Micro-opto-mechanical systems: applications in pulsed fiber lasers and optical switching

Y.-A. Peter, E. Rochat, H.P. Herzig

Institute of Microtechnology, University of Neuchâtel,
rue A.-L. Breguet 2, CH-2000 Neuchâtel, Switzerland

ABSTRACT

Two different applications of Micro-Opto-Electro-Mechanical systems (MOEMs) are described in this paper. The first one is a Q-switched fiber laser using a micro-mirror as switching element. We present the general concept, the latest experimental setup with results and simulations on the behaviour of the pulsed laser. The second application is an opto-mechanical switch for telecommunication ring networks. We describe a free-space optical switch using a micro-mirror, micro-optical elements and a fiber bundle.

Keywords: MOEM, laser, microlens, micro-mirror, Q-switch, telecommunication, optical switch, fiber.

1. INTRODUCTION

Micro-optical and micro-electro-mechanical technologies have been highlighted during the last few years. Thanks to their potential of batch processing and cheap replication, these technologies are merging to create a new and broader class of micro-opto-electro-mechanical (MOEM) devices. The development of commercial devices, such as torsional mirrors, laser scanners, optical shutters and dynamic micro-mirror displays, will benefit of this new technology.[1]
We will present two examples of micro-systems in which MOEM elements are key components. Both are using a micro-mechanical mirror as switching element. The first system, a pulsed fiber laser, has his quality factor switched from a low value to a high value. The second system is a fiber optical switch aimed to be used in telecommunication ring networks.

2. INTEGRATED Q-SWITCHED FIBER LASER USING A MICRO-MIRROR

In order to generate a pulse in a conventional Q-switched fiber laser, a modulator (acousto-optic, electro-optic or mechanical) has to be introduced into the cavity.[2] In our configuration, no additionnal elements are needed; the modulator is the reflector itself, thus we can build an all fiber laser with a closed and compact cavity. Moreover, it has the potential of integration in a compact micro-system. A first demonstration of a Q-switched fiber laser using a torsional micro-mirror has been realized in our Institute.[3] Here we present a more compact device using a vertical mirror as switching element.

2.1. Experimental setup

Fig. 1 shows the setup of the Q-switched fiber laser. The fiber laser is based on a 120 mm long Nd^{3+} doped fiber. The cavity consists of the switchable micro-mirror (torsional or vertical) described below and a Bragg grating with 48 % reflectivity and 0.1 nm bandwidth at 1071 nm. A Bragg grating has a high wavelength selectivity. Therefore we can use the grating to shorten the pulse duration, as proposed by Okhotnikov and Salcedo.[4] The fiber laser is spliced on a wavelength division multiplexing (WDM) coupler, allowing to use the Bragg grating as output reflector, while pumping through it. The pump source is a 200 mW GaAlAs laser diode emitting at 810 nm. For this configuration, we measured a laser threshold of 3 mW and a slope efficiency of 19 % (see Fig. 2). These results are in good agreement with the values commonly reported in the literature.[5]

Further author information:
Email: yves-alain.peter@imt.unine.ch; WWW: http://www-imt.unine.ch/
Telephone: + 41 32 718 3283; Fax: + 41 32 718 3201

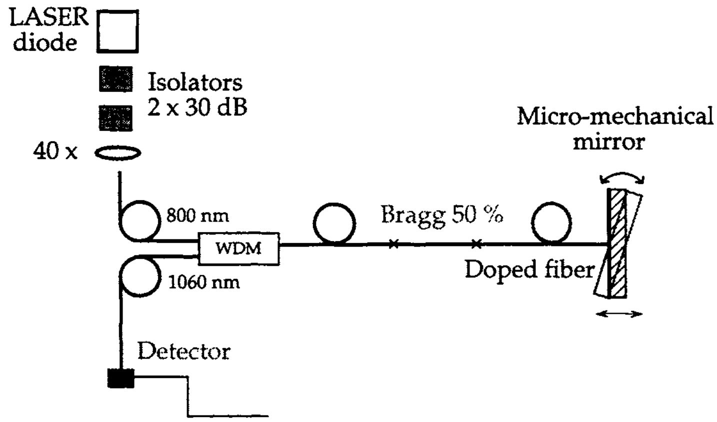


Figure 1. Schematic diagram of the Q-switched fiber laser system.

