Applications of SOI-based optical MEMS

Wilfried Noell, Pierre-André Clerc, Laurent Dellmann, Benedikt Guldimann, Hans Peter Herzig, Omar Manzardo, Cornell Marxer, Ken Weible, René Dändliker, and Nico de Rooij

Abstract-- **After micro-electro mechanical systems (MEMS) devices have been well established, components of higher complexity are now developed. Particularly, the combination with optical components has been very successful and have led to optical MEMS. The technology of choice for us is the silicon-on-insulator (SOI) technology, which has also been successfully used by other groups. The applications presented here give an overview over what is possible with this technology. In particular we demonstrate four completely different devices: a) a 2x2 optical cross connector (OXC) with an insertion loss of about 0.4 dB at a switching time of 500 µs and its extension to a 4x4 OXC, b) a variable optical attenuators (VOA), which has an attenuation range of more than 50 dB, c) a Fourier transform spectrometer (FTS) with a spectral resolution of 6 nm in the visible, and d) an accelerometer with optical readout that achieves a linear dynamic range of 40 dB over ±6g. Except for the FTS, all the applications utilized optical fibers, which are held and self-aligned within the MEMS component by U-grooves and small leaf springs. All devices show high reliability and a very low power consumption.**

Index Terms-- **MOEMS, optical MEMS, optical devices, switches, spectrometers, attenuators, accelerometers.**

I. Introduction

The significant impact of micro-electro mechanical systems (MEMS) in the sensor technology has lead to many new and very small and well controlled devices. In the optical domain MEMS components are becoming more and more relevant, particularly for the telecommunication industry and optical sensor technology.

Regarding the telecommunication industry, there are four main device domains: Amplifiers, switches or optical cross connectors (OXC), filters and variable optical attenuators (VOA). The amplifiers are made nowadays by optically pumped Erbium doped fibers and are usually referred to as EDFA (Erbium Doped Fiber Amplifiers). These purely optically working devices are fast and do not require any mechanical components. This becomes very different, when looking at the other three domains. OXC and VOA are based on mechanical elements and are hence relatively slowly working devices. This is accepted, because these devices have to work in routers and amplifiers and under conditions that are almost static compared to the modulation frequencies of typically several GHz of the optical signals. Filters for wavelength demultiplexing (WDM) are based on tunable thin film devices or integrated optical elements, which are tuned either mechanically or thermally, and are hence also relatively slow. Two different optical MEMS components that are relevant for telecommunication applications are presented in this paper: A 2x2 and 4x4 OXC and an attenuator.

Although many optical MEMS devices are driven by the telecommunication industry other research and industry areas are relevant as well. Optical spectroscopy is one of this fields. When high spectroscopic resolution is required, optical spectrometers are still relatively big. The same applies to infrared spectroscopes where almost no small solutions are available. In this branch optical MEMS can lead to important technological breakthroughs. A step towards this optical domain is a MEMS based Fourier transform spectrometer (FTS), which will be presented here.

Since it is very easy to measure optical intensities, the modulation of light by a MEMS component can be used as an effective measurement signal of a mechanical movement or displacements. Utilizing the light modulation of a MEMS based fiber coupler lead to an highly accurate accelerometer, the last device presented in this document.

This publication delivers a brief overview over different optical MEMS activities of IMT that are based on silicon-on-insulator (SOI) technology. It would be beyond the scope of this paper to describe all effects, particularities, and the in-depth theoretical background of the presented devices. The reader may refer to the corresponding

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The bi-stable 2x2 OXC, which is described in Chap. III.A. and in Fig. 2b, was fabricated by the University of Neuchâtel (IMT), Switzerland, under contract of OCLI, Inc./JDS Uniphase. It was first published as a postdeadline contribution by OCLI on the optical MEMS conference in Kauai, Hawaii, USA, in August 2000.

Financial support for part of the work was provided by the Swiss Federal Office for Education and Science (Collaborative Projects of the European Union).

previously published and specialized publications which are listed in the references.

