SELF ALIGNED VERTICAL MIRRORS AND V-GROOVES APPLIED TO A SELF-LATCHING MATRIX SWITCH FOR OPTICAL NETWORKS

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ABSTRACT

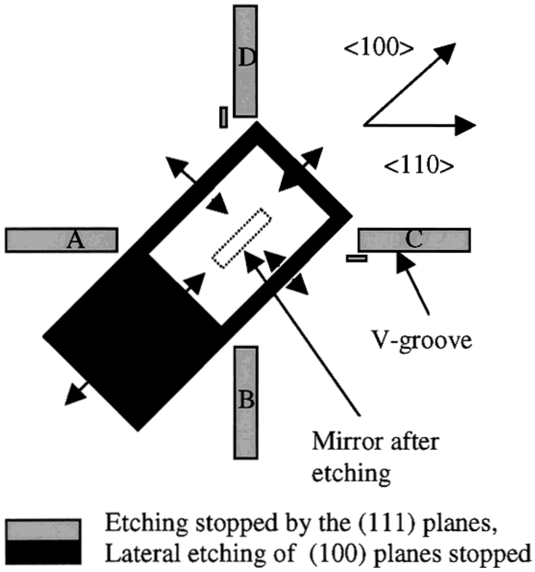
This paper reports a new and low cost method of fabrication for M*N matrix switch using wet etching of silicon: a self-aligned batch process allowing the fabrication of vertical mirrors and V-grooves is performed in one-level of mask in (100) silicon wafer. The feasibility of a self-latching system with electromagnetic force is shown for the actuation of switch. Promising performances such as insertion loss lower than 0.5 dB, submillisecond switching time (0.4 ms) and reliable operation (20 > million cycles) are achieved.

INTRODUCTION

The rapid growth of optical fiber communication networks has created a large demand for many optical components, including optical switches. Low-cost optical components are particularly important for fiber-based local area networks (LAN). Recently, there has been a growing interest in applying the MEMS technology to improve the performances and reduce the cost of opto-mechanical switches [1-7]. More importantly, the MEMS technology allows the monolithic manufacture of large matrix switches on a single chip. These optical matrix switches are the key missing components for dynamically reconfigurable DWDM network.

Different and combined aspects are involved in the design of matrix switch. These aspects become more critical than in the case of a single switch due to accumulation of uncertainties contributing to deteriorate performances of a matrix switch. The most critical aspect is from an optical point of view. Indeed, the quality of the mirror surface is primordial to obtain very low loss insertion even after multiple reflections. A self-aligned structure between mirrors and fiber alignments is mandatory to satisfy the accuracy of optical axis and also due to this passive alignment of optical fibers the cost of production will decrease dramastically.

Basically, three technologies are commonly used to manufacture optical switches in MEMS technology: deep RIE, surface machining and bulk machining.



Etching stopped by the (111) planes,
Lateral etching of (100) planes stopped by time.

Figure 1: Principle of the self-aligned optical structure (Arrows indicate the direction of underetching).

Deep RIE involves a slight underetching versus etched depth and ripples increasing optical losses if this surface is used as a mirror.

Surface micromachining does not allow fully batch-fabricated devices, due to external manipulation to fix mirror or micro-lens in position and active alignment of fibers.

A process using bulk micromachining seems the best candidate to satisfy quality of the mirror with passive alignment. Vertical (111) sidewalls used fo a mirror in (110) silicon wafer have been already performed but V-grooves for alignment can not be performed. The use of (100) sidewall in (100) silicon wafer that allows the simultaneous fabrication of mirror and V-grooves has been shown for passive devices as beam splitters but not in active devices [8].

PRINCIPLE

In this work, an optical structure satisfying a high quality of the mirror, self-aligned mirror and fibers passive alignment and low cost is performed in one-

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level mask in (100) silicon wafer. The etching principle is described in Fig.1.

This uses bulk micromachining taking the advantage of three points combined:

- The well-defined 45° angle between the <100> and <110> directions is used for a self-aligned vertical mirror and V-grooves. In the <100> direction, underetched vertical walls are used as a mirror, and in the same time V-grooves are performed in the <110> direction for optical fiber alignment,
- The surface of the mirror is strictly perpendicular at optical axes due to the (100) plane, thus minimizing optical loss,
- The selectivity against the (111) planes is used to perform two levels of structural depths. Because, the etching is stopped by the (111) planes, the width of V-groove in the layout fix height of optical axis. (100) planes are still etched until the etching is stopped by time in order to define the mirror and also the thickness of the cantilever, which will be define from backside for the actuation of the mirror. Moreover, the difference between these levels must be chose to avoid a contact between fibers and cantilever during operation.