2.2. Vertical micro-mechanical mirrors

The switchable mirror is a vertical micro-mirror (75 μm deep and 100 μm wide) fabricated by deep anisotropic reactive ion etching.[6] The mirror moves along the optical axis driven by two comb actuators. The displacement of the mirror is typically 5 μm with an applied voltage of 40 V and frequencies of 20 kHz. The vertical micro-mirror is covered with 2 μm of aluminum in order to improve its reflectivity which was measured to be 50 %. The SEM picture of Fig. 3 shows such a mirror with its two comb actuators and the U-groove for receiving the fiber.

2.3. Results

The micro-mirror showed sufficent optical quality to overcome the laser threshold $P_{th} \approx 3$ mW. Experimentally, the fiber is first placed close to the mirror with a slight air gap. Then the micro-mirror is actuated at frequencies between 100 Hz and 100 kHz to produce a modulation of the resonator losses. Finally, we adjust the fiber-mirror distance and the alignement to optimalize the output signal of the pulsed laser. In such a configuration, we were able to get pulses up to 200 mW which is about 100 times higher than the continuous emission. Fig. 4 shows a typical output train obtained with the vertical mirror at 16 kHz mirror frequency. The pulse width at half maximum is typically 2 μs, as shown in Fig. 5. If the mirror is operated at lower frequencies, the switching is too slow to get Q-switched pulses. The laser produces multiple pulses, corresponding to relaxation oscillations. Fig. 6 shows such relaxation peaks for 150 Hz mirror frequency.

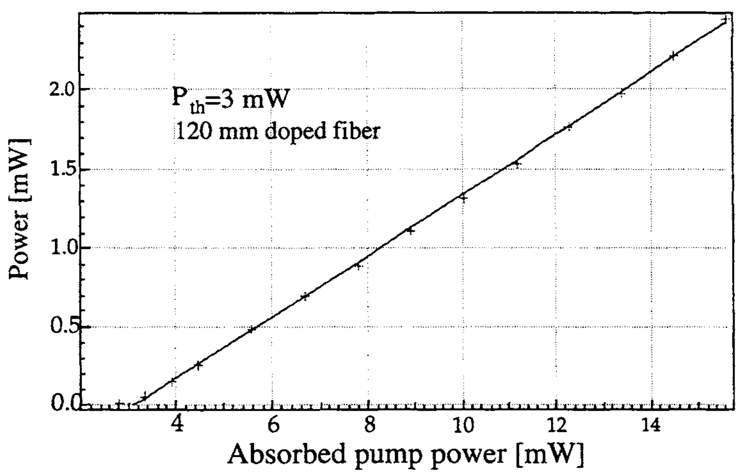


Figure 2. Characterisation of the cavity: output power vs absorbed pump power.