The authors focus on the activities of IMT. There are many other groups that have been working very successfully on similar devices based on SOI technology. E.g. the group around O. Solgaard (Stanford University, CA, U.S.A.) work actively on scanning mirrors, light modulators and other optical MEMS's. Ming Wu and Norman Tien (Cornell University, University of California of Los Angeles and Davis, respectively, U.S.A.) as well as Hiroshi Toshiyoshi and Hiroyuki Fujita (University of Tokyo, Japan) have shown many novel devices based on SOI surface micromaching. The department of Youn Tae Kim (Electronics and Telecommunications Research Institute (ETRI), Daejeon, Korea) works successfully on switchable mirrors in collaboration with Masayoshi Esashi (Tohoku University, Japan). Optical MEMS activities based on SOI technology are also pursued by the group of Young-Ho Cho (KAIST, Taejon, Korea). Many companies, e.g. JDS Uniphase, Lucent Technologies, Kionix, Tronics, OMM, Leti, Texas Instruments and many more utilize SOI processes for their products as well.

A particularity of the IMT silicon bulk micromaching lays in the used substrate: Handle and device wafer are both made of single crystalline silicon, which is different from the similar looking surface micromaching which utilizes polycrystalline silicon on top of the buried SiO_2 layer. The single crystal silicon delivers smoother surfaces after the dry etching and has in general better mechanical properties. All the optical MEMS components that we demonstrate here are based on one and the same technology, the SOI technology, whose basics will be briefly explained in the following paragraph.

II. SOI Technology

The big advantage of the SOI technology is its simplicity and small number of process steps, because there is usually only one patterning and one depositing step involved. The most critical process step, however, is the deep reactive ion etching (DRIE) that determines the structure itself and surface roughness of the sidewalls of the crucial optical elements of the device (Fig. 1).

The substrate for this process is a composite wafer, whose substrate is a silicon wafer of 100 mm in diameter. Above the substrate is a silicondioxide layer of 2 µm thickness. The top most layer is the so called silicon device layer, which has a thickness of 75 µm in our case (Fig. 1a).

The first step is the photolithography that patterns the positive photoresist (Fig. 1b). The photoresist is used to dry-etch the silicon of the device layer by deep reactive ion etching (DRIE) (Fig. 1c). The DRIE etched trenches comprise vertical walls. This way, rather narrow structures of about 2 to 5 µm can be achieved with very smooth sidewalls, which is not possible with wet etching solutions such as KOH. The buried SiO_2 serves as an etch stop for the DRIE. Since the etch rate is different in the middle of the wafer and at its outer regions as well as for narrow and wide structures, an etch stop is absolute necessary to guarantee that all structures have the very same height and width required by the mask design. After the DRIE the resist is removed by oxygen plasma etching.

