A monolithically integrated photonic MEMS subsystem for optical network applications

J. Li a,b, X.M. Zhang a, A.Q. Liu a,*, C. Lu a, J.Z. Hao c

a School of Electrical and Electronic Engineering, Nanyang Technological University, Division of Microelectronics, 50 Nanyang Avenue, Singapore 639798, Singapore
b Institute of Microelectronics, 11 Science Park Road, Singapore Science Park II, Singapore 117685, Singapore
c Institute for Infocomm Research, Unit 230, Innovation Center, 18 Nanyang Drive, Singapore 639798, Singapore

Received 7 May 2004; received in revised form 21 January 2005; accepted 25 January 2005

Abstract

A single-chip photonic subsystem with a dimension of 3.5 mm × 3 mm × 0.6 mm is developed by integration of a tunable laser with an optical switch using the microelectromechanical systems (MEMS) technology. The potential of the subsystem is also discussed for the niche applications in the reconfigurable optical add/drop multiplexers and the wavelength converters. The subsystem has a tuning speed of <1 ms between different wavelength channels within a range of 13.5 nm by stepwise tuning, and a switching time of <100 µs between different light paths, which are much faster than the conventional mechanical devices. The output power is about 1 mW. In addition to the compact size and fast tuning speed, the MEMS integration also brings in other advantages such as more functionality, high reliability, batch fabrication and low cost. More significantly, the prototype demonstrates the MEMS integration successfully. This is to our knowledge the first realization of a single-chip MEMS subsystem by integrating different functional MEMS components. © 2005 Elsevier B.V. All rights reserved.

PACS: WS 3274
Keywords: Tunable laser; OADM; Optical MEMS; Wavelength converter

1. Introduction

Integration plays a key role in the development of many technologies such as integrated circuits (IC) and planar lightwave circuits. The integration of various components into a subsystem or even a system can significantly improve the functionality, compactness and reliability while reducing the cost. Various devices have already been developed using microelectromechanical systems (MEMS) technology, for instance, optical switches [1], optical crossconnects (OXC) [2], variable optical
attenuators (VOAs) [3], tunable lasers [4–7], and optical add/drop multiplexers (OADMs) [8]. However, most of them work independently and function only at the component level. Many efforts have been put in the integration of single MEMS components with other components such as optical fibers [1,3], microlenses [9], IC control circuits and planar lightwave circuits [10]. Recently, with an increasing number of MEMS components becoming technologically mature, the integration of MEMS components into subsystems represents the latest trend and has attracted extensive research interests. For example, an optical disk pickup subsystem has been demonstrated by integrating several surface-micromachined components onto single chips [11,12]; various microspectrometers have been prototyped by integration of gratings, micromirrors and photodetectors within a small box [13], and a hybrid tunable laser is formed by the combination of a MEMS actuated mirror and a laser gain chip with other optical components [4,14]. In the optical communications, the components of optical switches and tunable lasers are key enablers for all-optical (or photonic) switching. Thus considerable efforts have been put to apply the MEMS technology to those single components [1,4–7]. Based on the previous works, this paper presents a monolithic photonic subsystem by integrating a MEMS switch component with a MEMS laser component. It provides system-level functions and should have its niche applications in optical networks, for instance, reconfigurable OADMs and tunable wavelength converters, etc.

2. MEMS photonic subsystem and applications

The overview of the MEMS subsystem is shown in the scanning electron micrograph (SEM) in Fig. 1(a). It consists of a tunable laser, a 2×2 optical switch and a microlens. Figs. 1(b) and (c) show the close-ups of the laser and the switch. The optical switch employs a vertical mirror to switch the light paths. Electrostatic comb-drive actuators are used to actuate the curved mirror and the vertical mirror. The microlens is used to couple the laser output to the optical switch. It is designed to have a focus length of 160 μm and a magnification of 1.14. All the MEMS structures are fabricated on a silicon-on-insulator (SOI) wafer by deep reactive ion etching (DRIE) process. The SOI wafer has a device silicon layer (75 μm thick) and a thermal oxide layer (2 μm thick) on a handle silicon wafer. The depth is about 70 μm for the mirrors and actuators, and 75 μm for the fiber

