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Deformable micro-electro-mechanical mirror integration in a fibre laser Q-switch system

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Abstract
We demonstrated active Q-switching of an erbium-doped fibre laser using a deformable metallic micro-mirror. The electrostatically actuated micro-mirror acts as one of the laser cavity reflectors and, at the same time, as a switching/modulator element. When actuated, its shape changes from planar to a concave curvature, allowing control of the Q-factor of the laser cavity. The mirror/switching element is small, compact, highly reflective and achromatic, with a great integration potential. The laser system operates at frequencies between 20 and 120 kHz and generates short pulses (FWHM down to 300 ns) and high peak powers, up to 160 times greater than the continuous emission.

Keywords: optical MEMS, deformable mirror, fibre laser, Q-switch

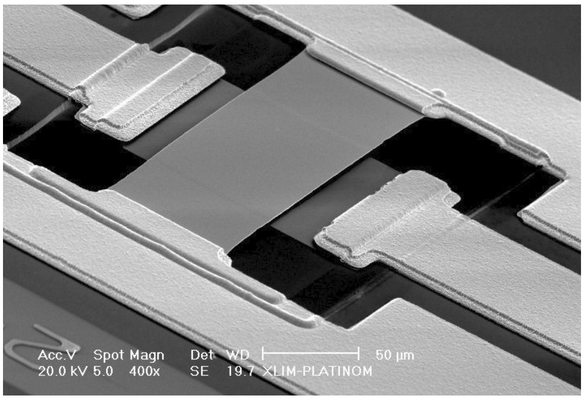
(Some figures in this article are in colour only in the electronic version)

1. Introduction

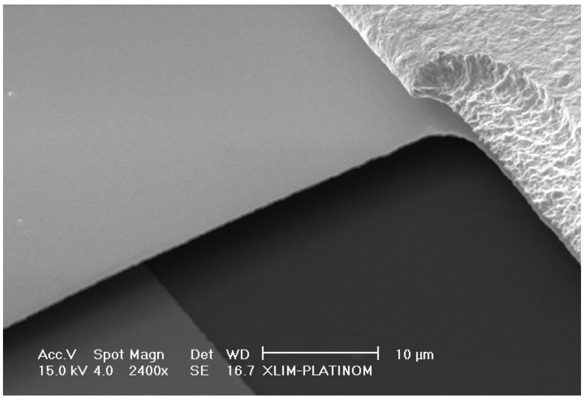
The association of micro-optics and micro-electro-mechanical systems (MEMS) creates a new and relatively broader area of devices, the micro-opto-electro-mechanical systems (MOEMS). Their properties (compact, scalable, low insertion losses, low cross-talk, polarization insensitive) along with their emerging functionalities as optical switches, micro-scanners and variable attenuators/shutters find extensive applications in telecommunications, astrophysics, biology and imaging etc [1]. Along with optical switches, tunable or high-power micro-lasers are key components in future optical networks. Within this framework MOEMS technology has been shown to be very promising for the fabrication of miniaturized tunable [2] or pulsed fibre lasers [3], adding merits of compactness, high speed and batch, and low-cost production.

In order to generate a pulse in a conventional Q-switched fibre laser, a passive or active modulator (acousto-optic or electro-optic, saturable absorbers, mechanical components) has to be introduced into the cavity [4]. Although the conventional solutions for laser Q-switch generation are based on solid, mature technologies, most of them present inherent disadvantages that restrain their integration in miniature, compact laser systems: degradation of the beam quality, high insertion losses for the acousto-optic modulators [5], high voltages and low modulation frequencies for the electro-optics solutions [6], bulkiness for mechanical choppers, low laser power level operation for piezoelectric Bragg gratings systems [7] or lack of control of frequency and pulse width for the passive modulators.

Our paper describes a fibre laser system coupled with an electrostatic-actuated micro-mirror, which acts as one of the two reflectors of the laser cavity and as a switching/modulator element. The goal is to obtain laser systems emitting short, high-power pulses and having a variable repetition rate. The advantages of such an element reside in its low fabrication cost and its high potential for integration in a compact micro-system.



a.



b.

Figure 1. Scanning electron micrograph (SEM) of a typical metallic micro-membrane (a) and a closer view of the suspended mirror over the actuation electrode (b).

