the applicability and increase the performance.
2. The key issues are low frequency response and high settling time after a large swing along synchronization of more mirrors.
3. Close loop control for better synchronization of more mirrors can provide better impact in applications of MOEMS mirrors like compact projection devices. MOEMS mirrors show higher settling time, but the driver execution time also increases.
4. Advances in fabrication technology can achieve $\lambda/2$ displacement for lower voltage. Driver circuit is important to drive all resonant axes and also for all MOEMS mirror devices.
5. Movable micro mirrors based on polysilicon micro hinge technology can be used for variety of applications with low-cost, batch-assembled, high-performance optoelectronic systems. Higher optical efficiency and improved contrast ratio can be achieved using hidden hinge DMD structure.

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