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MEMS Technology for Optical Switching

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Abstract

Over the last ten years, microelectromechanical systems (MEMS) devices have received attention in many application areas such microwave, wireless, and optical networks. Especially in optical networks, MEMS technology is employed to provide the advantages of large switch matrix size with low loss at an optimum cost [1,2]. Therefore, optical switches based MEMS technology are now widely used and are considered a good option for optical switching networks. Moreover, they also provide wavelength insensitivity, polarization insensitivity, scalability, and very low crosstalk [3-5]. MEMS optical switches provide fast switching speeds ranging from milliseconds to several hundred microseconds. In this article, MEMS-based optical switches are reviewed including their advantages and disadvantages.

Keywords: Microelectromechanical systems (MEMS), 2 dimensional MEMS (2D MEMS), 3 dimensional MEMS (3D MEMS), optical crossconnect (OXC), scalability

Introduction

MEMS are very small devices with a unit in the order of micrometers. They are generally made from silicon substrates by means of manufacturing process. Therefore, several MEMS devices can be produced using only one silicon substrate. The size of the devices is in the order of micrometers up to millimeters. For optical switches based MEMS technology, the positions of the mirrors determine the switching function of the switches. These positions can be changed by moving the mirrors [1,6,7]. Electrostatic or electromagnetic forces are used to alter the positions of these mirrors [8]. This indicates that the optical (or light) signals can travel from one place to another by deflection off the mirrors.

MEMS-based optical switches

This switch is one type of the mechanical switch called an "optomechanical switch" [6]. MEMS optical switches offer many advantages (such as scalability, insensitivities of wavelength and polarization, etc.) and hence, they provide various attractions in many areas, for example, research work, enterprise and manufacturing in telecommunication field. According to the fundamental operation mentioned in the previous section, MEMS-based optical switches can be categorized into three groups. These are MEMS optical switches based on micromirrors [1], membranes and planar moving waveguides [4]. The first two groups are called "free space switches" because of the use of free space as a guiding media [3,4]. The last one is a waveguide switch, which requires moving some parts of the switch once functioning [3,9-12]. The majority of the MEMS switches for optical switching are based on micromirrors [3], which can be categorized into two approaches, namely, 2D MEMS and 3D MEMS.

MEMS-based micromirrors switches

2D MEMS optical switches

There are two states for the positions of 2D MEMS optical switches. These are "ON" and "OFF" states. Thus, the switching function can simply be determined by these states. Several

features are employed in optical switching networks such as optical crossconnect (OXC), wavelength selective devices, optical add-drop multiplexing (OADM) devices, and protective devices [13], utilizing a MEMS-based optical switch technology as a vital key in order to provide reliability, flexibility, and survivability of the network. An example of a 2D MEMS switch is provided in **Figure 1** [1] (more details of 2D MEMS switch structures can be found in [8]). A 2D MEMS-based switch diagram using a crossbar configuration in **Figure 1** [1] has four input- and four output-ports and several deflecting-mirrors (micromirrors) for various achievements of the crossconnect in the MEMS-based optical switch. Once the switch is in the "ON" state, light beams, which pass through the input ports, will travel along the switch plane and deflect off the operated mirrors in order to change their direction and arrive at the destination port. However, if the switch is in the "OFF" state, light beams will pass through the switch plane and arrive at the output ports without deflecting on the mirrors. The switch in this configuration can transmit and receive multiple signals simultaneously. Moreover, during transmission, some of the transmitted signals can be ignored at the drop ports and new input signals can be transmitted at the add ports. This type of the operation of the switch is called "optical add-drop multiplexing (OADM)" [6]. However, the signal loss is increased with the distance or link length (and also the size of the switch matrix). Therefore, compromises between these parameters have to be made in a 2D MEMS-based optical switch.

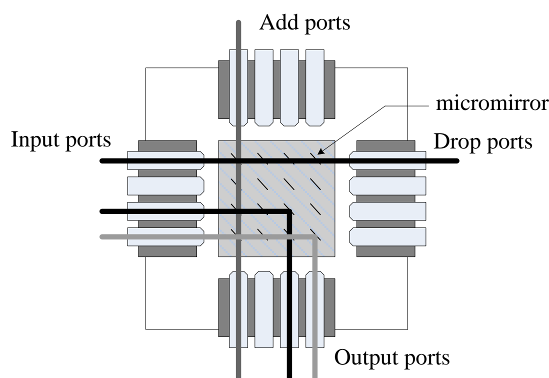

Figure 1 A diagram of 2D MEMS-based optical switch using a crossbar configuration [1].