2. Electrostatically actuated mirror

The fabricated micro-mirror consists of a 500 nm thick thermal evaporated gold membrane (bridge-type) suspended over an actuation electrode placed 2.2 μm underneath the membrane and covered with a dielectric thin film (Al_2O_3, 200 nm thickness). The bridge is sustained at its extremities by thick metallic anchorages (made of plating gold) in order to increase its stiffness. The fabrication steps follow the general MEMS manufacture technology and are similar to those described in [8]. Briefly, the electrodes (signal and ground lines) were patterned on a 5/150 nm thick Ti/Au bi-layer made by thermal evaporation on Si or quartz substrates. Then, the Al_2O_3 dielectric layer was deposited either by pulsed laser deposition (PLD) or plasma enhanced chemical vapour deposition (PECVD). A 2.2 μm thick photoresist layer (Shipley, S1828) was spin-coated and lithographically patterned as the sacrificial layer and a 0.5 μm thick gold layer was further evaporated to form the bridge. The anchors of the bridge and the electrodes were thickened up to $\sim$3 μm using gold electroplating in order to increase the stiffness of the device. The last steps included patterning of the mirrors using wet etching followed by releasing the suspended membranes (by removing the sacrificial layer using acetone and isopropyl alcohol).

Figure 1 shows a SEM micrograph of such a mirror having dimensions of 240 $\times$ 160 μm^2, which is the largest element of an array (partly shown in figure 2) containing 30 membranes with different dimensions (the smallest ones having an area of 120 $\times$ 60 μm^2).

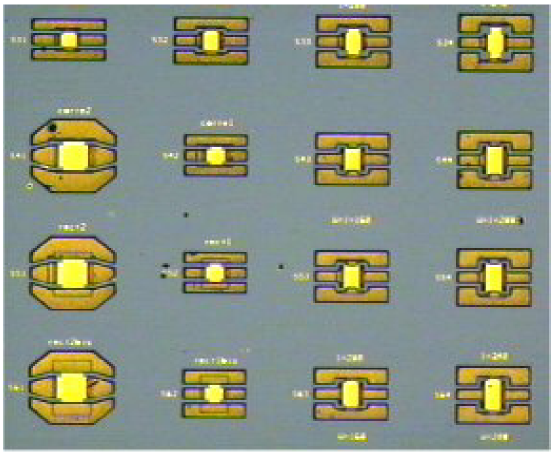


Figure 2. Optical microscopy overview of micro-mirrors with different dimensions.

When applying a pulsed modulated voltage between the membrane and the electrode, the bridge simply moves down and up (piston-like) by combining the action of the electrostatic force (between the bottom electrode and the bridge) and that of the mechanical restoring force given by the bridge stiffness. The dielectric assures an electrical isolation between the membrane and the landing electrode during the actuation. The parameters for the membrane fabrication (thickness, deposition rate, component dimensions, distance to the landing electrode) were optimized to obtain high-stiffness bridges (measured spring constants between 20 and 70 N m^{-1}, depending on the dimensions) with low switching times (1–3 μs) and low actuation voltages (15–35 V). The mirrors have low roughness ($\sim$2 nm rms as recorded by AFM) and reproducible mechanical and electrical behaviour. Most of them were actuated for more than 1 billion cycles with a bi-polar waveform voltage without any sign of mechanical degradation or switching failure.

When actuated, the membranes act like a mirror with variable curvature, passing from planar (in the non-actuated, off-state) to a curved-concave shape (in the actuated, on-state). Depending on the membrane dimensions, the maximum radius of curvature may vary from 1.45 mm for the 160 μm long bridges to 4.45 mm for the longest ones (240 μm long). In the off-state, the membrane reflects back into the cavity the incident radiation (high Q factor cavity), while in the on-state the incident beam is deflected under an angle of $\sim$9° outside the cavity (low Q-factor laser cavity). When the Q-factor modulation became fast enough the laser system reached the Q-switching regime (generation of narrow, high-power pulses).