An example of optical structure for the bypass is illustrated using IntelliCad software in Fig.2.

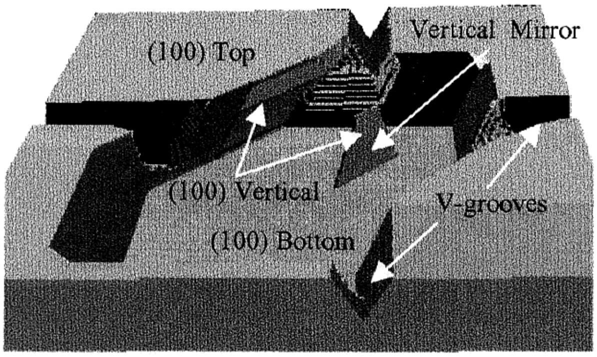

Figure 2: Simulation using IntelliCad software of wet etching of the optical structure showed in figure 1 (Tilted view).

FABRICATION

Fig.3 illustrates a vertical sidewall in a (100) silicon wafer. As the bottom and sidewall planes are all from the same {100} family, the lateral underetch rate is equal to the vertical etch rate. So, by this way, it is possible to define a vertical mirror. An example of such mirror during etching is shown in Fig.4. The thickness of this mirror can be decreased down to a few micrometers, see Fig.5. Structures of 3mm in length, 200 um in height and less than 3um in thickness were easily achieved. This possibility to get mirror with a small thickness is very attractive for fabrication of the bypass avoiding to privileged one path with respect to the other path. Generally speaking, an asymmetry is introduced by a lateral offset of the mirror to improve the coupling for one path to the detriment of the other.

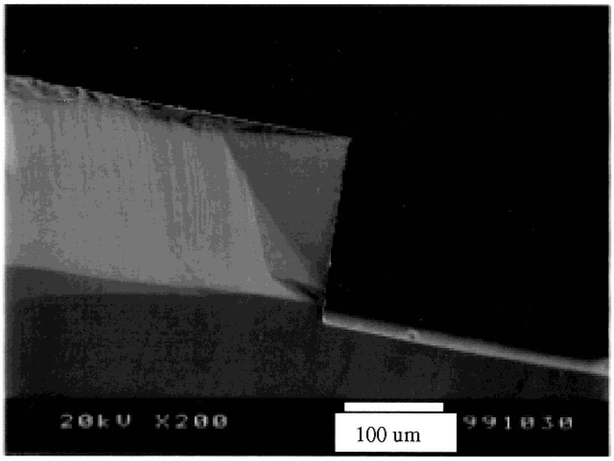

Figure 3: Vertical sidewall in a (100) silicon wafer.

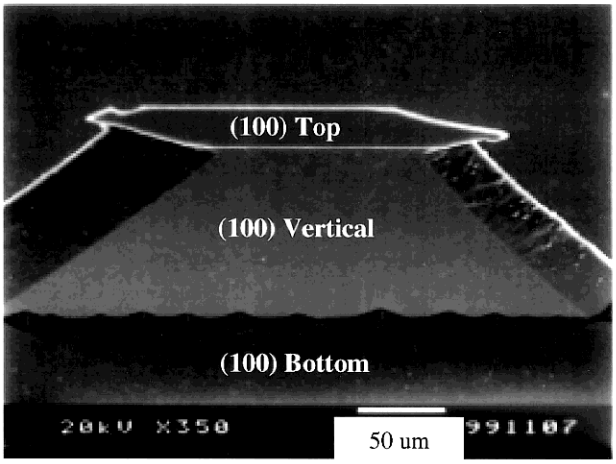

Figure 4: Vertical mirror performed from (100) planes.