Various 2D MEMS-based optical switches have been demonstrated. In 1996, Toshiyoshi and Fujita [14] developed an optical switch matrix of port size 2 utilizing silicon micromachining techniques. This switch is a new improvement for micromechanical switches employing micro torsion mirrors, which operate by applying electrostatic force, to deflect light in a free space. Small insertion loss (≤ −7.66 dB), small crosstalk (≤ −60 dB), and large switching contrast (≥ 60 dB) are achieved [14]. However, a long switching speed of 5 ms is recorded [14] due to a restriction of a settling time of the micro torsion mirrors [15]. A problem of reliability in this type of switch is also found when the switch has to remain at the same position for long time [15].

In 1997, Lee *et al.* [16,17] proposed the same size of optical switch matrix of port size 2 using MEMS technology, however, with different fabrication techniques. The first one [16] employs a surface-micromachining technique whereas the second one [17] uses a deep anisotropic reactive ion etching. In [16], the structure employs a bypass switch in order to provide a backup link for the ring network. A vibration test is also performed error free [16]. The switching times for the switch are 6 ms and 15 ms for rise and fall times [16], respectively. In [17], a structure of vertical mirrors is obtained with low signal loss (0.6 - 1.6 dB for "OFF" state and 1.4 - 3.5 dB for "ON" state) and small switching time (< 0.2 ms). Later on [18], the same group of authors in [17] illustrates a

completed version of the same switch matrix size using the same technique as in [17]. This time the signal loss is lower than 1 dB and 2 dB for "OFF" state and "ON" state [18], respectively. The switching speed is less than 1 ms [18].

In 1998, a MEMS optical switch called "free-space micromachined optical switch (FS-MOS)" was illustrated [15]. The switch matrix of port size 2 employs a structure of free-rotating hinged micromirrors in order to provide fast switching speeds (< 700 μs) and a large size switch matrix. This results in low crosstalk (< 60dB), a large extinction ratio (> 60 dB), and an open and clear eye diagram while ignoring polarization dependent loss (PDL) [15].

In 2000, Hagalin *et al.* [19] also proposed the same type of switch FS-MOS as in [15]. However, the size of the switch matrix is 4×4 and uses a different structure. [19] utilized a pair of micromirror arrays to deflect the directions of light in the free-space. The switch provides low insertion loss (−4.2 dB) and low crosstalk (−50.5 dB). The structure of this switch also supports large switch matrix size up to $N = 32$ as well as wavelength multiplexing with only a slight change in the insertion loss [19].

In 2002, Fan *et al.* [20] presented a 2D MEMS switch matrix of port size 16 using a crossbar configuration (as shown in **Figure 1**). As the size of the switch matrix is increased and thus the propagation path and switching time (12 ms) also increase. The other parameters such as insertion loss (< 6 dB), crosstalk (<−50 dB), PDL (< 0.4 dB), are achieved with good results [20]. A signal loss due to a beam divergence is also increased with the size of switch matrix (or the number of mirrors) [21-24]. Therefore, the size of the switches matrix for 2D MEMS-based technology is restricted to a maximum of $N = 32$ in order to reduce all these problems [21].

In 2003, Li *et al.* [25] demonstrated a 2D MEMS-based switch technology utilizing Spanke-Benes and Benes network structures to improve the signal loss in [20]. This implies that the structure also allows increasing of the switch matrix size. However, concave mirrors are required in this structure to improve the signal loss. This is more expensive and there is a difficulty in making the devices [21].

In 2004, Ma and Kuo [22] proposed a 2D MEMS-based switch technology for large port size. The switch combines several stages of Benes structure, employs the shuffle rule for connecting among the stages, and is called a Shuffle-Benes structure. Therefore, using the proposed switch, several advantages of decreasing signal loss, reducing the mirrors and substrates sizes, increasing the repeatability are obtained. The performance of the proposed switch is better than the one provided by the crossbar configuration switch [22].

In 2007, Basha *et al.* [26] presented a 2D MEMS-based switching technology which uses micromotor mirrors to provide a large port size up to N ports. Low insertion loss (1.04 dB) and maximum switching time of 24 ms are obtained. The advantage of the structure is to provide a wide range of rotating mirrors and thus a very good repeatability is also achieved.

In 2008, a combination of several stages using a Spanke-Benes structure was proposed for 2D MEMS-based switches and the performance comparisons among various structures of crossbar, L-switching, and Shuffle-Benes and Spanke-Benes were evaluated [21]. The connections among various stages are completed according to the proposed conditions in [21]. The performance evaluations reveal that the proposed structure provides the best results (such as signal loss, link length, repeatability, etc.) compared with the other structures.

