Silicon-Based Monolithic 4×4 Wavelength-Selective Cross Connect with On-Chip Micromirrors

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Abstract: A monolithic 4×4 wavelength-selective cross-connect (chip area = 3.2×4.6 cm^2) is realized by integrating four 4×1 MEMS wavelength-selective switches and four 1×4 passive splitters, together with a 4×4 waveguide shuffle network on a silicon-on-insulator. Wavelength-selective routing has been successfully demonstrated.

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

1. Introduction

1×N wavelength-selective switch (WSS) and N×N wavelength-selective cross connect (WSXC) are key enabling elements for reconfigurable optical networks. Free-space MEMS (micro-electro-mechanical-systems) WSS [1-4] and WSXC [5] offer many advantages, including high port count, low insertion loss and crosstalk, optical transparency, and polarization insensitivity. 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) [6]. Hybrid WSS's have been demonstrated using arrayed waveguide grating (AWG) and external MEMS micromirrors [7,8]. However, those WSS's still require bulk lenses between the PLC and the micromirrors for collimation and focusing. Complicated optical alignment and mechanical assembly are also needed.

We have previously reported on a monolithic 1×4 MEMS WSS for coarse wavelength-division-multiplexing (CWDM) networks [9]. The MEMS micromirrors, diffraction gratings, and silicon PLC are monolithically fabricated on a silicon-on-insulator (SOI) substrate. The SOI platform is particularly attractive because they are compatible with Si PLC [10] as well as SOI-MEMS technologies. All optical paths are defined by photolithography and no optical alignment is necessary.

In this paper, we extend our previous work to a single-chip 4×4 WSXC fabricated on an SOI substrate. A 4×4 WSXC can be realized by cascading either four 1×4 and four 4×1 WSS's (Fig.1b) or four 1×4 splitters and four 4×1 WSS's (Fig. 1c). The latter has a fundamental splitting loss of 6 dB but it allows broadcast and multicast functions. It also has a smaller chip area (~ 60% of the 8-WSS approach), making it attractive for monolithic integration.

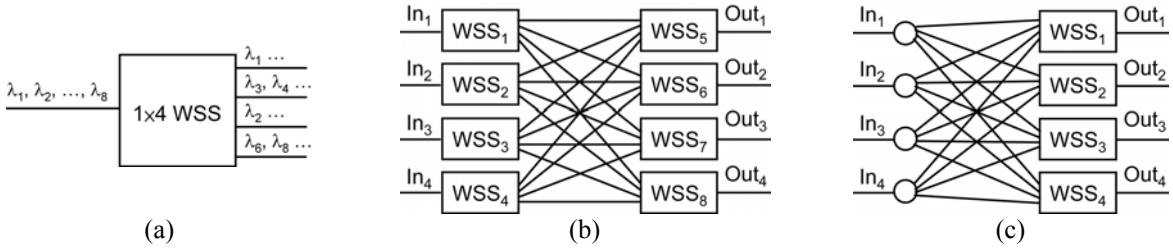

Fig. 1. Block diagrams of (a) 1x4 WSS with eight wavelength channels (b) 4x4 WSXC built with eight 1x4 WSS's (c) 4x4 WSXC built with four 1x4 passive splitters and four 4x1 WSS's.

2. Device Design and Simulation

The monolithic 1×4 WSS [9] is shown in Fig. 2a. The device consists of five 5μm-wide waveguides, each integrated with a collimating reflector and a micro-grating [11], a focusing reflector, and an 8-element micromirror array

matching to the CWDM (1470-1610nm) grids with 20-nm spacing. The MEMS mirror is actuated by a rotary comb-drive actuator. Total internal reflection (TIL) is used for the collimating and the focusing reflectors. All silicon-air interfaces are anti-reflection (AR)-coated by 180-nm-thick low-stress silicon nitride (n = 2.15). The micromirror is coated with aluminum to enhance its reflectivity.