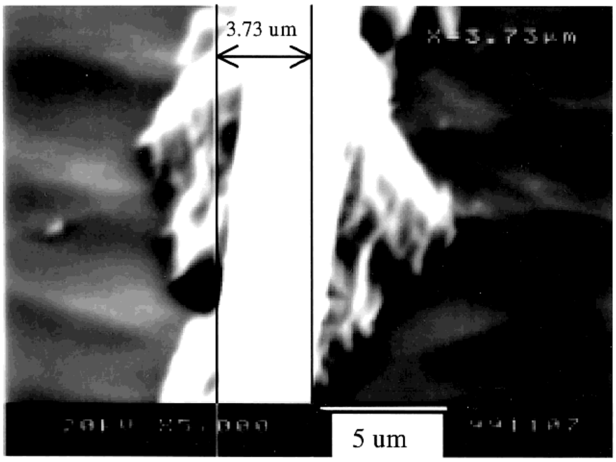

Figure 5: Close and side view of mirror showing the possibility to decrease thickness of mirror down to a few um.

The selectivity against the (111) planes to perform two levels of structural depth for the actuation of switch is shown in Fig.6.

Fig.7 shows a view of the self-aligned optical structure for a bypass during etching (using the layout of Fig.1). In order to avoid an overetching of a V-groove, in the layout V-grooves A and B do not have connection with mirror. V-grooves will open to the mirror only at the end of etching. This point is shown in Fig.6, overetching is minimized. Overetching is not very critical for switch operation but allows keeping a holder for fiber nearer of mirror. Concerning V-grooves C and D, inward sloping {111} facets are first introduced at the corners of the rectangular mask of the mirror and grow larger at the expense of the vertical sidewalls. When {111} facets reach small rectangles near V-grooves (see Fig.1), {111} facets will translate up to V-grooves according etching time, and V-grooves will be open just at the end of etching.

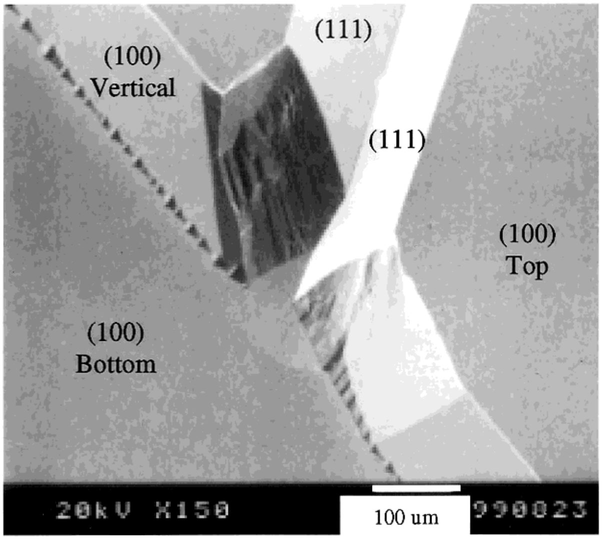

Figure 6: Close-up view of a V-groove showing two levels of structural depth.

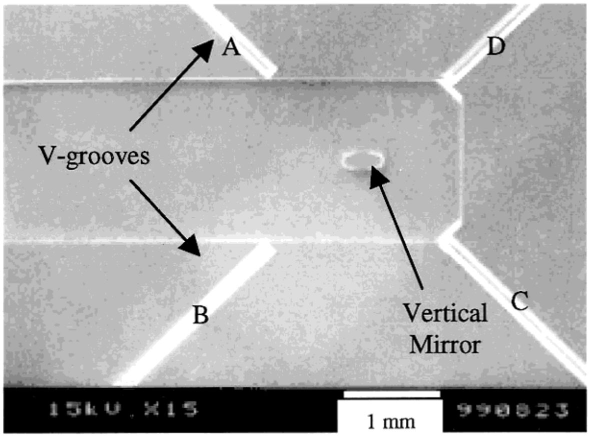

Figure 7: Example of optical structure for a self-aligned bypass during etching.

This principle of etching can be easily extended to perform M*N matrix switch. An example of optical structure for a matrix switch is shown in Fig.8.

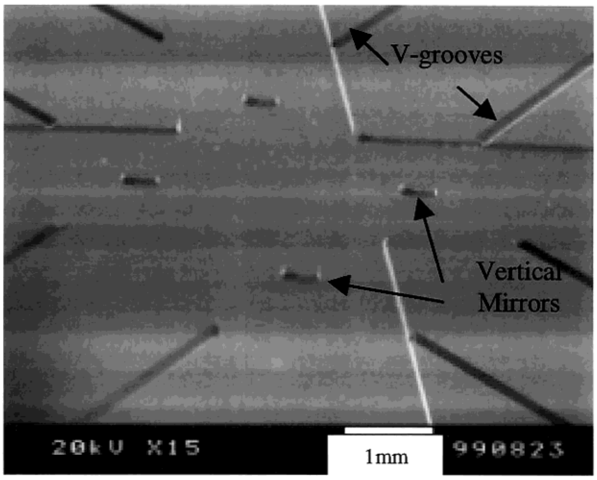

Figure 8: Example of optical structure for a self-aligned matrix switch.