3. Pulsed fibre laser system

An important parameter for generating high-energy pulses in a Q-switched fibre laser is the modulator speed. In our case, this parameter translates into the mirror-operation speed,

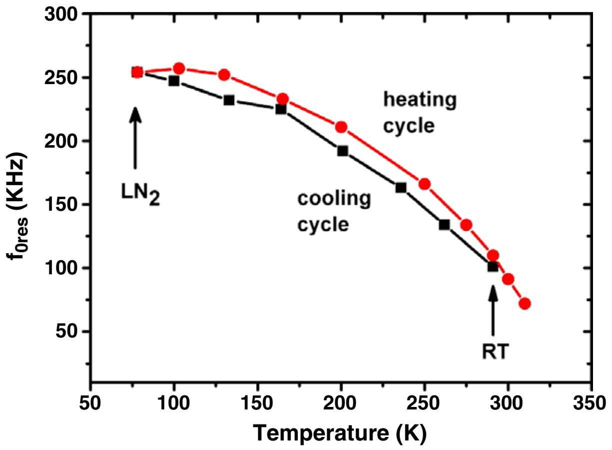


Figure 3. Mechanical resonant frequency evolution with temperature for a 240 × 160 μm^2-area micro-mirror.

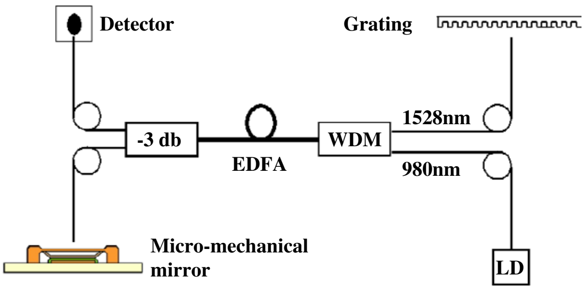


Figure 4. Schematic diagram of the pulsed fibre laser system using micro-mirror modulation.

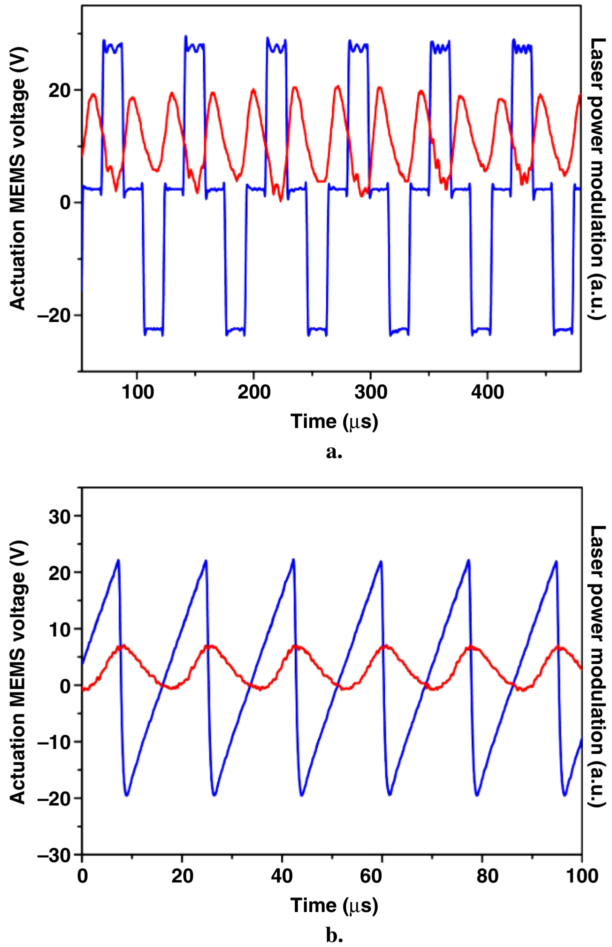


Figure 5. Overlap traces of the micro-mirror waveform actuation signal and of the output laser emission modulation for (a) bi-stable (ramp) actuation (28 kHz, 27 V) and (b) slope-type actuation (57 kHz, 23 V).

which is determined, in a first-order approximation, by the mirror's mechanical primary resonant frequency. The higher this frequency, the faster the laser modulation. The goal is then to reach the optimal modulation frequency to obtain maximum efficiency of the Q-switch operation.

Depending on the dimensions, the mirrors have a relatively high mechanical resonant frequency at room temperature (RT), ranging from ~90 kHz (for the 240 × 160 μm^2-area membranes) up to 170 kHz (for the 120 × 60 μm^2 ones). Figure 3 shows the temperature evolution of the resonant frequency for a 240 × 160 μm^2-area mirror undergoing a cooling–heating cycle between RT and liquid nitrogen (LN_2) temperature (77 K). During the cooling cycle, the resonant frequency increases up to 250 kHz but the membrane recovers its mechanical behaviour when heated back to RT.