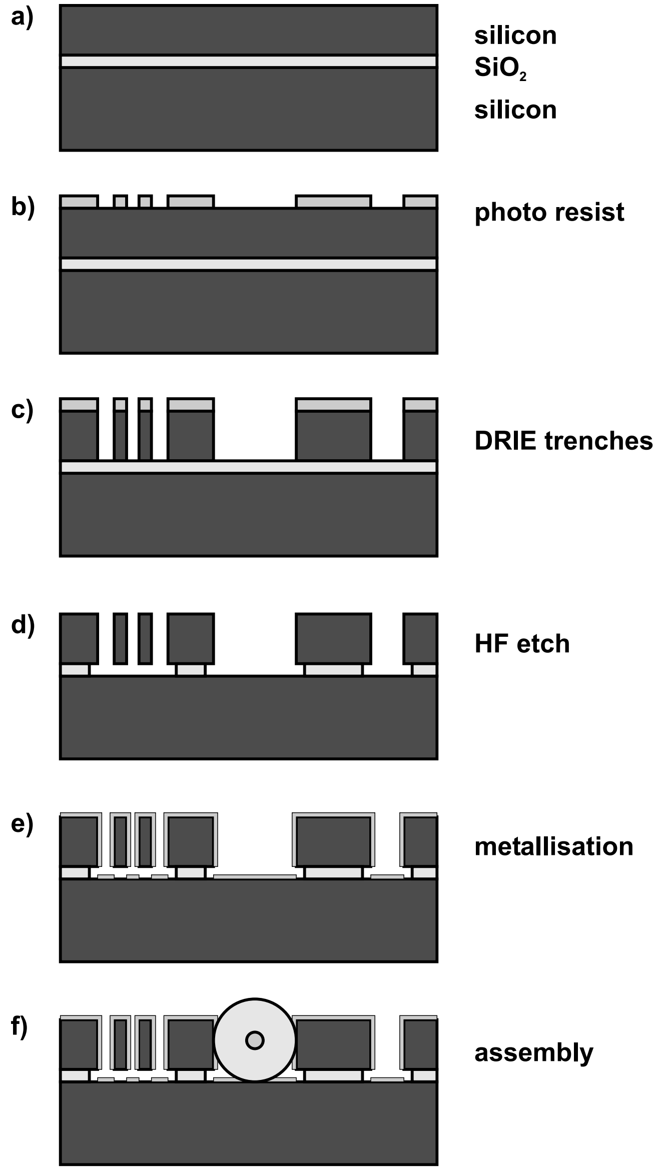

Fig. 1. SOI technology: a) The process starts with an SOI wafer which is a composite of a silicon substrate wafer, a buried silicondioxid (BOX) layer, and a device layer, which is in our case 75 µm high. b) and c) The wafer is patterned by DRIE utilizing a positive photoresist mask. d) The structures are released by wet-etching the BOX underneath the structures that have to move freely during the actuation. e) The metallisation improves the surface conductivity and reflectivity. The structures that are not connected via the patterned silicon are electrically isolated from each other by BOX pedestals. f) Integrated alignment structures such as U-grooves are used for the assembly of optical components, e.g. optical fibers.

To release the structures the buried SiO_2 has to be removed (Fig. 1d). The etching takes place in 50%

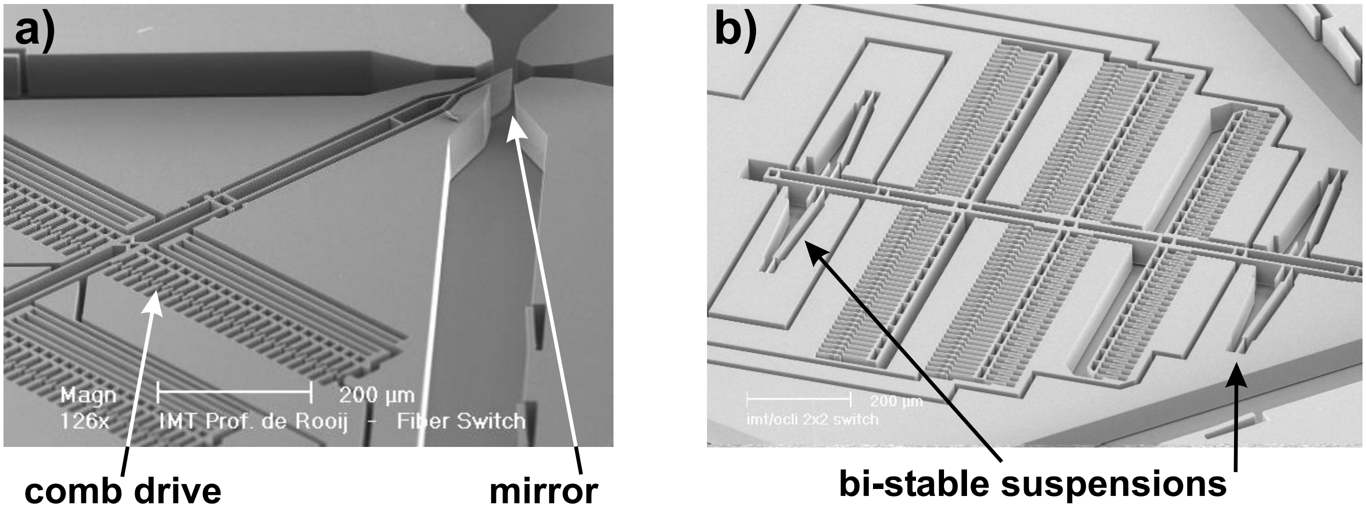

Fig. 2. a) The 2x2 switch can hold four optical fibers. The thin mirror is actuated by comb drive actuators. Leaf springs create the counter force and the suspension of the beam that holds the mirror. b) In a further design, the suspensions are bi-stable. In this design the switching is performed by voltage pulses. In both devices the optical fibers are held by small leaf springs which are integrated in the sidewalls of the U-grooves.

concentrated hydrofluoric acid (HF). The HF etch time is adjusted such, that those parts are completely underetched, which have to move freely during the later actuation. SiO_2 pedestals, however, have to remain under the supporting parts of the MEMS structure. The SiO_2 also serves as an insulator between the different electrodes of the final device.

To increase the conductivity of the device surface and for a proper reflectivity of the mirrors, gold is deposited by electron beam evaporation over the whole device without any masking or patterning (Fig. 1e). In the final step different optical components, e.g. optical fibers, can be attached to the MEMS component (Fig. 1f). Guiding structures, e.g. U-grooves, are integrated in the MEMS design to guarantee a high alignment among the different optical components. The U-grooves can comprise little leaf springs to hold the optical components in place.