In 2009, Yang and Liao [27] demonstrated a 2D MEMS-based switch matrix of port size 4 utilizing a one-step anisotropic etching process and a bistable mini-actuator array. The proposed structure provides better results than the one in [19]. Several advantages such as low power consumption, low cost and easy alignment [27] are achieved by the structure. Later on (mid of the year), the same research group as in [28] presented a 2D MEMS-based switch matrix of port size 2 using double-sided coated mirrors and two stages of alignments. This technique is different from other 2D MEMS-based switches of the same size, which use only one-sided coated mirrors for reflection. This coated metal is extremely thin to improve the reflection of the light beams. A mechanical relay is used to operate the mirrors. The testing results indicate that the insertion loss is very small (< 0.6 dB) compared with other switches of the same type and size. The advantages of the approach are the two stages of alignments, which provide very precise alignment, and double-

sided coated mirrors, which reduce the size and number of mirrors. However, the process of producing double-sided coated mirrors is rather complicated.

In 2010, Chia *et al.* [29], the same research group as in [27,28], proposed a 2D MEMS-based switch employing a split cross-bar (SCB) design and a bistable solenoid-based actuator. In the proposed technique, the propagating signal is done via the SCB and therefore double-sided coated mirrors are not necessary. Moreover, the proposed actuator provides a reliable actuation and reduces the device energy usage.

In 2011, Li *et al.* [30] illustrated a 2D MEMS-based switch of 1-input and 4-outputs for wavelength switching device or wavelength-selective switch (WSS). The approach uses a polarization-independent transmission grating together with a fill-factor micromirror array to improve the polarization dependent loss (PDL) and to select ports for the signals. The proposed approach provides low PDL (< 0.4 dB) and does not require any new devices for handling this part.

3D MEMS optical switches

In 3D MEMS-based optical switches, once light beams enter the input ports, they will be deflected on the two freely moving mirrors to arrive at the destination ports. An example of a 3D MEMS switch is shown in **Figure 2** [1] (more details of 3D MEMS switch structures can be found in [8]). This indicates that the links of propagating signals are created by two moving mirrors. Therefore, various propagating links are generated in order to support a large number of input and output ports (> 1000 ports) for improving the scalability of the OXC [1,8]. Nevertheless, there is a difficulty in terms of controlling the positions of the mirrors, and thus the insertion loss, when there is an external disturbance. Therefore, a complicated circuitry, called a feedback system, is required to solve this problem [1]. This implies that there is an extra cost in the design of this circuit.

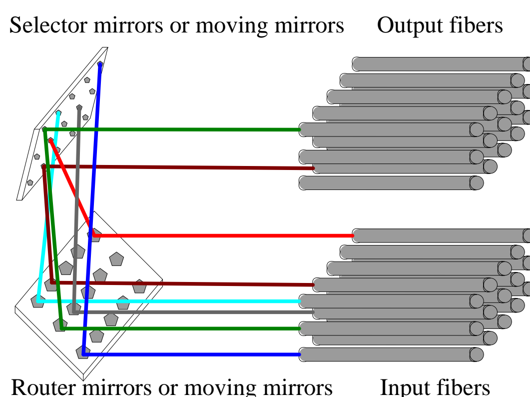

Figure 2 A diagram of a 3D MEMS-based optical switch [1].

Several 3D MEMS-based switches are reported [31-38]. In 2001, a 3D MEMS-based switch matrix of port size 112 was demonstrated [31]. The approach uses a beam steering configuration, which contains a 2D MEMS mirrors array, an integrated fiber array and collimating microlens array, and a fold mirror [31], to complete all connections in the switch. The test results show that all connections are obtained as well as a very high combination data rate (35.8 Tb/s) using this MEMS switch. The other parameters insertion loss, crosstalk, and switching time are 7.5 ± 2.5 dB (at 1550 nm range), < −50 dB, and < 10 ms [31], respectively. The advantage of the approach is the number of mirrors is reduced to 2*N* in order to provide the scalability for large port size compared with other 2D MEMS-based switches.

In 2001, Ryf *et al.* [32], the same research group as in [31], reported a 3D MEMS-based

switch matrix of port size 1296 using the same configuration as in [31]. However, the difference is that the 2D MEMS mirror arrays were replaced with two integrated 1296-MEMS single crystal silicon mirror arrays [31]. The measured insertion loss and typical switching time were 5.1 ± 1.1 dB and 5 ms [32], respectively. This proposed switch, once fully operated and using the Dense Wavelength Division Multiplexing (DWDM) technique, can handle a very high capacity up to a few Petabit rate for transmitting data. This indicates that this switch configuration provides a better performance than the one proposed in [31].