FABRICATION OF SWITCH

The process starts with a (100) silicon wafer. After a cleaning, wafer is oxided by a wet oxidation with 0.5 um of silicon dioxide. This silicon dioxide is patterned in the front side to define optical structures, then, the backside to define the cantilever. After protection of the frontside, first etching is performed to define the cantilever, then optical structures. By this way, the cantilever will appear just at the end of etching that permits to keep control on the thickness of the mirror. Cr/Au layers are deposited by vacuum evaporation.

Fig. 9,10 show a full view of a bypass and a switch matrix

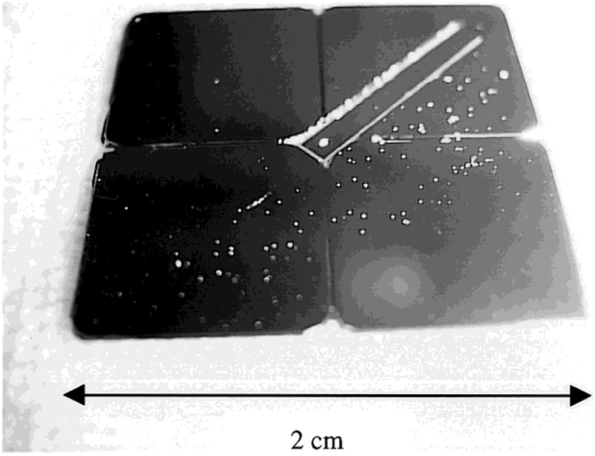

Figure 9: View of a self-aligned bypass.

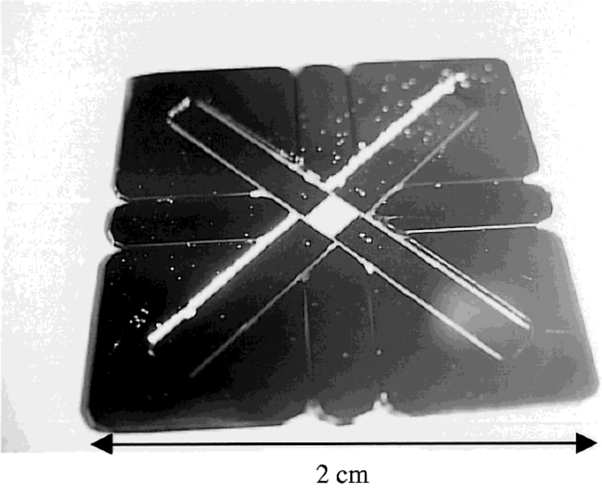

Figure 10: View of a self-aligned matrix switch.

PRINCIPLE OF ACTUATION

A self-latching system with electromagnetic force is developed to have no power consumption in holding the ON-OFF positions.

The micro-optical switch includes 2 parts separated by an air gap:

- A movable monolithic silicon part, which consists of a vertical mirror and a deformable cantilever beam, with a 100µm-thick permalloy piece on top of it.
- A fixed small electromagnet realized in conventional technology, including a yoke, a winding and a permanent magnet.

The bi-stable behavior without power consumption is obtained thanks to a stable mechanical position (OFF position) due to the cantilever stiffness and a second stable position (ON position) of magnetic nature due to the permanent magnet. Switching operation is provided by the electrical current in the winding. The ON position is released in reversing current in the winding. This operating principle is described in Fig.11.

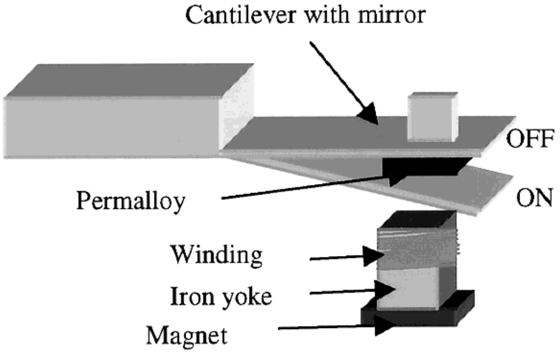

Figure 11: Principle of the operating mechanism of a switch with a self-latching system.