Figure 4 shows a simplified set-up of the pulsed fibre laser oscillator with integrated micro-mirrors. The fibre laser is based on an Er_3^+-doped fibre amplifier (EDFA), longitudinally pumped by a laser diode emitting at 980 nm, spliced to a wavelength division multiplexing (WDM) coupler enabling the use of a grating (1200 tr mm^{-1}, 94% reflectivity at 1064 nm) as an output reflector. On the opposite side, the fibre amplifier is spliced to a 3 db coupler: an output is directed to the micro-mirror while the other one goes to the detection system. The laser cavity is formed between the grating and the deformable micro-mirror (87% measured reflectivity at 1064 nm). At the other coupler output, the laser emission could be tuned according to the grating position (here $\lambda = 1528$ nm).

Experimentally, the output fibre from the laser is placed close to the micro-mirror and slightly tilted with respect to the normal incidence to facilitate greater reflectivity discrimination between the off- and on-states of the mirror. The micro-mirror was actuated with bi-stable (ramp) voltage waveform at frequencies between 600 Hz and 140 kHz. Figure 5(a) shows the laser emission pulse train obtained with a 180 × 80 μm^2-area mirror actuated at 28 kHz with voltage amplitudes of 27 V. The full width at half maximum (FWHM) of the laser pulse is 20 μs. A similar actuation with a triangular-type waveform at 57 kHz and an amplitude voltage of 23 V allows us to obtain pulses of less than 10 μs (FWHM) (figure 5(b)).

Depending of the modulation frequency of the MOEMS, the peak power of one laser pulse is only 25–50% higher than that of the continuous laser emission. Moreover, the pulses are always superposed over a laser continuous emission. This can be explained by the extremely high-gain of the laser fibre for which a single pass of the pumping light is enough for lasing corroborated with the relative difficulty in aligning the end of the fibre laser to the mirror in a way that allows us to obtain the greatest reflectivity discrimination during the

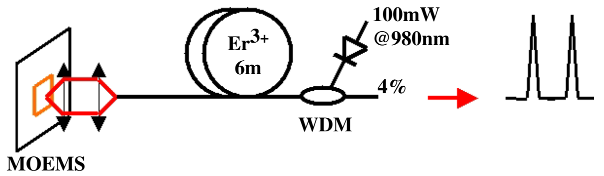


Figure 6. Set-up of the laser fibre system using an imaging scheme for aligning the laser beam onto the optical MEMS element.

mirror actuation. In order to resolve the alignment problems, the set-up was modified by introducing an imaging system based on two confocal lenses between one of the fibre ends (angle cleaved) and the optical MEMS element, as presented in figure 6. The other end of the fibre is right-angle cleaved and used as an output mirror. The EDFA is side pumped by a laser diode (100 mW, $\lambda = 980$ nm) through a WDM.

In such configuration, the laser can be exploited to perform Q-switching. We were able to produce high-power train pulses with a repetition rate that can be continuously tuned from 20 to 120 kHz and which depends directly on the actuation frequency of the micro-mirror. For 80×140 μm^2 area membranes the FWHM of the pulses runs from 320 ns for lower actuation frequencies (around 30 kHz) up to 1 μs for higher frequencies (120 kHz). Figure 7 presents a typical pulse train for two different actuation frequencies. The average output power of the laser system is around 30 mW, which demonstrates that pulses with peak power of several watts can be achieved. For actuation frequencies below 20 kHz, the modulation is too slow to obtain an efficient Q-switching process: the laser produces multiple pulses corresponding to mechanical relaxation oscillations of the mirror [9].

The wavelength spectrum of the pulsed laser emission (figure 8) shows a maximum of intensity at ~1530 nm, which corresponds well to the Er^{3+} gain band pass.

We are currently designing and implementing similar types of optical switching elements that are faster and present higher reflectivity discrimination states during actuation. Shortening of the switching time of the membranes/mirrors will lead to narrower laser pulses with higher peak powers as well as higher pulse repetition rates. The high reflectivity discrimination states will avoid the use of the additional imaging system and will lead to a smaller, more compact system.