III. Devices for Telecommunication

There are two devices that have proven successful when entering into applications for fiber optic communication: a) A 2x2 optical fiber switch and b) a variable optical attenuator (VOA) [1,2]. An extension of the 2x2 switch towards a 4x4 switch of higher complexity will also be presented.

A. *2x2 Optical Fiber Switch*

The 2x2 OXC has two input and two output fibers. In the MEMS component, the four fibers sit in 75 µm high U-grooves and are oriented at right angles to each other. Their endfaces all meet at one point, where a movable gold-coated mirror is located. This way, the light of either one of the input fibers can be switched to either one of the output fibers.

To enhance the optical performance and minimize the loss, all the optical components are completely surrounded by refractive index matching fluid. The device is placed into a hermetically sealed housing to prevent leaking of the oil. The index matching fluid reduces two effects: first the index step between the fiber endfaces and the ambient and secondly the divergence of the freely propagating light in the ambient and hence the beam diameter, which both leads to an increasing coupling efficiency between the fibers.[1]

The mirror is attached to a long beam that is electrostatically actuated by comb drives (Fig. 2a). In the first design suspending leaf springs created the restoring mechanical force. The driving voltage to overcome the linearly acting mechanical counter force is in the order of 50 to 100 V. Applying no voltage resets the switch back into its zero or ground position.

In a further more advanced design, the switch is bi-stable or more mechanically spoken latching (Fig. 2b). Every time the switch needs go from one to the other of its two possible positions only a short voltage pulse needs to be applied. The mirror then remains in the corresponding position without any driving voltage.[3]

The optical and mechanical properties of the switch are excellent. The insertion loss is between 0.3 and 0.5 dB. The switching time is about 500 µs and the live time was tested to be $5 \cdot 10^9$ cycles at 85°C (corresponds to $2 \cdot 10^{11}$ at room temperature). The cross talk between the fibers is as low as -70 dB. There is basically no polarization dependency to the coupling efficiency.

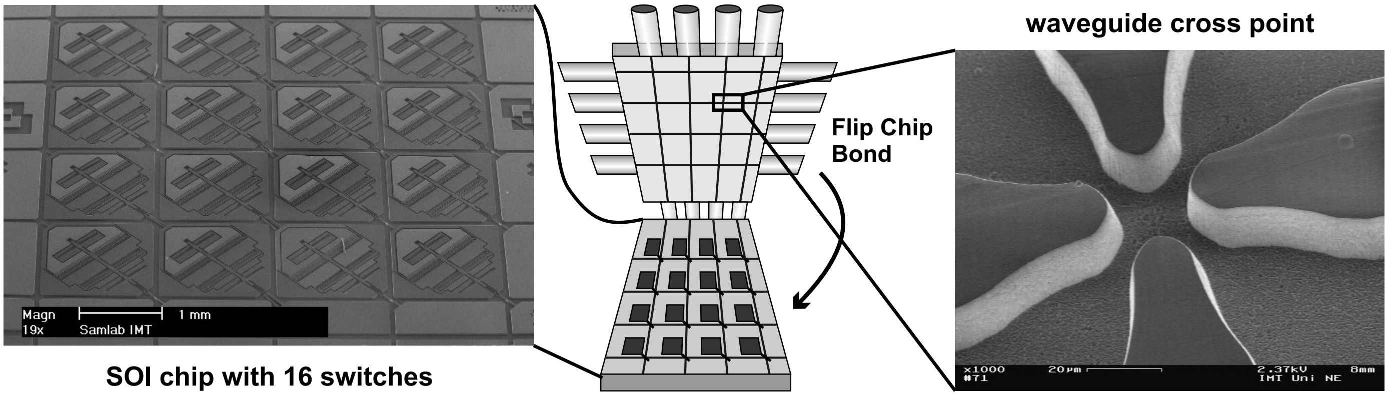

Fig. 3. In the new concept of the 4x4 OXC, the scalability of the 2x2 OXC is tested. The design includes two chips. The bottom chip holds 16 electrostatically actuated mirrors. The switches are bi-stable trough a latching mechanism. The top chip includes the integrated optical waveguides and the electronic wiring for the bottom chip. Attached to the waveguide chip are the optical fibers. In order to insert the waveguides into the chip structure in the same fashion as the optical fibers into the 2x2 OXC, the waveguides are etched by DRIE. The two chips are to be connected by flip-chip bonding.