CHARACTERIZATION OF A BYPASS

This principle of actuation is applied to the bypass of Fig.9. Dimensions of the cantilever and piece of permalloy are 11.7mm*1.2mm*20um and 1mm*1mm*100um, respectively. The size of the iron yoke is 6mm*6mm*10mm surrounded by a winding of 300 turns. The cantilever is driven by a sinusoidal wave. Its frequency response is measured by means of a vibrometer and plotted in Fig.12. A measured resonant frequency is 67.2 Hz with a quality factor of 33.

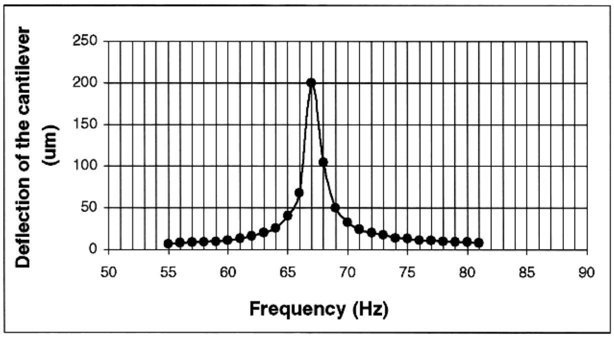

Figure 12: The frequency response of the bypass.

The magnetic force exerced by the winding on permalloy is proportional to the divergence of magnetic field. So, the cantilever deflection should be equal at zero in the center of iron yoke to increase at its maximum value near corner of iron yoke. The cantilever deflection is plotted in this case as a function of applied current in Fig.13.

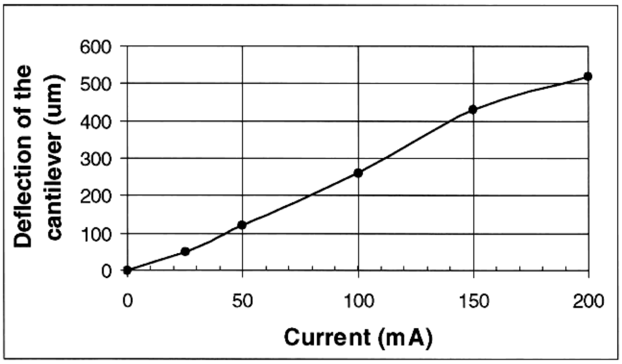

Figure 13: Deflection of the cantilever versus applied current.

Diameter of single and multimodes fibers are 9 um and 50 um, respectively. So, assuming a maximal displacement of 100um of the mirror, which is enough high to perform switch operation correctly, power consumption will be less than 10mW.

Optical switching has been performed with an infrared wavelength at 1.55um. First results were obtained using multimode fibers. The diameter of the beam is smaller than the size of the mirror (100um*200um), which ensures complete coverage of the optical beam. The optical insertion losses are 0.46 dB and 0.53dB in the ON and OFF positions, respectively.

The dynamic response of the switch is measured by means of a photodetector in silicon using a laser diode source operating at a visible wavelength of 633 nm. A typical oscilloscope trace of response of the switch is plotted in Fig.14. The rise time is 0.4 ms, corresponding to the motion of cantilever to go in the ON position. The fall time, 2 ms, is the return of cantilever in the OFF position. Both of these values include light switching and delay between the oneset of the bias and the switching-on of light. Thus, in optimizing height of fibers with respect to mirror, it should be possible to reach sub-millisecond switching time (>500us), taking into account slopes very steep of Fig.14.

Experiments on lifetime are under investigation. After 20 million cycles, no operational degradation of the switch is observed.

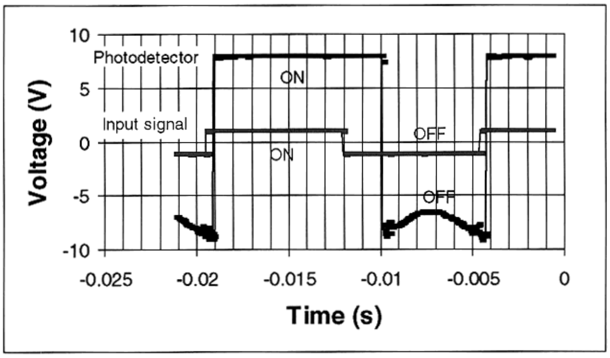

Figure 14: The dynamic response of the switch. Rise time (0.4 ms), fall time (2ms).