In 2003, Kozhevnikov *et al.* [33-38] demonstrated and evaluated the performance of large port size for 3D MEMS-based switch. [33] presented a 3D MEMS based switch using surface micromachined mirrors that supports a port size up to 64 with low insertion loss (1.9 dB). Zheng *et al.* [34] reported the design structure (for port sizes 256 and 347), which allows transparency and modularity, for the photonic crossconnect (PXC). The structure consists of 3 parts. These are the 3D MEMS optical core switch, 2 × 2 protection switches, and the splitter for observing the power [34]. The testing results revealed that a low insertion loss (1.4 dB), low PDL (0.1 dB), and low wavelength dependent loss (1.5 dB) are obtained at the core switch [34]. With the proposed structure, any devices can be added for new functioning (such as monitoring, regeneration, wavelength multiplexing and demultiplexing, etc. [34]) without modifying the core switch part. Later on (2005), Kaman *et al.* [35] reported experimental results using this switch. The experiment is based on passing a data stream in and out of the switch for 60 rounds. A low power loss (1.7 dB) was measured. The switch was also shown to be a good wavelength selective switch (WSPXC).

In Aksyuk *et al.* [36], the proposed switch structure (port size 238) used surface micromachined mirrors and Fourier lens to improve loss of the switch. By using this lens, the moving angle of the mirrors and the beam diameter can be decreased and thus loss can be minimized. An excellent result was obtained for the insertion loss (2 dB maximum) of all possible connections. Later on, in [37], the same research group as in [36], further evaluates the functionalities of the same structure of mirrors array for large scale OXCs (for port sizes 256 and 1024). Excellent testing results of the optical properties (such as fast switching test, moving angle, insertion loss, etc.) were obtained. Finally, Kim *et al.* [38] reports a large scale of 3D MEMS-based switch (with greater than 1000 ports) using this structure. The mean and the worst values of insertion losses are 2.1 dB and 4 dB [38], respectively. However, Aksyuk *et al.* [36-38] do not indicate the maximum number of connected ports which can be linked at the same time.

In 2009, Mizukami *et al.* [39] demonstrated a 3D MEMS-based switch matrix of port size 128 with all ports capable of being connected at the same time. The switch worked without problems from temperatures of −5 to 50 °C. The mean and maximum insertion losses are 2.6 dB and < 4.8 dB, respectively.

It can be observed that, for 3D MEMS-based switches, the insertion loss doesn't increase with the number of ports and therefore loss is not the main problem. However, stability, reliability, and cost are the primary concerned and need to be improved [22,25,40,41].

Membranes and planar moving waveguide [3] (MEMS-based waveguide switch)

A waveguide switch is shown in **Figure 3** [3]. The operation is based on deflecting the cantilever beam by applying a voltage on a pair of electrodes, which can be either connected to U1 or U2 as shown in **Figure 3**, and thus an electrostatic force is generated to move or deflect this part. This indicates that the position of the cantilever beam is changed and the waveguide switch is now selecting the output. By applying a voltage to a different pair of electrodes, the operation of the switch is altered to a different state. The function of the switch is operated via deflection of the cantilever beam in order to change/select the light path. This is different from 2D MEMS and 3D MEMS optical switches, which employ deflection of light via mirrors for selecting the light path. Therefore, losses from PDL and wavelength sensitivity can be reduced. [42,43] proposed the same waveguide switch using different materials. The advantage of the method is that the proposed structures require a low voltage (< 50 V) to operate the switch.

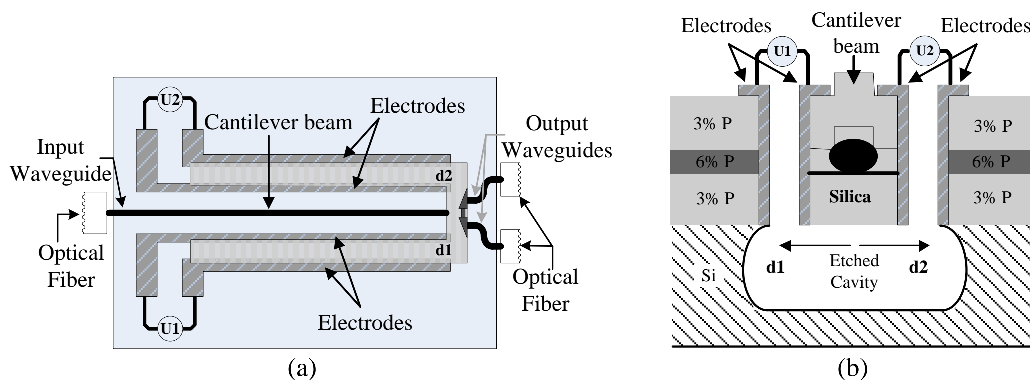

Figure 3 A diagram of a MEMS-based waveguide switch (a) top view and (b) cross-section view [3].