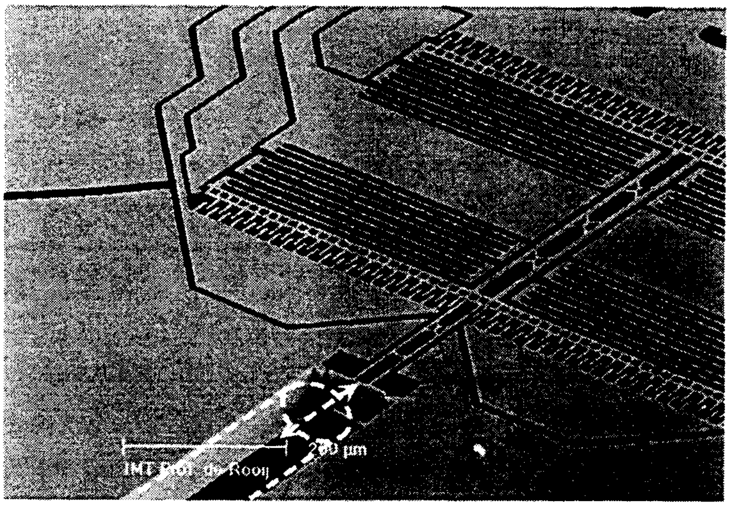


Figure 3. Top view (SEM) of the vertical mirror with the comb actuators and the fiber (drawn as dashed line) in the U-groove.

2.4. Simulations

In order to investigate the behavior of our device, we simulated the generated pulses by using the rate equations of the fiber laser:

$$\frac{dN}{dt} = -2N(t)\eta(t)\sigma c \tag{1}$$

and

$$\frac{d\eta}{dt} = N(t)\eta(t)\sigma c - \eta(t)\beta(t)c, \tag{2}$$

where N(t) is the population inversion, η(t) the photon density, σ the transition cross-section, c the speed of light, and β(t) the resonator losses. The emission cross-section $\sigma \approx 1.39x10^{-24}m^2$ was calculated with the Fuchtbauer-

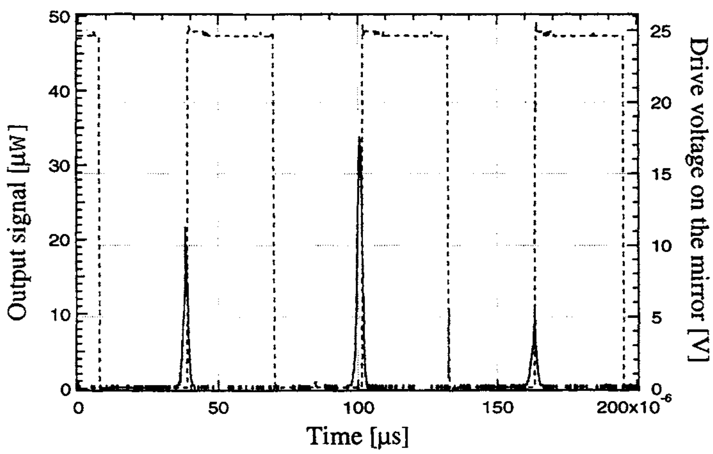


Figure 4. Q-switched pulse train for repetition rate $f = 16kHz$.

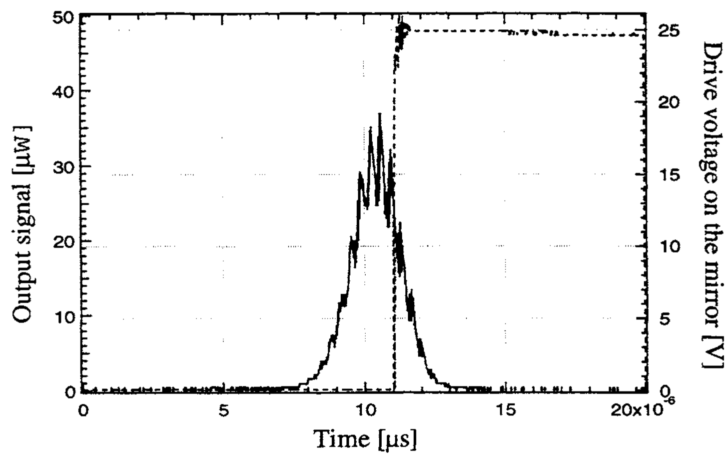


Figure 5. Single peak obtained with the vertical mirror modulated at $f = 16kHz$.

