Proceedings of ICCT2003

Two Novel 2x2 Models for MEMS-Based Optical Switches

LUO Tie
National Lab of Switching Technology and Telecom Networks
Beijing University of Posts and Telecommunications
Beijing, P.R. China
luotie@glorisoft.com

Abstract—**The next generation all-optical IP network is calling for optical switching, among all implemental technologies of which optical MEMS seems to be the most promising candidate. However, the road leading to the pure optical world is not so smooth; complexity, reliability and scalability are among the most threatening challenges. This paper proposes two novel models for designing 2x2 MEMS-based optical switches, which surmount the obstacles with distinguishing features respectively. Optimizing the overall performance of optical switches, they are anticipated to play critical roles in the future all-optical networks and make those cost-effective optical switches eminent on the communications arena.**

Keywords—optical switch; MEMS; MES; double-sided, micromirror, microlens

I. INTRODUCTION

During the last few decades, the explosion of Internet traffic has dramatically expedited the network growth in size and bandwidth, which in turn brought forth remarkable changes. The traditional four-layer Internet architecture of IP/ATM/SDH/DWDM is evolving toward a two-layer architecture of IP (w/GMPLS) over DWDM (w/optical switching). This trend calls for the so-called O-O-O processing mode which makes concrete the optical layer concept and leads us to the predictable all-optical broadband IP network.

Underlying optical switching thus is unquestionably required, and among several implemental technologies the optical micro-electro-mechanical system (MEMS) is regarded as the most promising candidate due to a variety of attractive attributes. However, problems are also challenging us: (1) the complexity of fabrication involving a series of micromachining procedures is formidable; (2) the reliability is rather low hence necessitates the adjunctive fault protection and restoration system, which in turn elevates complexity and cost; (3) the scalability is unoptimistic owing much to the previous two reasons.

Plentiful research has been done and still ongoing for more than a decade. Aiming at improving performance of MEMS-based optical switches, most work focuses on enhancing the precision [6], lowering optical loss [7,9], boosting switching speed [8], fault tolerance and restoration, and so forth. However, the previously presented problems are still impeding the progress of optical MEMS. New approaches are in great need.

This paper proposes two novel models, which make remarkable modification to conventional design of 2x2 MEMS-based optical switches, for addressing the issue. One substitutes a single double-sided micromirror for the original four micromirrors, the other, named as "MES", eliminates mechanical actions by replacing micromirrors with microlenses. To indicate additionally, free-space optical MEMS can be classified into two categories: two-dimensional (2-D) and three-dimensional (3-D). Generally a 2-D MEMS is more advantageous for its easier fabrication, simpler controllability, and more mature techniques. In this paper, we focus on this category.

A brief survey over the related research is made in section II, then section III explains the novel models in detail. Finally in section IV, concluding remarks are made on the issue.

II. RELATED WORK

The related research for improving optical MEMS can be briefly described as the following three aspects.

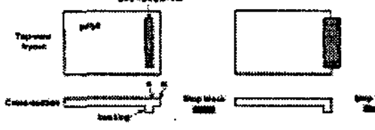
A. Enhancing precision

One typical approach aims at addressing the challenge presented by the tight angular tolerances imposed by free-space interconnection. It reports on enhanced integrated-mechanical designs for the free-rotating hinges and microactuators that are capable of achieving better than 0.1° angular precision.

As shown in Fig. 1, to register the hinge-pin position with the precision that the maximum mirror-angular variation is less than 0.19°, polysilicon pushbars are integrated with the translation stage. When the translation stage moves forward, the pushbars on both sides of the mirror frame also move forward, and eventually push the hinge pins against the front-side of the hinge staples, thus eliminating the uncertainty in hinge-pin position. This then allows one to attain angular precision that is limited only by photolithography precision, independent of hinge-pin clearances.

Figure 1. SEM of the microhinge and the pushbar structure for hinge-position enhancement [6]

Fig. 2 illustrates the proposed design employing scratch-drive actuators (SDA's), through which the angular precision is seen to improve from ~1° to 0.15°. As the pushrod is rotated up, the hinge pin starts to touch contact the hinge staple when the mirror angle approaches 90° (pushrod angle 70°). The pressure from the hinge staple presses the hinge pin down and backward, thus preventing it from sliding.