Fig. 1. The on-chip MEMS subsystem: (a) overview; (b) close-up of the tunable laser; (c) close-up of the optical switch.
grooves. With a shadow mask, a metal layer (0.2 μm thick gold) is coated on the mirrors to improve the reflectivity of the curved mirror and to increase the extinction ratio of the optical switch. At the same time, the microlens is protected from coating. After the MEMS fabrication, the laser chip and the optical fibers are integrated and packaged. The laser chip has a stripe contact on the top surface and emits light from its two end facets. The emitting points are close to the top surface. In packaging, the laser chip is placed face down into a trench in the silicon wafer (Fig. 1(b)). A layer of indium foil about 45 μm thick is sandwiched between the laser chip and the trench bottom. This foil serves two purposes. It bonds the laser chip to the trench, therefore providing better ohmic contact and heat transfer. It also raises the optical axis of laser emission to align to the other optical components (i.e., the curved mirror, the microlens, the switch mirror and the optical fiber). Since in the MEMS fabrication the upper part of the deeply etched sidewall (between about 20 and 75 μm high from the bottom) has good profile fidelity and surface quality, the optical axis is chosen at 45 μm height. The fiber is etched by the 49% hydrofluoric acid to reduce the radius to 45 μm (etching rate 3.5 m/s). In the experiment, two probes are employed to apply the injection current. The negative probe contacts with the exposed surface (i.e., backside) of laser chip, while the positive touches a coated area in the wafer surface but close to the trench. Due to the thick metal layer, the wafer surface is electronically connected to the bottom of the trench. The system has a dimension of only 3.5 mm × 3 mm × 0.6 mm (excluding the full length of the optical fibers), which is quite small compared with the conventional devices that have the size of at least a shoebox.

The tunable laser uses a curved mirror as the external reflector to form an external cavity of the Fabry–Perot (FP) semiconductor laser. The laser output can be tuned to different wavelengths by actuating the mirror to change the cavity length. This configuration is an improved version of the simple configuration that uses a flat mirror as the reflector [5]. The purpose of the curved mirror is to focus the diverging laser light and as a result, to improve the feedback efficiency. Here the feedback efficiency is defined as the portion of the laser beam that is reflected by the external reflector and is then coupled into the laser internal cavity. As shown in the simulation results of Fig. 2, the curved mirror has an ideal feedback efficiency ranging from 4% to 9% when the mirror moves back and forth within ±4 μm to its original position. In contrast, the flat mirror has only 0.5–0.6%. In the estimation, the wavelength is 1.55 μm; the reflectivity of mirror surface is assumed to be 100%; the laser emission is an elliptical Gaussian beam (1.75 and 1.53 μm for the radius in the major axis and the minor axis, respectively). The beam size of the laser emission is estimated by the far field beam profile, which measures divergence angles of 31.5° and 35.7° in the horizontal and vertical direction, respectively (nominal angles all <28° from the test report of Product Code DL-CG5203A-00-008, DenseLight, Singapore).

The subsystem has some potential applications in the optical networks. Fig. 3 illustrates how it can be used as a reconfigurable OADM. The multiple wavelength channels from an input fiber are first separated into different links by a demultiplexer. In the switching state as shown in Fig. 3(a), the wavelength channel to be dropped is connected to the desired destination through the 2 × 2 optical switch. At the same time, the tunable laser provides a local channel and adds it through the optical switch. The added channel and the other

![Fig. 2. Comparison of the ideal feedback efficiency when the curved mirror and the flat mirror are used as the external reflector, respectively.](image-url)
pass-through channels are then combined into an output fiber using a WDM combiner [15], which can merge several fiber links into one fiber at very low insertion loss and wavelength dependence loss (WDL). Compared with a common multiplexer whose input ports work at fixed wavelength, the combiner allows the input wavelength to change within a certain range and therefore can receive the added channel at different wavelength provided by the tunable laser. To avoid conflict, the added channel should not use any of the wavelengths that are being used by the other channels. The local data signal can be added to the tunable laser by direct modulation or external modulation. The optical switch can also be set in the idle state as shown in Fig. 3(b). It allows the incoming channel to pass through directly to the output end without adding/dropping any channel. Compared with the fixed-wavelength lasers, the tunable laser has a particular advantage that the wavelength of the added channel can be changed intentionally. The local signal can use the wavelength of the dropped channel or any other idle wavelength even though the dropped channel may have fixed wavelength. This property is very useful for the wavelength-based switching/routing networks. For example, in a passively routing network [16], each user is assigned to receive a fixed wavelength while being able to send out one of many wavelengths, the path and the destination are only determined by the signal wavelength through passive router. By tuning the wavelength of the added channel, one end user can delivers the signal directly to the desired recipient without any intermediate processing, switching, or reconfiguration at intermediate nodes. In addition, the tunable laser in the reconfigurable OADM makes it possible to reuse the idle wavelengths, which can save the wavelength conversion significantly. It would help to cut the cost since wavelength is a rare and expensive source in the optical networks. Moreover, a multi-channel OADM can be implemented by using an array of these subsystems. Compared with a recently developed MEMS OADM that integrated MEMS switches with optical circulators and thermally tuned fiber Bragg grating filters [17], this monolithic subsystem has small size, high reliability/stability (less sensitive to environmental temperature variation) and wavelength reconfigurability.

