Integrated 1x4 Wavelength-Selective Switch with On-Chip MEMS Micromirrors

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Abstract: A monolithic 1x4 wavelength-selective switch is realized by integrating silicon planar lightwave circuits and MEMS micromirrors on silicon-on-insulator (1.4x2 cm^2) for CWDM networks with 20-nm spacing.

OCIS codes: (060.1810) Couplers, switches, and multiplexers; (060.4510) Optical communications

1. Introduction

Free-space MEMS (micro-electro-mechanical-systems) wavelength-selective switch (WSS) offers many advantages, including high port count, low insertion loss and crosstalk, optical transparency, and polarization insensitivity [1-4]. However, their sizes are often limited by the bulk optical elements (such as lenses, gratings, etc.) and the long free-space propagation distances. Optical alignment and assembly are also cumbersome processes.

Compact switches can be realized by combining MEMS components and planar lightwave circuits (PLC) [5]. Hybrid WSS has been demonstrated using arrayed waveguide grating (AWG) and external MEMS micromirrors [6,7]. However, bulk lenses are still required between the PLC and the MEMS micromirrors for collimation and focusing. Complicated optical alignment and mechanical assembly are also needed. These leads to reliability concerns as well as cost.

In this paper, we proposed and demonstrated a fully integrated 1x4 MEMS WSS for coarse wavelength-division-multiplexing (CWDM) networks. The MEMS micromirrors, diffraction gratings, and silicon PLC are monolithically integrated on silicon-on-insulator (SOI) substrates. The SOI platform is particularly attractive because they are compatible with Si PLC [8] as well as SOI-MEMS technologies. All optical paths are defined by photolithography and no optical alignment is necessary. Theoretical calculation shows that 4.1-dB insertion loss can be achieved. Experimentally, a 1x4 CWDM WSS with 20-nm channel spacing has been integrated on a 1.4x2-cm^2 SOI chip. Switching time less than 1 msec has been achieved. The switch configuration is scalable to larger port count and denser wavelength channels. Multiple 1xN WSS's can be cascaded to form NxN wavelength-selective cross connect (WSXC) on a wafer scale.

2. Device Design and Simulation

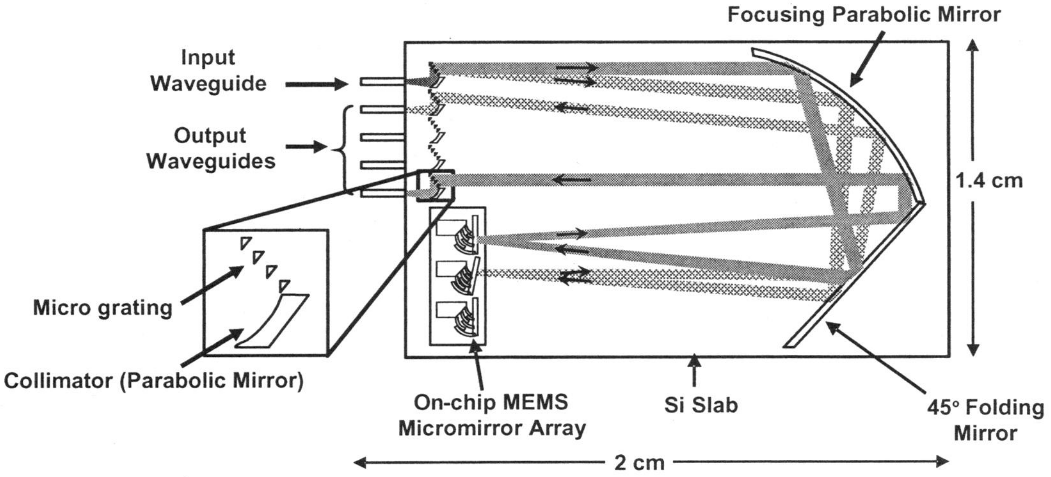

Fig. 1. Schematic of the monolithic 1x4 MEMS WSS.