(a) (b)

Figure 2. (a) Conventional SDA design, where the stop position of the SDA is not clearly defined. (b) Improved SDA design. The stop

Supported by the China National Science Fund for Distinguished Young Scholars (60025104)
Supported by the Major Research Plan of National Natural Science Foundation of China (90104023, 90204002)
Supported by the General Project of National Natural Science Foundation of China (60202003)

position of the SDA is clearly defined when the front-wall of the busing hits the stop block. [6]

B. Lowering optical loss

One approach proposes a retroreflector-based optical system using a fiber collimator (FC) array, which offers the easiness of alignment, highly efficient optical coupling (low loss), and compactness. The system can obtain minimum coupling loss of 0.29dB at 1.75-mm spacing and coupling losses lower than 0.36dB at 1.5- and 2.0-mm spacing.

Fig. 3(a) illustrates the system configuration for 2x2 optical switches. The system is composed of the FC array with four FCs and a switching device based on a retroreflector. A retroreflector has property that it reflects back incident light by 180° exactly regardless of its incident angle.

Fig. 3(b) shows a 2x2 micromechanical optical switch module employing the proposed optical system. Minimum insertion loss of 1.5dB and switching time of <20 ms were obtained.

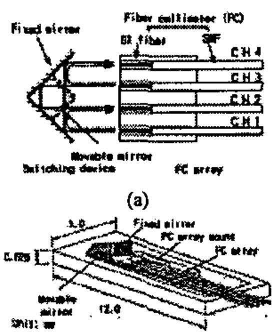


Figure 3. (a) Optical system for 2x2 optical switches; (b) switch inner structure. [7]

C. Boosting switching speed

A free-space micromachined optical switch utilizing free-rotating hinged micromirrors is demonstrated, showing less than 700μs switching time, satisfying crosstalk and extinction ratio, negligible polarization-dependent loss, and nice bit-error-rate (BER) performance. A schematic drawing of the actuated mirror is shown in Fig. 4.

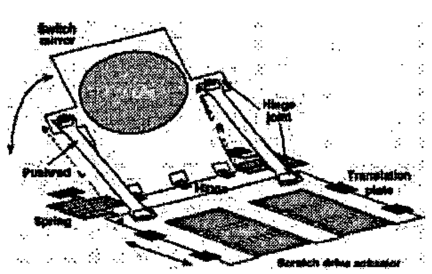


Figure 4. Schematic drawing of the microactuated switch mirrors [8]

In summary, these approaches improve optical MEMS to some extent and facilitate the realization of all-optical network. However, complex fabrication, low reliability and poor scalability are still bothering. Since all the work is confined to limited alteration on the original design schema, the inherent defects are difficult to be fixed. Introduction of seminal design conception is being in great need.

III. Novel Models

Conventionally, the structure of a 2-D MEMS device is straightforward and it comprises a matrix of hinged micromirrors to route light signals from an array of input fibers to an array of output fibers (see Fig. 5). Collimated beams of light propagate parallel to the substrate plane and, if none of the mirrors are activated, pass over the mirror array unaffected. When a mirror is activated it moves up into a beam's path and redirects the light into one of the outputs. As the mirrors have "binary" states, i.e. they only have two positions - "on" or "off", they can be controlled digitally.

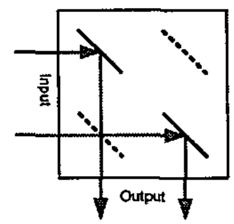


Figure 5. Schematic drawing of the conventional 2-D MEMS

Two novel models are presented in this section to serve as substitutions for the conventional one. They solve the problems from different angles respectively.

A. One vs. Four

It seems apparent that a 2x2 2-D MEMS requires four micromirrors, but this model only utilizes a single double-sided micromirror – both sides of it are identically reflective – to perform the same switching function. This model has two variants labeled A1 and A2 which are interpreted successively.

1) Model-A1 (Popup-mirror)

Fig. 6 schematically shows the structure and operating mechanism of the first variant. When the mirror is popped up, as in (a), both sides reflect the input light beams and redirect them into the two output ports respectively. When it is pulled down, as in (b), each of the incident beams goes toward the opposite output port straightforwardly. By alternating the mirror's state between (a) and (b) under a digital control system, the 2x2 optical switching is implemented.