Ladenberg method.[7] We measured the coupled power $P_{cpl} \approx 10$ mW and the threshold power $P_{th} \approx 3$ mW. They are directly related to the population densities by

$$\frac{N_i}{N_{th}} = \frac{P_{cpl}}{P_{th}}, \tag{3}$$

where N_i is the initial population inversion and N_{th} the population inversion at threshold. The population inversion at threshold is obtained from

$$N_{th} = \frac{P_{th}\lambda}{hcV\tau}, \tag{4}$$

where V $\approx 7.4x10^{-12}m^3$ is the volume of the cavity, $\lambda = 810$ nm the pump wavelength, and h the Planck constant. The fluorescent lifetime $\tau \approx 507$ μs was determined by measurement of the frequency transfer function of the fiber.[8] Fig. 7 shows the linear losses β, the population inversion N and the photon density η during one switching period.

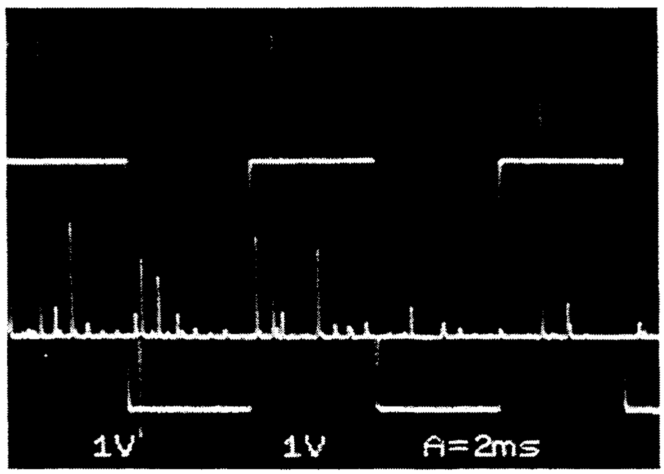


Figure 6. Multiple-pulse train (relaxation oscillations) for repetition rate $f = 150Hz$ and pump power $P = 8.8mW$.