B. *4x4 Switch Design*

The 2x2 switch has demonstrated high reliability. Thus our current development examines the scalability of the technology to achieve NxN OXC [4]. The first approach aims at a 4x4 OXC and consists of 16 2x2 MEMS switches that will be optically interconnected by integrated optical waveguides (Fig. 3). The input and output connections will be 16 standard single mode optical fibers. The 4x4 OXC essentially consists of two components, a bottom chip, which contains the 16 bi-stable silicon switches, and a top chip holding the waveguides and the electrical connections for the switches. The two chips will be combined by standard flip chip bonding technology. The particular challenge in this projects are a) the deep reactive ion etching (DRIE) of the integrated optical waveguides so they can be inserted into the switches in the same fashion as in the 2x2 fiber switch and b) the assembly of the complete system.

The weakly guiding and strip-loaded integrated optical waveguides are fabricated on a silicon wafer with 8 µm thermally grown SiO_2 [5]. The buffer layer, the strip-loaded core layer as well as the cladding layer are deposited by plasma enhanced chemical vapor deposition (PECVD). The buffer layer consists of 3 µm SiO_2. The strip layer and core ridge are made of SiO_xN_y by depositing a 350 nm thick layer, which is thinned down next to the 6 µm wide waveguide core to 100 nm by reactive ion etching (RIE). In the last step a SiO_2 cladding layer of 15 µm thickness is PECVD deposited on top of the SiO_xN_y structure. The specific loss of the integrated optical waveguides can be as low as 0.2 dB/cm at $\lambda_0 = 1300$ nm and 0.4 dB/cm at $\lambda_0 = 1550$ nm.

Due to the thin core ridge, the waveguide is rather weakly guiding perpendicular to the layer plane. Thus the beam shape is expanded in this direction, which leads to an overall relatively round beam shape and a highly improved coupling efficiency between the integrated waveguide and the attached fiber.

To connect the integrated optically waveguides with optical fibers, the waveguide wafers need smooth endfaces. This can be achieved by either a special polishing dicing technology or standard dicing and additional polishing with diamond powder. This way fiber-to-waveguide coupling loss can be as low as 0.35 dB per facet.

In order to insert the integrated optical waveguides into the U-grooves of the switches and in between the mirrors, the waveguides need to be pattern by DRIE [6]. After performing etched tests on quartz glass wafers with an SU-8 photoresist mask [7,8], the silica-on-silicon wafers with the waveguides were patterned identically (Fig. 3, right image). The surface roughness is still to be optimized but can be smoothed out optically to a certain degree by index-matching oil.

C. *Variable Optical Attenuator (VOA)*

When optical signals are traveling in fibers for several kilometers their intensity becomes less due to absorption, scattering and bending losses in the fiber network. When the signal intensity falls under a certain threshold, the signal is amplified by EDFA. The amplification, however, is wavelength dependent. Therefore, the channels are split after the amplification by WDM and the different intensities of each channel are equalized to the same value. Instead of additional amplification of each channel, the intensities are attenuated to the required value by a VOA. After the attenuation the channels are combined again by a wavelength multiplexer (WM). Since the amplification is relatively constant, the VOA has to be set to a certain attenuation value where it remains statically until readjustments have to be done due to losses in the WDM or a change in the EDFA.