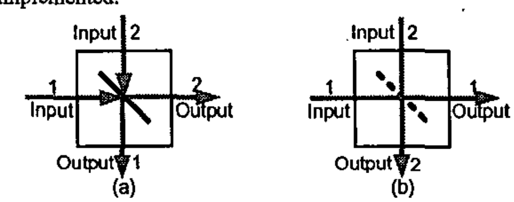


Figure 6. Schematic drawing of Model-A1

2) Model-A2 (Rotating-mirror)

At the first look Model-A1 and Model-A2 (see Fig. 7) appear same as each other, but an essential distinction does exist with regard to the mirror's motion. Pay attention to the location of the ports: each pair of the input/output ports are directly opposing to each other. In (a) the input light beam 1 are reflected and redirected to the downside output fiber, and beam 2 to the upside one. Once the mirror rotates for 90° horizontally, i.e. in the paper plane, as in (b), beam 1 will be deflected to the upside port whereas beam 2 will go downward.

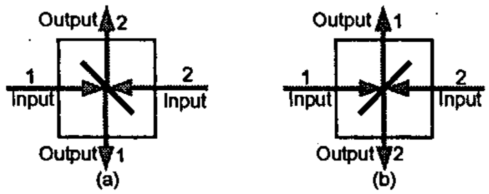


Figure 7. Schematic drawing of Model-A2

Another implicit distinction deserves mentioning. In Model-A1, light beams can pass through the internal free space of MEMS without any reflection if the mirror is pulled down. Yet in model-A2, input light will always be reflected in either state. This should be taken into account because Model-A2 keeps a constant reflection loss ratio whereas Model-A1 is featured with "asymmetric" reflection loss.

Model-A2 has two alternative operating modes for fulfilling a complete moving cycle from (a) to (b) then back to (a). One is called circle-mode which means rotating the mirror for 90° per stop in a unique direction, either clockwise or counter-clockwise. In seesaw-mode, dissimilarly, the mirror rotates in both two directions alternately, notwithstanding also for 90° per stop.

3) How to Scale Up

Staying with 2x2 model makes no sense unless scaled up to larger capacity. Fig. 8 illustrates a universal method for constructing 4x4 and 8x8 modules using 2x2 modules.

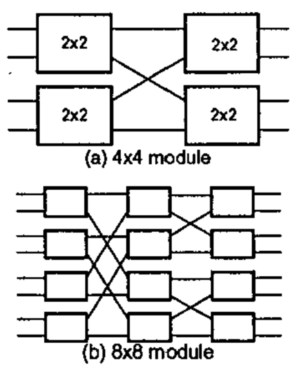


Figure 8. Larger-scale switch module assembled using 2x2 modules

Additionally we can see, since a conventional 2-D MEMS requires N^2 mirrors to route N inputs to N outputs, that an earlier 4x4 switching module will contain 16 mirrors whereas the novel counterpart only contains 4; similarly, an earlier 8x8 module contains 64 mirrors whereas a novel one only contains 12.

4) Benefits

- Complexity of assembling will be notably decreased due to fewer required parts and elimination of the arduous task of aligning multiple mirrors.
- The control system will be remarkably simplified for the original motion-synchronization of the four mirrors is not required any longer while maintaining the binary-control style.
- Reliability will be greatly enhanced as, theoretically, the removal of 3/4 of the number of micromirrors excludes 75% of the probability of failure.
- Scalability of optical switches will be improved to a large extent because embedding fewer parts sharply shrinks the size of a single switching module.
- Model-A2 provides two alternative operating modes, leaving engineers space to choose the optimal mode from so as to obtain a more cost-effective solution.
- Differing from the conventional popup motion, the mirror in Model-A2 rotates horizontally, which is supposed to be easier to implement mechanically.

B. "MES" vs. MEMS

Currently any designer takes it for granted that physically moving mirrors is intrinsic to MEMS since the name literally mandates "mechanical" elements. This principle, unfortunately, entangles us with numerous troubles. For instance, the interior components are vulnerable to physical impacts while high-speed switching dictates the frail parts to move thousands of times per second, making the ultimate system prone to failure.

Starting from a disparate viewpoint, this approach eliminates mechanical actions by replacing micromirrors with microlenses. Named as "micro-electric system", MES deletes the letter "M" in the acronym "MEMS".