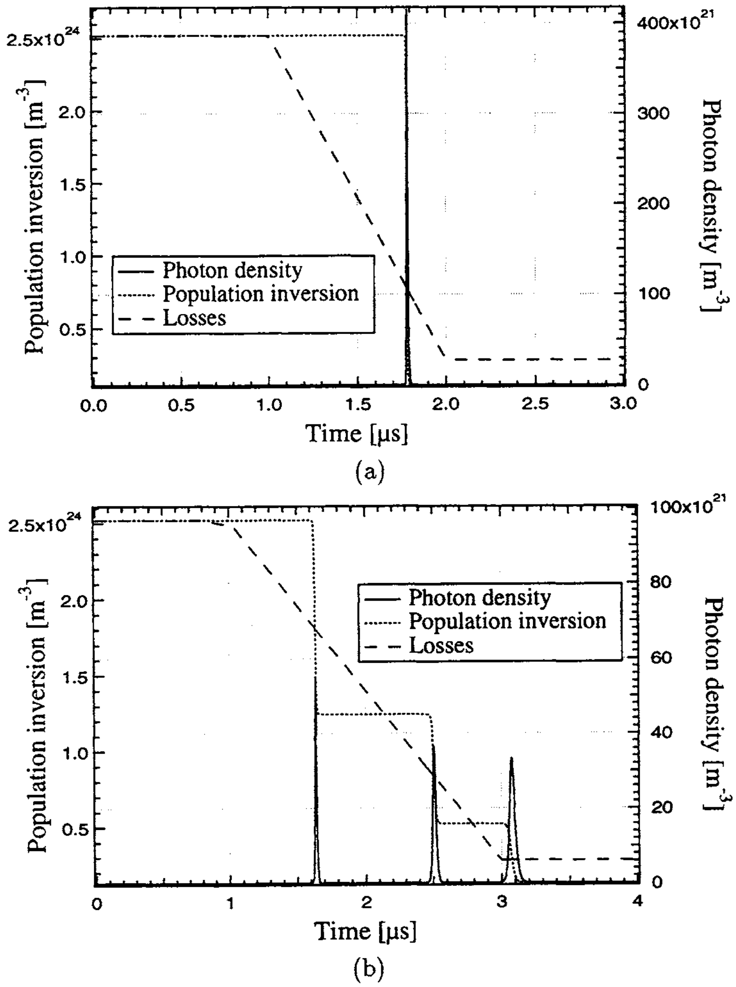


Figure 7. (a) Simulation of a Q-switched pulse with a quality factor rise time of $1\mu s$. (b) Simulation of a Q-switched pulse with a quality factor rise time of $2\mu s$.

The losses are first kept high and are then suddenly switched down with different rise times: 1 μs for Fig. 7(a) and 2 μs for Fig. 7(b). Fig. 7(b) shows three peaks, the two secondary peaks are due to a too slow switching time. If we consider Fig. 7(a), we can see that shortening the switching time from 2 μs to 1 μs leads to a single and higher peak. The rise time of the switching losses is of main importance to improve the output power of our pulsed laser. We can see that in shortening the rise time of the mirror, we will shorten the rise time of the losses and thus shorten the pulse duration. As a consequence, the peak power increases (see Fig. 7). However, if we compare with the measured pulse duration (see Fig. 5) we can see that the experimental pulse width is around 40 times larger than the simulated one. This difference is not very well understood at the moment, but corresponds to a difference in the simulated ouput power (typically 10 W) and the measured output power (typically 200 mW).

3. OPTO-MECHANICAL SWITCH FOR TELECOMMUNICATION RING NETWORKS

New concepts of photonic networking are being developed to increase dramatically the data capacity of optical fiber communication networks. A prototype system based on the wavelength division multiplexing (WDM) principle is developed at the IBM Zürich Research Laboratory. It makes possible to transmit multiple data channels simultaneously at different wavelengths over a single fiber. Optical switches bring reconfigurability for transmitters and receivers as well as easy bypassing nodes by using just one redundant fiber (see Fig. 8). Opto-mechanical switches will enhance the versatility of the prototype significantly.

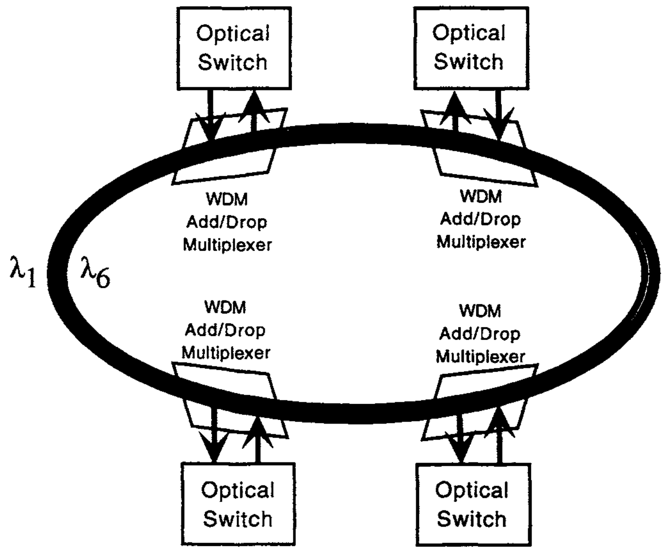


Figure 8. WDM ring network.

3.1. Optical Switches

Optical switches are an attractive alternative to electrical switches in electro-optical systems, because of their low weight and immunity to electromagnetic interference, and because they eliminate the need for optical-to-electrical and electrical-to-optical conversion at the switch. Some non integrated switches are already commercialized, but all use big mechanical systems for fiber positioning and are extremely expensive. Optical switches that utilize micromechanical switching elements are best suited for integration (low price mass production); they can provide high contrast, large bandwidth and have multiple wavelength compatibility. Two different concepts for a micro-opto-mechanical switch have been considered.