The MEMS subsystem can also be used as a wavelength converter as shown in Fig. 4. The tunable laser provides the targeted wavelengths while the optical switch selects the wavelength converter to work in either an idle state or a conversion state. In the idle state as shown in Fig. 4(b), the optical switch directly forwards the input to the output, and the tunable laser is idle. In the conversion state as shown in Fig. 4(a), the input signal at a wavelength of $\lambda_i$ is switched by the optical switch to a receiver for optical-to-electrical (O/E) conversion. The electrical signal is then used to directly modulate the tunable laser, whose wavelength can be adjusted to the desired wavelength of $\lambda_j$ independently. It is noted that the tunable laser in the photonic subsystem is able to work at continuous wave (CW) as well as direct modulation. Other than the direct modulation, external modulation is also possible. The tunable laser provides CW...
light as the carrier while the electrical signal is applied to an external modulator to code the laser light on the output side of the optical switch (not shown in Fig. 4(b)). Compared with the conventional wavelength converters which have bulky size and fixed output wavelength, the MEMS subsystem is compact and batch fabricated, and is capable of handling wide ranges of input and output wavelengths.

3. Experimental results and discussions

In the MEMS subsystem, the laser works in the wavelength domain to provide the light source for different wavelength channels, while the optical switch works in the spatial domain to switch the laser light to different light paths. The laser tunes its wavelength by changing the external cavity length. The position of the curved mirror is controlled by applying an electrostatic voltage to a comb-drive microactuator. When the driving voltage is greater than 2.5 V, the mirror displacement increases with higher driving voltage, and reaches 4 µm at 18 V. The external cavity length is initially at 66 µm. The laser chip is made of multiple-quantum-well InGaAsP/InP materials, and has a dimension of 210 µm × 300 µm × 100 µm. The laser facets are not coated (i.e., $r_2 = 0.56$). The effective reflectance of the curved mirror is estimated to be $r_3 = 0.03$ by measuring the threshold current variation while moving the curved mirror. The effective reflectance takes into account the losses due to the curved mirror reflectance, the dispersion of the laser beam, the misalignment and the coupling of the reflected light into the laser. The laser chip can respond to 2.5 GHz small-signal square-wave driving current over the threshold, making it possible for direct modulation.

The spectra of all the output states during the wavelength tuning are shown in Fig. 5. The injection current is kept at about 28% over the threshold current 18.2 mA. At this current level, the laser can be operated in continuous wave (CW) without additional heat sink. In addition, it is able to maintain single longitudinal mode (due to homogeneous broadening) when tuned to different wavelengths. The output power is about 1 mW, and varies with the wavelength tuning (variation <6 dB). The suppression ratio of the side mode is about 20 dB. Fig. 6 shows the change of the laser wavelength with the mirror displacement. In the experiment, we measure the laser spectra at different driving voltages, and then convert the voltage

![Fig. 4. Application of the MEMS subsystem as a tunable wavelength converter. (a) The conversion state and (b) the idle state. O/E stands for optical-to-electrical converter. The dotted frame indicates the scope of the subsystem.](image)

![Fig. 5. Spectra of all the output wavelengths of the MEMS subsystem.](image)
into the mirror displacement. The wavelength is initially at 1570.04 nm and is kept constant at very small mirror displacement. Further movement of the curved mirror makes it drop to 1556.56 nm abruptly (the shortest wavelength). After that, the wavelength appears at the positions of the laser modes, and increases by a constant step of 1.69 nm. A tuning range of 13.5 nm is obtained. Further displacement of the curved mirror does not produce higher wavelength. Instead, the wavelength changes periodically. The mirror shift corresponding to one period is about one wavelength. The abrupt drop and stepwise increase of the wavelength are the evidence of discrete wavelength tuning, which is different from those tunable lasers whose wavelengths can be tuned continuously [18,19]. The output wavelength is well locked to the positions of FP laser modes that the wavelength difference between the output and the nominal laser mode is less than 0.04 nm. It is observed that at any wavelength the output is stable single mode when the mirror displaces within a certain region (stable region is about 0.11–0.14 μm).