1) Structure

The overall structure of MES is schematically drawn in Fig. 9(a). It consists of four identical right-triangle lenses, the common focus of which is located at the central point *F*. The lenses are made of a special kind of transparent and refractive medium which has a distinctive feature that its refractive index can vary with a certain electric control. Put in more detail, under normal conditions without electric impact, each lens's refractive index keeps equivalent to that of vacuum, i.e. *1*, permitting light to pass in a straight line without deflection; once it is electrified with a certain electric voltage, its refractive index switches to *n* (larger than 1) immediately. Such media, sounding imaginary, are indeed available in the reality as GaAs, $NiNbO_3$, etc.

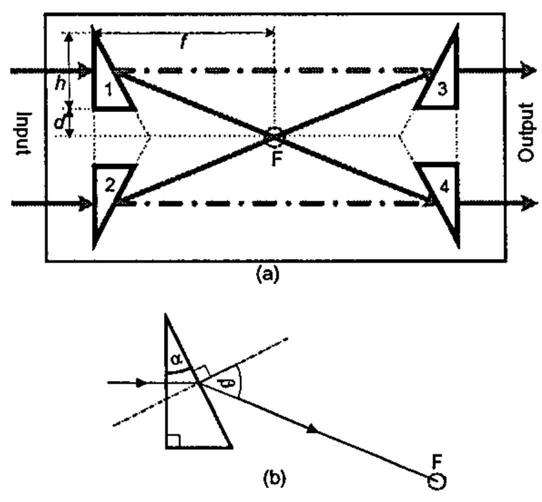


Figure 9. Schematic drawing of "MES": (a) the overall structure; (b) one of the lenses shown in detail.

2) Operating Mechanism

Initially, two input light beams pass through the lenses straightforward along the two paralleled dash-dot lines respectively, heading for the opposite output ports, as shown in Fig. 9(a). Next instant the lenses are galvanized simultaneously when their refractive index shifts to *n*, the beams will switch their paths onto the solid lines concurrently, fulfilling an optical switching. As is evident that the whole process is purely composed of "tranquil" procedures without any "boisterous" mechanical actions.

As a supplemental explanation, lens 1 and 2 initiate the switching once electrified, while lens 3 and 4 are utilized to collimate the oblique beams and make them project onto the output port erectly.

3) Calculations

Fabrication necessitates establishing certain formula to determine the geometrical properties of the model. A series of mathematical calculations are presented below to discover the association between the geometrical parameters and the refractive index of the electrified lenses,

Parameters f, h and d are depicted in Fig. 9(a), while α and β in (b). We also assume the refractive index of the electrified lenses is n.

The first crucial equation is deducted from (a) and (b) as ①, assuming the incident point is at the midpoint of the right-angle side of the triangular lens:

$$\tan(\beta-\alpha)=\frac{d+h/2}{f-h\tan\alpha/2} \quad ①$$

The refraction formula is referred to as ② and other two trigonometric-function formulas are also quoted:

$$n=\frac{\sin\alpha}{\sin\beta} \quad ②$$

$$\tan(\beta-\alpha)=\frac{\tan\beta-\tan\alpha}{1+\tan\beta\times\tan\alpha} \quad ③$$

$$\frac{1}{\cos^2\theta}=1+\tan^2\theta \quad ④$$

Thus we derive an equation group:

$$\begin{cases} n^2\tan^2\alpha+(n^2-1)\tan^2\alpha\tan^2\beta-\tan^2\beta=0 \\ h\tan^2\alpha-2f\tan\alpha+2f\tan\beta-2(h+d)\tan\alpha\tan\beta=2d+h \end{cases}$$

By canceling the variable β, we get equation (A) which determines the relationship between n and the geometrical parameters:

$$2n[(f-(h+d)\tan\alpha]= [2f-h\tan\alpha+(2d+h)\cot\alpha]\sqrt{1-(n^2-1)\tan^2\alpha} \quad (A)$$

As an alternative design, lens 1 and lens 2 can be attached to each other as a single lens, with the same rule applied to lens 3 and lens 4. Under this situation, the variable d becomes equal to 0, thus equation (A) can be simplified as equation (B):

$$2n[(f-h\tan\alpha]=(h\cot\alpha-h\tan\alpha+2f)\sqrt{1-(n^2-1)\tan^2\alpha} \quad (B)$$

To point out, another equation relating the refractive index n to the electric voltage v can be established, too. But it varies with different kinds of medium the lenses are made of, and it is involved in material physics that is beyond the scope of this paper, hence it is omitted.