The first concept (see Fig. 9 (a)) is based on a fiber holder, a focusing optical element (micro-lens) and an array of torsional micro-mirrors (see Fig. 10). The mirrors are in the back focal plane of the lens. In our case, we use microlenses which have been fabricated at our institute with the melting resist technology.[9] For this configuration a diameter $\phi = 1050$ μm and a focal length f=3.7 mm have been choosen. The fibers are held in grooves with a pitch of 250 μm.

The second concept (see Fig. 9 (b)) consists of an array of fibers in a star configuration, an array of micro-lenses and an array of micro-mirrors (see Fig. 10). In such a configuration the output fiber is imaged onto the micro-mirror, which provides more freedom in the choice of the magnification and the length of the device. In this case, the micro-lenses have a diameter $\phi = 245$ μm and a pitch of 250 μm. The fibers are placed at a pitch of 250 μm and are rotated by an angle of 5.2°. In the imaging configuration, the spot size can be adapted to the size of the micro-mirror. Whereas in the first concept (Fig. 9 (a)) the light spot on the mirror is determined by the beam waist radius ω_{01} at the fiber output and the focal length f of the lens, i.e. by

$$w_{02} = \frac{\lambda f}{\pi w_{01}} \tag{5}$$

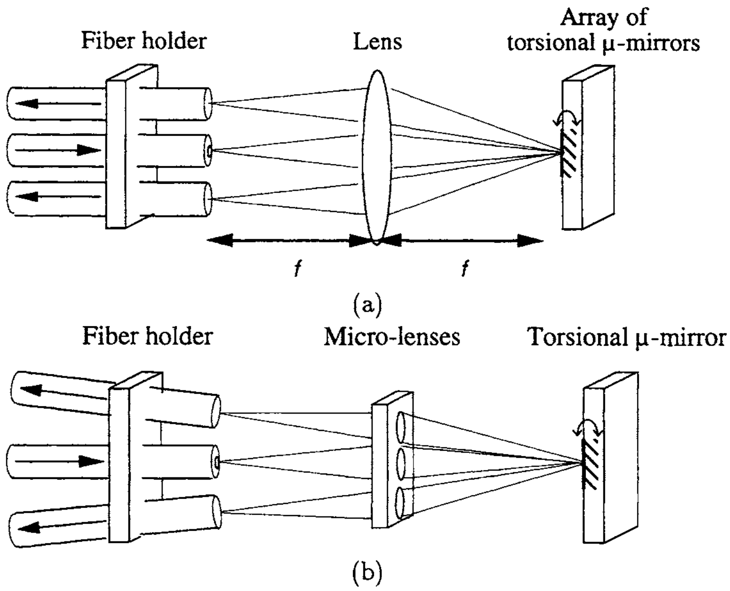


Figure 9. (a) First concept for a free space optical switch with one micro-lens. (b) Second concept for a free space optical switch with image formation.

where w_{02} is the waist radius after the lens and λ the wavelength. We are actually investigating arrays of micro-mirrors (see Fig. 10) fabricated by polysilicon micromachining[10] at our institute. They can be rotated by $\pm 2.6°$ which deflects the light by $\pm 5.2°$. Similar arrays of micro-mirrors are now commercially available.[11] Considering three fibers with a pitch of 250 μm, we need a lens with a focal length of around 2.75 mm to deflect the light from one fiber into the other. From Eq. 5 we can now calculate the diameter of the beam on the micro-mirrors. For a single mode fiber with a core diameter of $10\mu m$ at $\lambda = 1.55\mu m$, we get a diameter of $2w_{02} = 542\mu m$ ($2w_{01} = 10\mu m$). Such a size in the waist diameter requires to use several micro-mirrors, one micro-mirror being $50\mu m x 70\mu m$. The array has a fill factor of 62% thus providing some intrinsic losses. Using one bigger micro-mirror would increase the switching time.