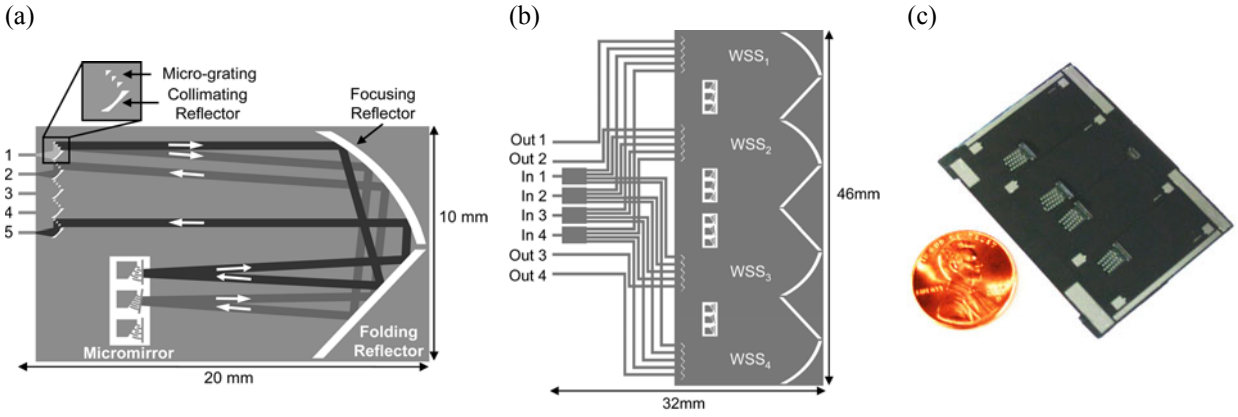

Fig. 2. (a)Schematic of the 1x4 MEMS WSS (b) Layout of the 4x4 WSXC (c) Fabricated 4x4 WSXC chip.

The 4×4 WSXC is realized by connecting four 4×1 WSS's and four 1x4 splitters with an integrated waveguide shuffle network (Fig. 2b). No fiber connections or external splitter are required. The 1×4 multimode interference (MMI) splitter is 890 μm long and 40 μm wide. The shuffle network employs 90° waveguide bend (R = 100 μm) and 90° waveguide crossing to minimize loss and crosstalk. The curved waveguide is offset laterally from the straight waveguide by 1 μm to optimize the mode-matching. The calculated optical loss is 0.02 dB/crossing and 1 dB/bend, respectively. The two lower WSS's are flipped vertically to reduce the number of waveguide crossings. There are no more than 10 crossing in any configuration.

3. Fabrication

The waveguides, parabolic mirrors, gratings, and on-chip MEMS micromirrors were patterned by optical lithography and then dry etched in an Applied Materials Precision 5000 etcher. 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° tilt 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 Applied Materials Centura etcher. The chips were self-separated after dry release. No cleaving or dicing is needed. The fabricated 4×4 WSXC chip is shown in Fig. 2c. The fabricated chip size is 3.2×4.6 cm^2.

4. Experimental Results

A lensed fiber array with 5μm beam spot size was used to couple light to our 4×4 WSXC. An external cavity laser tunable from 1460nm to 1580nm was used as optical source. Figure 3a shows the optical insertion loss characterization by a static device with fixed mirror. Signals in In 1 was split and distributed to Port 2 of WSS_1 and WSS_2, and Port 5 of WSS_3 and WSS_4. At zero bias, the signals in WSS_3 and WSS_4 were reflected to Port 1, and then sent to Out 3 and Out 4. The fiber-to-fiber insertion loss was measured to be 24 dB, which includes the 6-dB splitting loss. The crosstalk is less than -25 dB.

Table 1 shows the breakdown of the insertion loss, which was measured on test structures fabricated on the same chip. The most critical parameter in fabrication is the verticality of the etched sidewalls. The measured 0.06 dB/TIR corresponds to a sidewall angle of 0.3°. The major discrepancy between theoretical and measured loss comes from the grating loss. Rounding and imperfect etching profile of the small triangular grating trench contributed to the extra losses. It could be improved by using reflective-type grating to reduce the loading effect.