The optical switch in the MEMS subsystem is also actuated by a comb-drive actuator. Its displacement is proportional to the square of the driving voltage so that a large displacement can be obtained using a low driving voltage. It can displace 30 μm using a static voltage of 30 V. Fig. 7 shows the dynamic response of the optical switch under a 400 Hz quasi-square wave driving signal. The rise time is about 84 μs and the fall time is about 52 μs. Although the switch structure experiences some oscillation before it is settled at the on or off state (observed under small driving voltage), this oscillation is not reflected in the optical response since the mirror displacement is large enough to keep the light path fully open or switched even during the oscillation. In this way, the ripple of the light power during the switching is avoided. The polarization dependence loss (PDL) is shown in Fig. 8 when the optical switch is in the cross state (i.e. the mirror reflect the light). The PDL falls in a range between −0.06 and 0.05 dB when the polarization angle is rotated by...
90° using a polarization controller. In the bar state (i.e., the mirror does not intercept the light), the PDL is smaller than 0.1 dB. The insertion loss of the optical switch is measured to be 0.64 dB at the cross state and 0.55 dB at the bar state. The crosstalk is well beyond 40 dB. In lifetime test, the optical switch has been run for 25 million cycles without operational degradation being observed.

The WDL of the MEMS subsystem is shown in Fig. 9. When the optical switch is in the cross state, the laser light is reflected by the optical switch and coupled to the fiber by the microlens. The coupling ratio varies slightly with the laser wavelength. The influence of the laser power variation during the tuning is normalized by monitoring the power change. When the wavelength sweeps from 1556.56 to 1570.04 nm, the WDL varies from −0.05 to 0.12 dB (in total, 0.17 dB). The WDL tends to decrease with longer input wavelength.

The coupling loss from the tunable laser to the output fibers is quite large since the deep etched microlens cannot focus the light in the vertical direction, which accounts for about −13 dB loss. The reflection in the air-silicon surfaces of the microlens costs about −3 dB loss. Although the low coupling efficiency may prevent the MEMS subsystem from practical uses, it demonstrates the MEMS integration. To reduce the losses to acceptable level, hybrid lenses or tapered silicon rib waveguide can be used.

The photonic subsystem inherits from the MEMS technology and the MEMS integration the merits of compact size, low weight, batch fabrication, high mechanical reliability and easy integration with the IC circuits. Although the MEMS laser here are not advantageous over the best commercial devices in the output power and tuning range, it can be further improved by increasing the injection current to improve the output power, inserting a dispersive element (e.g., grating) to maintain the single mode operation and using other tuning method for large tuning range. In addition, low coupling loss can be expected by introducing silica waveguide for the coupling from the tunable laser to the optical switch.

The experimental data show that the MEMS subsystem has some distinct advantages. First, the output wavelength does not change when the external reflector moves within the stable regions, which greatly improves the mechanical stability/reliability of the laser. Second, since the laser employs the discrete wavelength tuning, all the possible output wavelengths are automatically aligned to the ITU grids if the original laser output is intentionally adjusted to an ITU wavelength and the mode spacing is selected to match the ITU grid interval. Finally, the MEMS subsystem has fast optical switching and fast wavelength tuning. All these characteristics make it suitable for the applications of reconfigurable OADMs and tunable wavelength converters.

4. Conclusions

MEMS integration has been demonstrated by integrating a tunable laser and an optical switch onto a single-chip subsystem. The MEMS structure has been fabricated by deep etching on an SOI wafer, and then packaged with the optical fibers and the semiconductor laser. The output wavelength can be tuned to discrete values within a range of 13.5 nm, and the output path can be switched within 100 μs. The new subsystem has the capability to switch simultaneously between
different wavelength channels and different light paths, and has applications in optical networks such as reconfigurable OADMs and tunable wavelength converters.

References