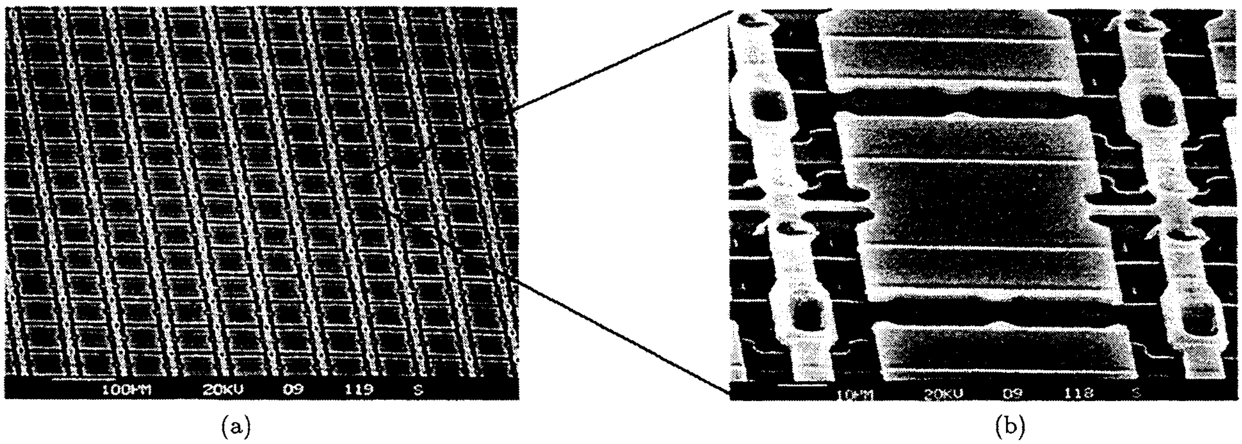
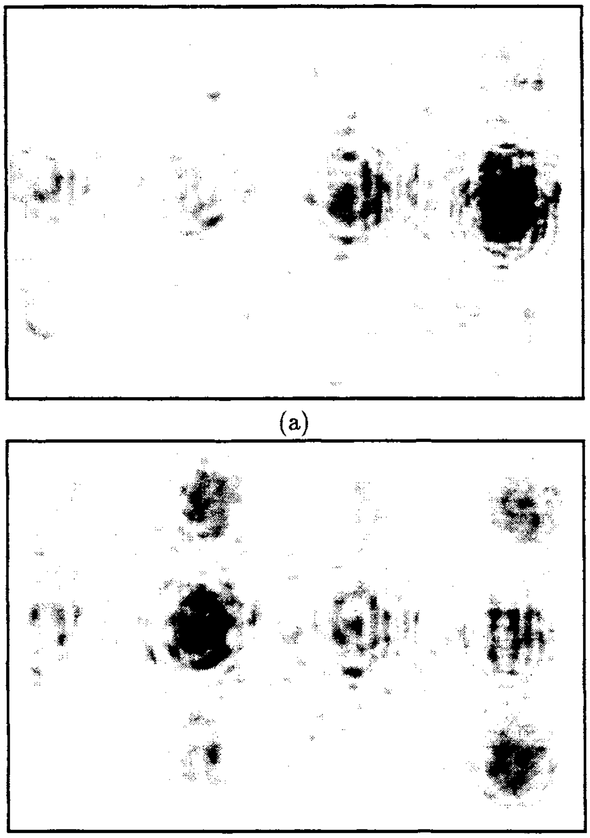


Figure 10. (a) Array of torsional -mirrors (SEM view). (b) Single micro-mirror (SEM view).