Figure 3b shows the transfer curve (transmission-vs-voltage) of Out 4 with inputs from In 1, 2, 3, and 4, respectively. The maximum transmission occurs at 69V, 117V, 145V, 159V, respectively. The dependency of actuation voltage enables power equalization per port or per wavelength. Six micromirrors (mirror 3 to 8) have been tested with the available tuning wavelength range from 1460-1580nm. Fig. 3c shows the spectral response of switching from In 4 to Out 4 by scanning different micromirrors. The 3 dB passbands were identified as 1477-1482nm, 1488-1494nm, 1507-1517nm, 1527-1535nm, 1539-1553nm, and 1561-1573nm. An extra passband at <

1472nm was observed from adjacent grating order. We have also performed dynamic response of the MEMS switches. The temporal response time is on the order of ~ 0.5 msec.

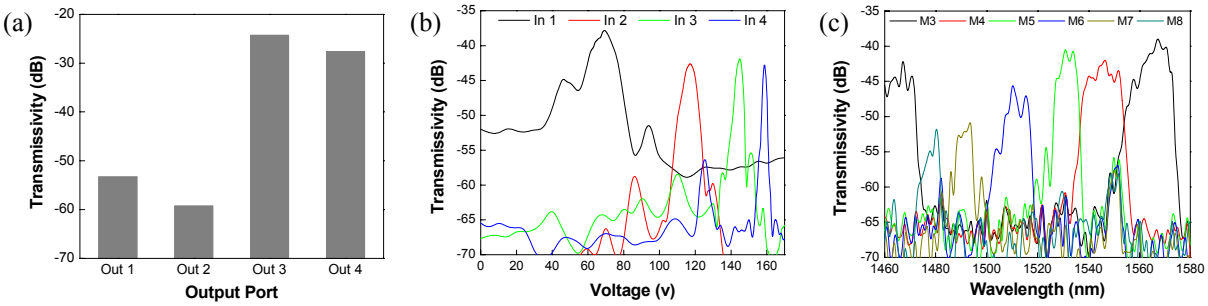

Fig. 3. (a) Measured insertion loss on a static 4x4 WSXC. (b) Transmissivity from the four input ports to Out 4 versus micromirror actuation voltage (c) Spectral response of In 4 to Out 4 by scanning mirror 3 (M3) to mirror 8 (M8).

Table 1. Estimation of insertion loss

Sources of Insertion Loss	Theoretical (Fundamental Limit)	Theoretical (Current Design)	Measured
Fiber Coupling × 2	0.2	1.3	2.3
Sidewall Effect of TIR × 8	0	0	0.5
Grating*	0	0	6
Diffraction (10 μm Air Gap)	2.3	2.3	2.8
Fresnel Loss (Imperfect AR Coating) × 4	0	0.4	0.4
Total (1x4 WSS)	2.5	4.0	12
MMI	6	6	7.5 ~ 9
Bending × 4	0	4	2
Crossing × 10	0.2	0.2	0.5 ~ 1
Total (4x4 WSXC)	8.7	14.2	22 ~ 24

* Scalar behavior at central wavelength on the assumption of perfect blazing

5. Conclusion

We have reported on the design, fabrication, and experimental results of a single-chip 4×4 WSXC, realized by integrating four 1x4 splitters and four 4×1 WSS's. The Si planar lightwave circuits and the MEMS micromirrors are monolithically fabricated on a silicon-on-insulator (SOI) wafer. The resulting 4×4 WSXC has a chip area of 3.2×4.6 cm^2. The breakdown of optical insertion loss is: 12 dB from the 1×4 WSS and 12 dB from the passive splitter and the waveguide shuffle network. Wavelength-selective routing has been demonstrated by scanning individual micromirrors. The power equalization per port or per wavelength can be realized by adjusting the actuation voltage. The monolithic WSXC can be scaled up to DWDM or with higher port counts.

This project is supported by DARPA CS-WDM program under MDA972-02-1-0020.

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