The simplicity of this Q-switch generation technique makes it suitable for implementation in more complex set-ups including solid-state micro-lasers, multi-wavelength fibre lasers or different families of fibre lasers (Yb- or Er–Yb-doped) actuated independently or synchronous for wavelength mixing/tuning applications. The combination of this active Q-switch system with a passive nonlinear technique should permit us to provide shorter pulses with higher peak power.

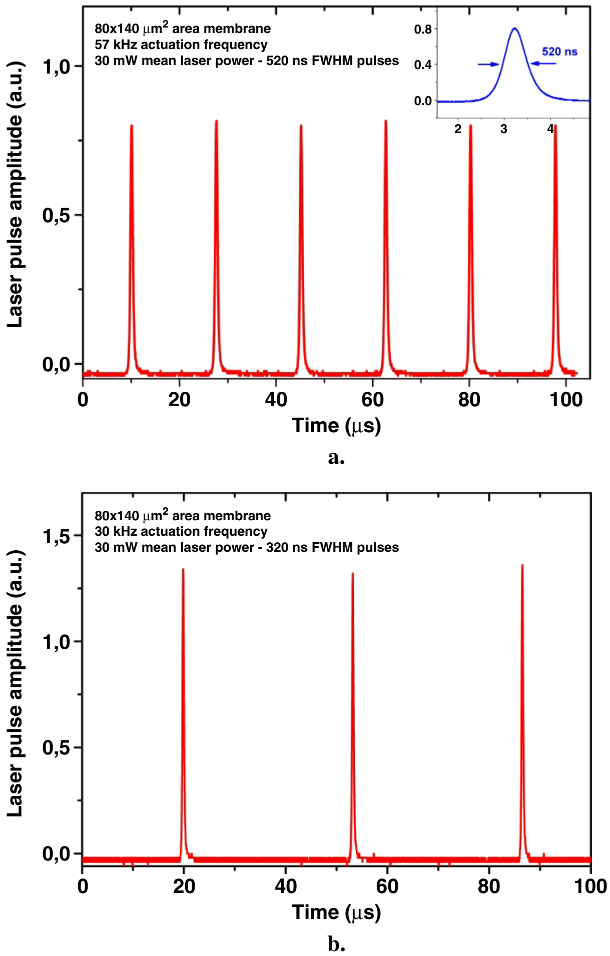


Figure 7. High power pulse train generation using an optical MEMS element for different actuating frequencies: 57 kHz (a) and 30 kHz (b).

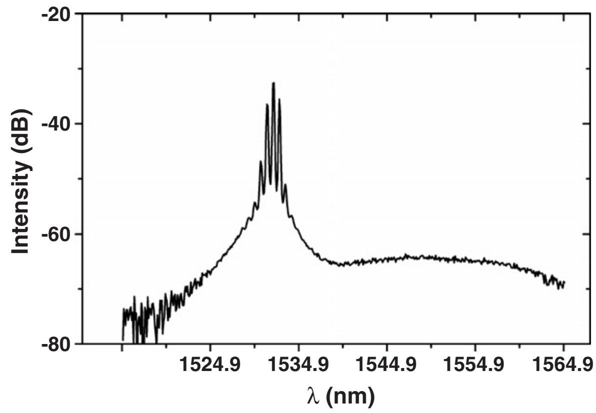


Figure 8. Wavelength spectrum of the Q-switched EDFA laser emission.

4. Conclusions

In summary, we reported a simple, suitable technique to produce active Q-switching in a fibre laser system. Our contribution represents a first approach for developing miniature, high-power lasers integrated with deformable micro-mirrors. The switching element is based on an electrostatic-actuated micro-mirror that is coupled with a fibre laser. The optical element presents very good mechanical, electrical and optical performances (high reflectivity, achromatic, polarization insensitive) and is fabricated using a low-cost, batch, and simple, standard fabrication process. The repetition rate of the active Q-switching system can be tuned between 20 and 120 kHz. Using a pump power of 100 mW, pulses of several watts peak power can be obtained, with a pulse width as low as 320 ns. The switch can be integrated with various types of laser amplifiers running at different wavelengths. Optimization of the laser Q-switching using such micro-mirrors will enable immediate development of applications like laser wavelength mixing or multi-laser emission synchronization.

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