The VOA presented here is based on the same MEMS

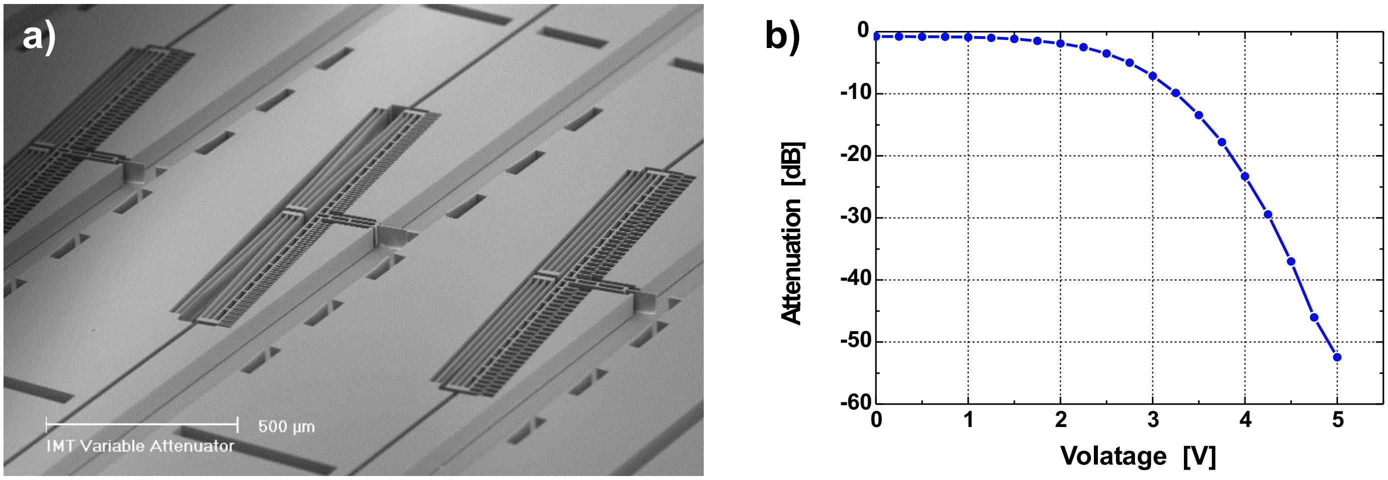

Fig. 4. a) The variable optical attenuator (VOA) moves a shutter in between two fibers. B) The attenuation of the VOA has a dynamic range of over 50 dB.

concept as the switch described above: A mirror that is rotated by 82° to the axis of light propagation can move linearly between two opposing fibers that are held by small leaf springs in two U-grooves (Fig. 4a).[2] The slight tilt prevents the back reflection into the input fiber. The attenuation efficiency versus the driving voltage is depicted in Fig. 4b.

The attenuation is not linear with the driving voltage and thus the VOA has to be calibrated prior to its use in a power management setup.

Since the footprint of the MEMS VOA is very small, several VOA's are fabricated on one chip very close to each other.

IV. Fourier Transform Spectrometer (FTS)

Fourier transform (FT) spectroscopy is a well-known technique to measure the spectra of a weak and extended light source whereas it offers a higher signal-to-noise ratio than other methods [9]. Commonly used FT spectrometers require a mirror scanning mechanism with very high precision, resulting in a large device size at high costs. Low-cost miniature spectrometers, however, are key components that permit the fabrication of small-size, portable sensor solutions for applications such as photometers in quality management and spectrometers in analysis tools.

The most common way of fabricating an FTS is utilizing a Michelson interferometer configuration with scanning mirrors. The output signal of the interferometer is the variation of the light intensity I_R as a function of the optical path length δ. The relation of I_R to δ is referred to as the interferogram. The wavelength power spectrum and the recorded interferogram $I_R(\delta)$ are related by a Fourier transformation. Therefore, a spectrum of a light source can be obtained by simply recording $I_R(\delta)$ and a subsequent FT.

Most microfabricated FTS utilized a tilted mirror and a photodiode array in a stationary Michelson interferometer configuration [10]. Such set-ups, however, offer only a rather poor resolution. Therefore, a new fabrication concept was pursued that includes a compact MEMS scanning mirror with a small footprint of only 5x4 mm^2.[11] The schematics of this Michelson