The schematic of the integrated 1x4 WSS is shown is Fig. 1. The SOI has a device layer with 5-um thickness. The device consists of five channel waveguides with 5um width, each integrated with a collimating reflector and a diffraction grating [9], a focusing reflector, and an analog MEMS micromirror array. To minimize the spherical and chromatic aberration, reflective parabolic mirrors are used for the collimators and the resolution reflector. The diffraction grating, an array of deep etched triangular elements, is blazed for 14th order diffraction at 90° angle. The period is 4.5um, allowing the WSS to be patterned by standard optical lithography. The corresponding dispersion strength is 0.074°/nm. Using a 45°-folding mirror, the device footprint is reduced to 1.4x2 cm^2. Total internal reflection (TIL) is used for the collimating and the resolution reflectors. The 4-f configuration ensures the geometric focusing position occurs at the minimum spot size of the Gaussian beam. Moreover, the focused spot size on the MEMS micromirror can be adjusted by changing the focal length of collimators independently.

An 8-element micromirror array matching the CWDM (1470-1610nm) grids (20-nm spacing) is integrated at the focal plane of the resolution reflector. Each MEMS mirror is actuated by a rotary comb-drive actuator. The micromirror array has a pitch of 400um and the corresponding focal length of the resolution parabolic mirror is 15.5 mm. The required mechanical scan angle is 1.6° for switching between adjacent ports with 250um spacing. 4.8° mechanical angle is required for the 1x4 WSS. All silicon-air interfaces are anti-reflection (AR)-coated by 194-nm-thick silicon nitride ($n = 2.0$). The micromirror is coated with aluminum to increase its reflectivity.

Table 1 shows the theoretically simulated optical insertion losses. The coupling loss between a lensed fiber with 5um spot size and the Si channel waveguide is 0.7dB, calculated by beam propagation method. The grating loss, estimated by scalar diffraction theory, is 1.1dB. The vertical beam divergence loss due to the 5-um gap between the mirror and the slab waveguide is 0.5 dB. The total fiber-to-fiber insertion loss is estimated to be 4.1dB. Our current device employs a wider mirror-to-slab spacing of 10um, which increases the beam divergence loss by 2.1dB.

Table 1. Estimation of insertion loss

Loss source	Loss (dB)
Fiber coupling	0.7 x 2
Grating efficiency	1.1 x 2
Diffraction between micromirror and slab	0.5
Total	4.1

3. Fabrication

The waveguides, parabolic mirrors, gratings (Fig. 2a), and on-chip MEMS micromirrors (Fig. 2b) were first patterned by optical lithography and then dry etched in an Applied Materials Precision 5000 etcher. To reduce the sidewall roughness for better optical performance, the sample was annealed in pure hydrogen at 1000°C, 1atm for 10 minutes, which reduces the root-mean-square sidewall roughness to as small as 0.26nm [10,11]. The nitride was deposited by low-pressure chemical vapor deposition (LPCVD). Aluminum was deposited on the sidewall of MEMS micromirrors by e-beam evaporation with a 30° tilting angle. The backside of MEMS micromirror was etched by deep reactive ion etching (DRIE), followed by a dry release process, in which the buried oxide was removed by an STS Advanced Oxide Etcher (AOE). The chips were self-separated after dry release. No cleaving or dicing is needed.

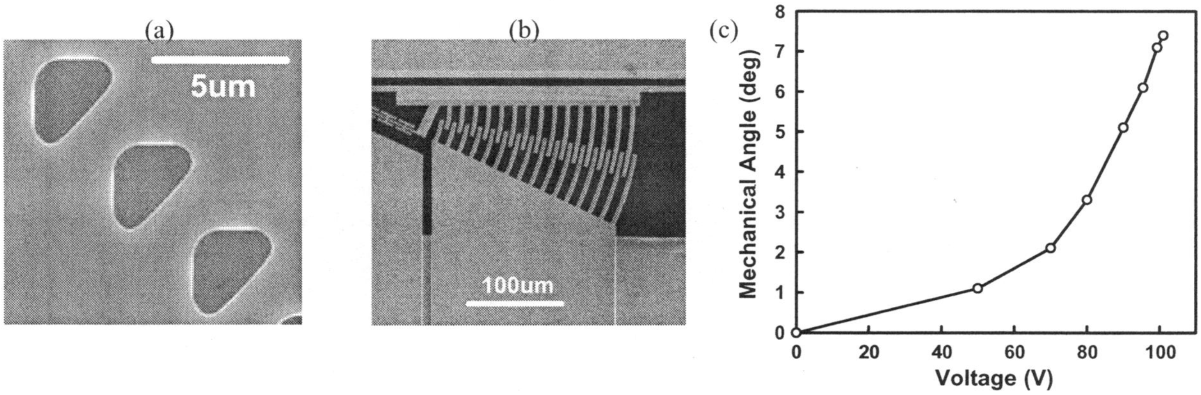

Fig. 2. (a) SEM image of fabricated grating. (b) SEM image of fabricated MEMS micromirror. (c) Transfer curve of MEMS micromirror. A maximum mechanical angle of 7.4° was achieved at a driving voltage of 101V.