Two technologies based on planar moving waveguides have been introduced, namely, the integration of planar lightwave circuits (PLCs) and MEMS [44], and the MEMS-based photonic crystal [44]. In 2004, Marom *et al.* [45,46] proposed the switches based on the first technology. The structure is combined into one chip using a monolithic integrated method to allow several wavelength functions to be performed. Marom *et al.* [45] illustrated a switch with 1-input and 3-outputs as a wavelength selective switch (WSS). It was a combination of free-space and PLC structure. The testing result revealed an insertion loss of 5 - 6.8 dB [45]. Chi *et al.* [46] also proposed a hybrid free-space and PLC waveguide switch (1-input and 8-outputs) as in [45], however, with different structures and coupling methods. An insertion loss and operating voltage of 6.3 dB and < 8 V are obtained [46], respectively. Clouet *et al.* [47,48] demonstrated the utilization of WSS with good results in [47] and high insertion loss in [48]. In 2006, Kozhevnikov *et al.* [49] presents the integrated array structure, which allows the scalability up to 1×*N* switches. Several compact switches are connected using a cylindrical lens. A low insertion loss is obtained (average of 2.5 dB). This structure can also be employed in the WDM application.

Iwamoto *et al.* [50-52] illustrated a switch based on the second technology (MEMS-based photonic crystal) in 2005, 2006 and 2009, respectively. The structure is based on resonance theory to allow high reflectivity in the waveguide. Iwamoto *et al.* [50] revealed the first experimental result based on this type of switch with rather poor performance (extinction ratio around 10 dB) compared with the other types of the MEMS-based switch. Lee *et al.* [51] reported a performance of a different structure using a 1D photonic crystal with MEMS actuators. The testing result (extinction ratio of 11 dB and the switching time of 0.5 ms) is slightly better than in [50]. Later on, [52] reported the features of 2D photonic crystal switches.

Recently, Cai *et al.* [53] presented an optical switch based on nanotechnology called a nano-optical switch. The structure contains a double-ring resonator and two bus waveguides. A good result of fast switching time in the order of nano seconds with an improve extinction ratio is found.

Conclusions

This article reviews recent research on MEMS-based devices technology employing an optical switching network. It is categorized into 2D (digital) MEMS, 3D (analog) MEMS, membranes and planar moving waveguides, and recent MEMS technology. For MEMS-based optical switches the following conclusions can be drawn:

For 2D MEMS switches, a $N \times N$ switch requires a total number of N^2 mirrors. The number of ports can be increased by cascading of the switches. Consequently, the distance of the input port to the output port is increased and not constant. Hence, the insertion loss is also rapidly increased and non-uniform. This is due to a non-uniform shape of Gaussian beams propagations. Therefore, 2D MEMS switches are not suitable for large port size ($N > 32$) because of high insertion loss.

3D MEMS switches, provide the most recommended technology for very large switch matrices for OXC, because this approach provides very large scalability (> 1,000 ports), small size, low lost, and low power consumption [54]. However, the position of mirrors is unstable to the surrounding disturbance. Hence, a feedback system is needed to stabilize the positions of the mirrors. Nonetheless, it also increases the cost of the switch. This implies that stability, reliability, and cost are the main problems for 3D MEMS-based switches.

For membranes and planar moving waveguides switches, the operation of the switches relies on the deflection of the cantilever beam employing an electrostatic force to select the output waveguide. Consequently, the sensitivities of wavelength and polarization can be controlled with a proper design of the switch. The disadvantage of this type of switch is that it is sensitive to external disturbance such as shaking or vibration. Moreover, the structure of the switch does not support large port sizes (scalability).

MEMS-based photonic crystal switches are still in the primitive stage and need to be developed and improved in order to realize many kinds of functional photonic crystal devices.

A new technology of nano-mechanical optical switch has been proposed. The approach provides a very promising technology for fast switching speed for optical network with several advantages. However, it is in the early stages of development and needs to be improved and developed in order to realize various functions of this switch.

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