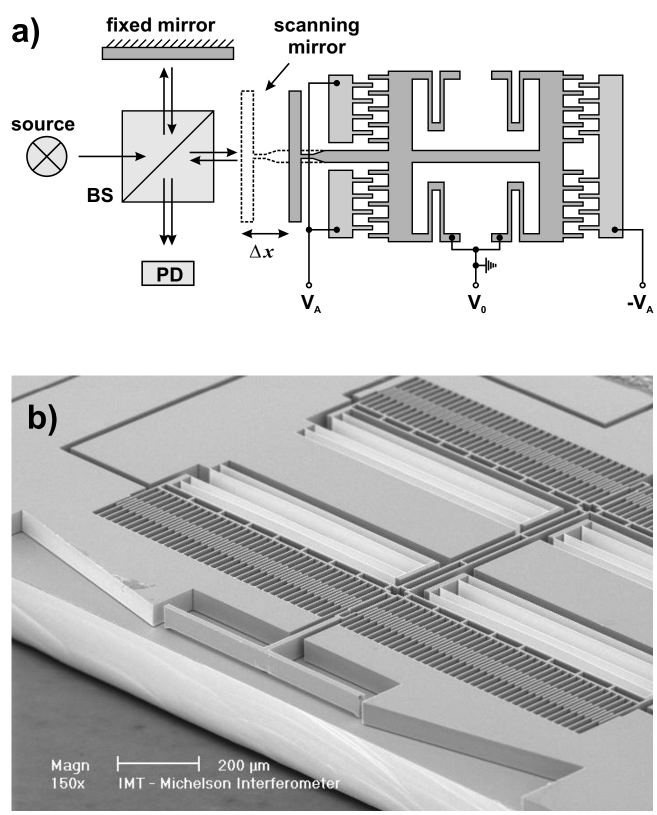

Fig. 5. a) Concept of Fourier transform spectrometer (FTS). In the real setup, the beam splitter (bs) and the fixed mirror are macroscopic. The movable mirror was driven by a push-pull configuration. b) The MEMS mirror is much larger than in the OXC and the VOA to increase the reflecting area.

interferometer set-up is depicted in Fig. 5a. The light from the source is divided by a standard macroscopic beam splitter to the movable MEMS mirror and the photodetector. The other mirror opposing the photodetector (PD) is fixed. The design of the MEMS mirror is derived from the 2x2 switch structure by rotating the mirror by 90° in respect to the actuation direction (Fig. 5b). The mirror size was enlarged to increase the reflecting surface.

In order to achieve the obligatory linear relation between the driving voltage and the mirror displacement, a push-pull type driving voltage configuration was chosen by setting the inner combs to one and the same electrical potential V_0 and the other two combs on opposing voltages V_A and $-V_A$, respectively. This way Δx is proportional to V_A, when at the same time V_0 is kept constant.

To test the set-up a He-Ne laser was focused onto the two mirrors via the beam splitter. The driving voltage for the movable mirror was either $V_A = \pm 5$ V for half the travel distance or $V_A = \pm 10$ V for the maximum achievable travel distance of $\Delta x = 38.5$ µm which corresponds to an optical path difference of $\delta = 77$ µm. While the small voltage range yielded an almost linear mirror displacement response, the full range showed a slight non-linearity as well as a small hysteresis. Both effects, however, remained almost constant for several cycles and could be eliminated by calibrating the voltage response of the mirror displacement. After this interferometric calibration, the linewidth of the He-Ne laser was measured to be about 6 nm, whereas the peak position was repeatedly accurate to about 1 nm. Since the real linewidth of the laser is only a few picometers, the measured linewidth corresponds to the actual resolution of the MEMS FTS.[11]

A new design with integrated collimators, fixed mirrors and guiding structures for a sheet-type beam splitter as well as a tunable laminar grating are currently under investigation.[12]

V. ACCELEROMETER

Accelerometers are needed in several technical areas where the changing speed of an object has to trigger an important action or simply needs to be monitored. The probably most famous application for an accelerometer is the airbag activator in vehicles. Other more general applications are quantitative vibration measurements for heavy machines. The change of a direction of a moving object induces a change in its angular velocity, which can be measured with an accelerometer.

Although there are many accelerometers that are based on piezoelectric ceramics or the electrical detection of a moving mass, silicon MEMS based accelerometers with optical readout become more and more sensitive, reliable, and important.[13,14,15,16]

The accelerometer presented here is based on the measurement of an optical modulation caused by a moving mass (Fig. 6a). Using purely optical signals has the big advantage, that the device performance is immune to electromagnetic interferences (EMI).[17] The optical source is an LED. The optical detection utilizes the partial and simultaneous light coupling from one source fiber into two output fibers. The fibers are held and self-aligned by integrated U-grooves in the same fashion as in the OXC and VOA described above (Fig. 6b). The light of the source fibers hits the point of a V-shaped mirror, which splits and couples the light evenly into the two identical output