The array of micro-mirrors generates a discrete diffraction pattern :

$$sin(\theta_m) = m\frac{\lambda}{\Lambda} \tag{6}$$

where m is the diffraction order, λ is the wavelength and Λ is the period of the micro-mirror array. We can now deflect the beams by tilting the micro-mirrors. However, only discrete directions θ_m can be adressed. Fig. 11 shows the diffraction pattern for $\lambda = 633\ nm$, $\Lambda = 75\ \mu m$ and different tilt angles of the mirrors. Note that it is not possible to compensate alignement errors by a linear adjustment of the mirror angle. The fine tuning of the beam direction has to be done differently, e.g. by shifting the positions of the fibers.



(a)

(b)

Figure 11. (a) Diffraction pattern generated with mirrors at rest position. (b) Pattern generated with tilted mirrors; the spot switched to the 2nd diffraction order.

3.2. Outlook

We are investigating the fundamental limitations (limited number of fibers, speed, losses) of the presented concepts for a compact reconfigurable opto-mechanical switch based on diffractive and refractive micro-optical elements. In order to further miniaturize the system, we are also developing a new integrated optical switch (see Fig. 12) which uses U-grooves for the fibers, integrated lenses and a vertical mirror micromachined in silicon by deep anisotropic reactive ion etching.[6] The focusing elements are planned to be either micro-lenses, ball-lenses or even integrated self-aligned lenses. The reconfigurability of the system will be enhanced in another developing step. We plan to use a 2-dimensional fiber bundle to get a 3-dimensional system, as shown in Fig. 13.

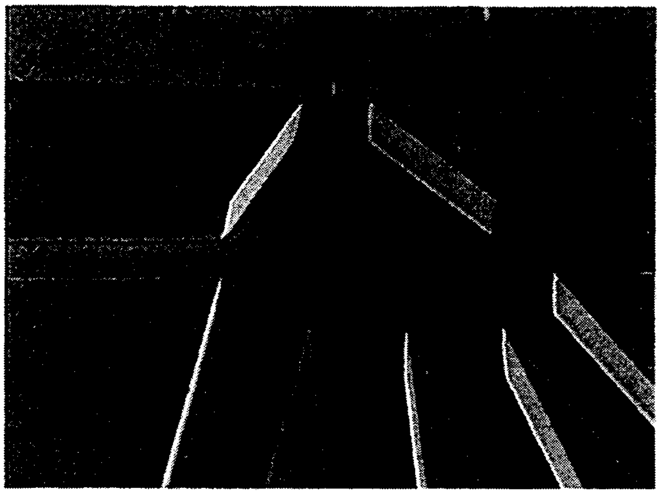


Figure 12. SEM view of a vertical mirror with U-grooves.

4. CONCLUSIONS

Two different applications of micro-mirrors have been presented. The first is a compact pulsed fiber laser. Compared to our previous prototype,[3] the pulses generated are similar, but the stability of the device was greatly improved. The second application is an optical switch for telecommunication ring networks. Two different concepts have been presented; first switching tests have been performed using an array of micro-mirrors. Furthermore, the technology for the fabrication of the mirrors is compatible with the fabrication of other micro-optical elements, such as microlenses, fan-out and fan-in elements[12] which enables the realisation of compact microsystems.

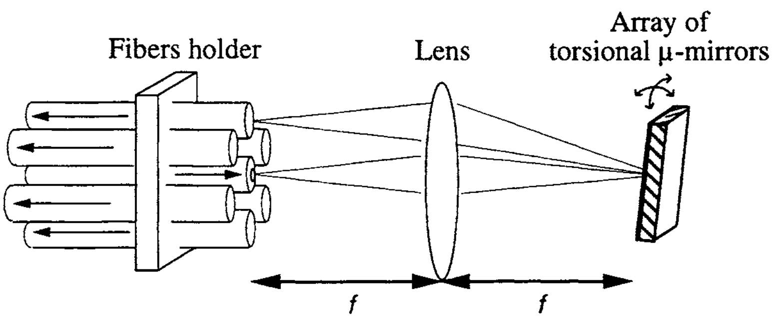


Figure 13. Schematic drawing of a 3D optical switch with a fiber bundle (one input fiber and six output fibers.

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