4) Benefits

- The most appealing advantage that MES brings us is the remarkably enhanced reliability. By eliminating mechanical damaging factors coming with MEMS, the consequent system will be much more robust, further enabling working without accessory fault protection and restoration subsystem, which is conducive to lower cost.
- Great simplicity is foreseeable in the control system for it just acts as an electric switch turning on and off to change voltage between *0* and a preset value.
- Scalability will be improved as a result since obstruction imposed by low reliability and high complexity is considerably minified now.

IV. Conclusion and Future Work

This paper has proposed two novel 2x2 models for designing 2-D MEMS-based optical switches. Dedicated to conquering the defects of the conventional optical switch from different angles, both of the models achieve enhancing reliability and scalability, reducing complexity and lowering cost. They are, therefore, anticipated to open the path to more cost-effective optical switches and pave the way for advancing to the next generation all-optical network.

Future work may include inventing new techniques for manufacturing the double-sided micromirrors utilized by Model-A, discovering ideal material for making the microlenses embedded in Model-B, and experimental performance evaluation of both models.

References

[1] P. Green, "Progress in Optical Networking", *IEEE Comm. Mag.*, pp. 54-61, Jan. 2001.

[2] D. J. Bishop, C. R. Giles, and G. P. Austin, "The Lucent LambdaRouter: MEMS Technology of the Future Here Today", *IEEE Comm. Mag.*, pp.75-79, Mar. 2002.

[3] P. B. Chu, S-S. Lee, and S. Park, "MEMS: The Path to Large Optical Crossconnects", *IEEE Comm. Mag.*, pp.80-87, Mar. 2002.

[4] P. D. Dobbelaere, "Digital MEMS for Optical Switching", *IEEE Comm. Mag.*, pp.88-95, Mar. 2002.

[5] A. Banerjee, et al. "Generalized Multiprotocol Label Switching: An Overview of Routing and Management Enhancements", *IEEE Comm. Mag.*, pp. 144-150, Jan. 2001.

[6] L.Y. Lin, E. L. Goldstein, and R. W. Tkach, "Angular-precision enhancement in free-space micromachined optical switches", *IEEE Photonics Tech. Letters*, vol. 11, no. 10, Oct. 1999.

[7] S. Kanekia, A. Uemura, T. Matsuura, K. Tsusumi, and T. Hatta, "Micromechanical optical switch using retroreflector-based optical system", CLEO/Pacific Rim 2001.

[8] L.Y. Lin, E. L. Goldstein, and R. W. Tkach, "Free-Space Micromachined Optical Switches with Submillisecond Switching Time for Large-Scale Optical Crossconnects", *IEEE Photonics Tech. Letters*, vol. 10, no. 4, Apr. 1998.

[9] V. Aksyuk, et al. "Low insertion loss packaged and fibre connectorised MEMS reflective optical switch", *Electronic Letters*, vol. 34, no. 14, 9th Jul. 1998.

[10] L.Y. Lin, E. L. Goldstein, and R. W. Tkach, "Free-Space Micromachined Optical Switches for Optical Networking", *IEEE J. of Selected Topics in Quantum Electronics*, vol. 5, no. 1, Jan./Feb. 1999.

[11] S. D. Robinson, "MEMS Technology -- Micromachines Enabling the "All Optical Network", *Electronic Components and Technology Conference*, 2001.

[12] L. Y. Lin, E. L. Goldstein, and R. W. Tkach, "On the Expandability of Free-Space Micromachined Optical Cross Connects", *J. of Lightwave Tech.*, vol. 18, no. 4, Apr. 2002.

[13] G. Shen, T. H. Cheng, S. K. Bose, C. Lu, and T. Y. Chai, "Architectural design for multistage 2-D MEMS optical switches", J. of Lightwave Tech., vol. 20, no. 2, Feb. 2002.

[14] OMM Inc., "Optical switching: unraveling the myths about MEMS", *FibreSystems Europe*, pp.2-4, Jun. 2002.