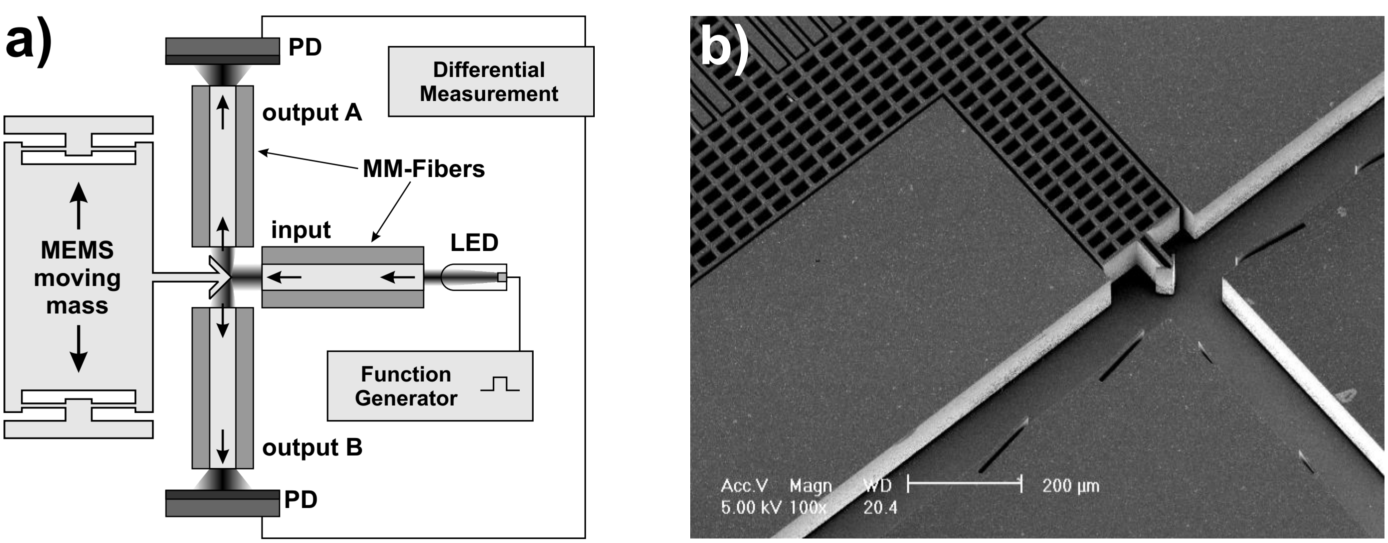

Fig. 6. a) In the optical MEMS accelerometer the light from the input fiber is split by a V-shaped mirror simultaneously into the two output fibers A and B. The signal from the photodectors are subtracted from each other to achieve a differential measurement. The dynamic range of the usable and linear response of the moving mass is about 40 dB for ±6g at a bandwidth of 300 Hz. b) The fibers are inserted into the MEMS component via U-grooves and held by small leaf springs. The accelerometer is damped by a squeezed air film which is in a small gap in between the moving mass and the surrounding structure, which is visible in the upper left corner.

multimode fibers. The mirror is attached to a movable mass, whose moving is damped during its displacement by squeezing an air film, which is located in between the mass and its surrounding silicon structure and which can be seen in the upper left corner of Fig. 6b.[18]

The output fibers guide the light to two photodiodes. This arrangement allows a differential measurement of the optical power. To obtain a sufficiently linear response, however, only tiny displacements around the zero position are allowed. Therefore, the device is designed to have a maximum displacement of ±0.8 µm, which is a tenth of the damping air gap width and only a small fraction of the displacement necessary to achieve the maximum possible light modulation. Since the total light modulation corresponds to an electronic signal-to-noise level of 102 dB at 300 Hz, the mechanical limitations only allow to use an effective dynamic range of about 40 dB or a measurable displacement of about 0.6 Å. Thermal-mechanical noise is negligible. In spite of this limitations the performance is comparable to more sophisticated and more expensive Fabry-Perot based devices of Ref. 16 and it outperforms previously published opto-mechanical MEMS accelerometers.

VI. Conclusion

Optical MEMS components based on the relatively simple SOI technology offer several advantages over standard components. They deliver a high reliability, need only a small footprint of a few square millimeters, integrate alignment structures for small optical components, and show negligible power consumption when driven with electrostatic actuators. This means, that optical MEMS components offer the opportunity to create small, comprehensive, and highly sophisticated systems of a high level integration. Since the DRIE etch depth is not limited to the presented device layer heights of 75 and 100 µm, other heights can be utilized as well when it is required by the application. More sophisticated MEMS designs with a higher level of integration are conceivable, although more functions complicate the device fabrication and can lead to a lower process or trade-off in the functionality of the single components.

Acknowledgment

The authors like to thank the staff members of their corresponding groups for useful help in finding out useful details in the process development as well as in the microassembly. Particularly, we are very grateful to Martin Hoffmann from the University of Dortmund (Germany) for providing the integrated optical waveguide wafers.

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