The operating mechanism of the self-latching system was also demonstrated, keeping the ON position without applied current. A current of 0.5A is necessary to pass the switch from ON-OFF positions but this system has been not yet optimized.

CHARACTERIZATION OF A MATRIX SWITCH

First results obtained on the matrix switch of Fig.10 are also reported. Cantilevers are smaller in length (8.8 mm) than that of the of bypass. Thus, resonance frequencies are higher, 170 Hz, as plotted in Fig.15.

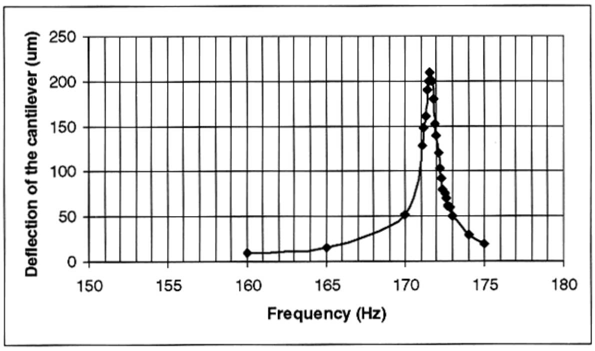

Fig.15 : Frequency response of one of the cantilever of the matrix switch.

In a first time, multimode fibers are used to measure insertion loss between fibers 1 and 2 of Fig.16. Insertion loss is higher (>10dB), this result is due to the large working distance between fibers (2.8mm). In the next step, fibers with GRIN lens at the end of fiber will be used to reduce dramastically insertion loss. Insertion loss of less than 1.5 dB should be expected. An other way to reduce insertion loss is to reduce distance between mirrors.

The operating principle of matrix switch is illustrated in Fig.16. One winding is placed under each cantilever for actuation of this one. This system must be design in such way that actuation of one cantilever by its winding has a negligeable interaction on the nearest cantilevers. To check the purpose of this solution, a current is applied on the winding 1 and the cantilever deflection is measured by means of laser vibrometer at the end of cantilevers 1 and 2. These deflections are 280 um and 7 um, respectively. As a displacement of 100 um is enough for switch actuation, the influence on the other cantilever is enough low for the purpose.

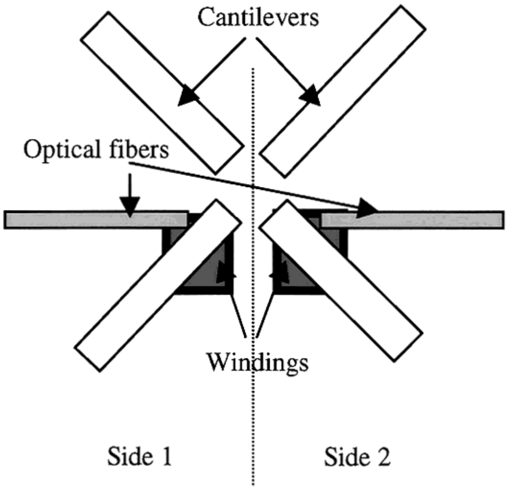

Fig.16 : Schematic view of operating principle of matrix switch.

CONCLUSION

We have reported a novel, easy and low cost method of fabrication to perform M*N matrix switch using anisotropic etching of silicon. This method presents the main interests to get a self-aligned vertical mirrors and V-grooves, and mirror is strictly perpendicular to optical axis. These both features are obtained thanks to the silicon lattice.

Using this method a bypass and matrix switches for optical network are manufactured. A displacement of 100 um of the mirror is reached with less than 10mW power consumption. A maximal switching time of 2 ms is obtained, the value below 500 us should be reached in optimizing the height between fibers and mirrors. Operating frequencies of 67Hz and 171Hz are demonstrated and higher frequencies can be achieved with shorter cantilevers.

The insertion losses are 0.46 dB and 0.53 dB in the ON-OFF positions, respectively.

A self-latching system with electromagnetic force is developed and demonstrated to have no power consumption in holding the ON-OFF positions. Switching operation is provided by the electrical current in the winding.

These first results are promising to an extension of larger matrix switches.

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