4. Experiment Results

A lensed fiber array with 5um beam spot size was used to couple the light to our 1x4 WSS. Port 1 (the first waveguide from the top) is used as the input and port 2 to 5 as the outputs. When there is no bias on the MEMS mirror, the reflected light is coupled to port 5 (the symmetric waveguide at the bottom). An external cavity laser tunable from 1500nm to 1580nm is used as optical source. The MEMS micromirror exhibits a maximum mechanical scan angle of 7.4° at a driving voltage of 101V (Fig. 2c). The switching time is less than 1 ms (Fig. 3a). Four MEMS mirror (mirror 4 to 7) have been tested with the available wavelength range. The measured wavelength range is within 5nm of the designed values (Fig. 3b). The optical insertion loss is measured on a test chip with fixed micromirror. The fiber-to-fiber insertion loss is measured to be 23 dB. The discrepancy between the measured and the calculated losses is attributed to the non-verticality of the etched sidewalls. The TIR is sensitive to the sidewall angle. Our calculation shows that a 1° deviation leads to a loss of 0.8 dB, while a 2° angle produces a loss of 3.2 dB. Since there are 8 TIR's in the round-trip optical path, it is important to optimize the etched profile of the PLC.

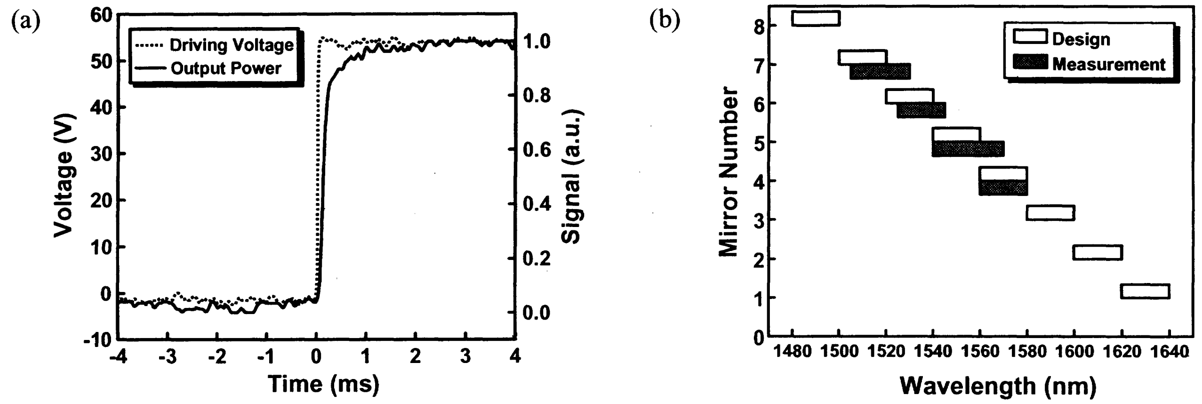

Fig. 3. (a) Dynamic switching from port 1 to 4. The switching time is less than 1 ms. (b) Designed and measured wavelength range for micromirror 1 to 8.

5. Conclusion

We have reported on the design, fabrication, and experimental results of an integrated 1x4 WSS for CWDM networks. The Si planar lightwave circuits and the MEMS micromirrors are monolithically fabricated on a silicon-on-insulator (SOI) wafer. The resulting 1x4 WSS with 20-nm CWDM channel spacing has a chip area of 1.4x2 cm^2. The total optical insertion loss is measured to be 23 dB (theoretical minimum is 4.1 dB). Switching time is less than 1 msec. The measured wavelengths are within 5nm of the designed values. The monolithic WSS is scalable in both spatial and wavelength port counts, and can be cascaded to form single-chip wavelength-selective cross-connects.

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6. Reference

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