

Silicon-on-Insulator (SOI) Phased-Array Wavelength Multi/Demultiplexer with Extremely Low-Polarization Sensitivity

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Abstract—We demonstrate the first phased-array wavelength multiplexer fabricated in the silicon-on-insulator (SOI) waveguide technology. The four-channel wavelength division multiplexer (WDM) has a channel spacing of 1.9 nm centered at 1550-nm wavelength and a 3-dB channel bandwidth of 0.72 nm. The crosstalk to neighboring channels is less than -22 dB and the on-chip insertion loss is below 6 dB for all channels. The TE-TM shift is less than 0.04 nm which is the smallest attained without compensation techniques in any integrated optic technology.

Index Terms—Phased-array wavelength multiplexer, SOI, silicon integrated photonics, SOIPIC, wavelength-division multiplexing.

I. INTRODUCTION

WAVELENGTH-division multiplexing (WDM) technology promises increased transmission capacity and flexibility in future broad-band optical fiber telecommunication networks. The wavelength multiplexer/demultiplexer is one of the central components in WDM networks. Various material systems including Al_2O_3 , InP, LiNbO_3 , polymer, and silica (glass) have been used to implement wavelength multiplexers around the 1.55- μm optical fiber communication wavelength and excellent performance has been reported [1]–[8]. Silicon-on-insulator (SOI) technology has shown to be a promising technology for guided wave photonic devices operating in the infrared ($\lambda > 1.2 \mu\text{m}$). A number of SOI guided wave optical devices and circuits with high performance have already been demonstrated [9]–[13]. The recent emergence of SOI-CMOS integrated circuits as the future low-power, high-speed electronic technology ensures the availability of high-quality low-cost substrates. In addition, silicon-germanium heterostructures permit the realization of silicon-based photodetectors within the 1.2–1.6- μm infrared wavelength window over which crystalline silicon is highly transparent [14]–[16]. Therefore, SOI technology offers tremendous potential for cost-effective integration of a monolithic multi-wavelength optical receiver system including the wavelength demultiplexer, photodetectors, and electronic circuitry. In this letter, we present the design, fabrication and the performance of a four-channel phased-array wavelength mux/demux in

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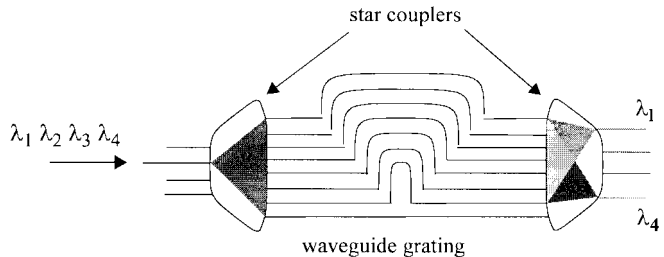


Fig. 1. Schematic of the phased-array waveguide grating multiplexer.

the silicon-on-insulator photonic integrated circuit (SOIPIC) technology. The SOIPIC technology is fully compatible with the silicon CMOS integrated circuit process.

II. DESIGN AND FABRICATION

The filter is based on the phased-array waveguide concept [1], [3], [17] consisting of two slab waveguide star couplers connected by an array of waveguides of constant incremental path length difference. The array and input/output waveguides are positioned based on Rowland circle mounting [18]. Fig. 1 shows the schematic of the wavelength multiplexer. The input light diverges in the first slab and couples to the array waveguides. After traveling through the array waveguides, the light beams interfere constructively onto the focal point in the second slab and couple to the output waveguide. The array disperses the different spectral components of the signal to the different outputs. The center wavelength of the device satisfies the relation: $n\Delta L = m\lambda_o$ where n is the effective refractive index of waveguide, ΔL is the path length difference of array waveguides, m is the diffraction order of the grating, and λ_o is the center wavelength. The dispersion of the focal position x with respect to wavelength is given as

$$\frac{dx}{d\lambda} = \frac{fm}{nd}$$

with f is the focal length of the slab region and d is the array waveguide pitch. The periodicity of the multiplexer is obtained by assigning $\text{FSR} = N\Delta\lambda$. The design goal was a four-channel Mux/Demux filter with a channel spacing of 2 nm at 1550-nm center wavelength and a free-spectral range (FSR) of 8 nm. The device is designed to operate at the grating order of 193, with a path length difference of 86.7 μm between adjacent grating waveguides, and star coupler focal length of

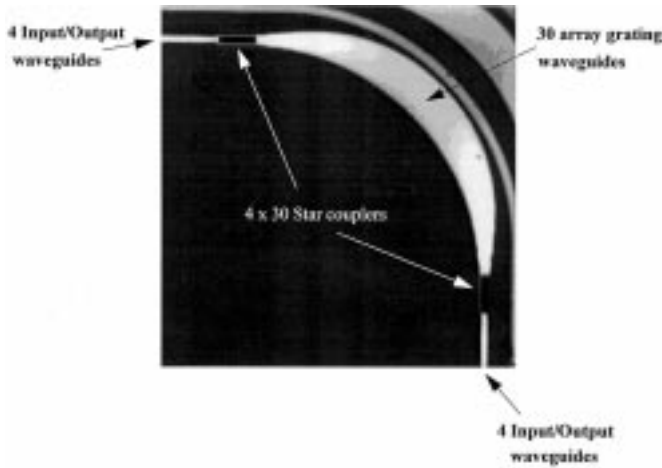


Fig. 2. Photograph of the fabricated SOI wavelength multiplexer.

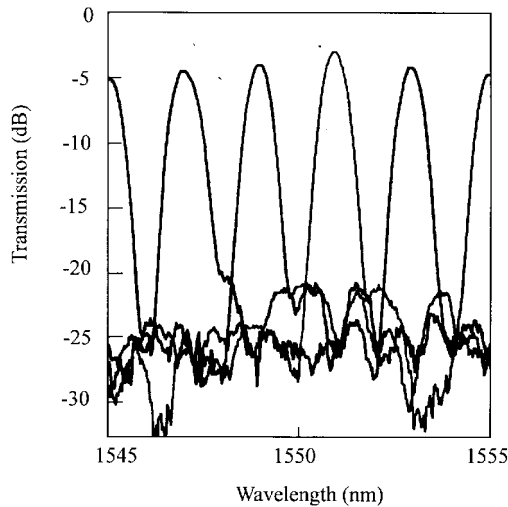


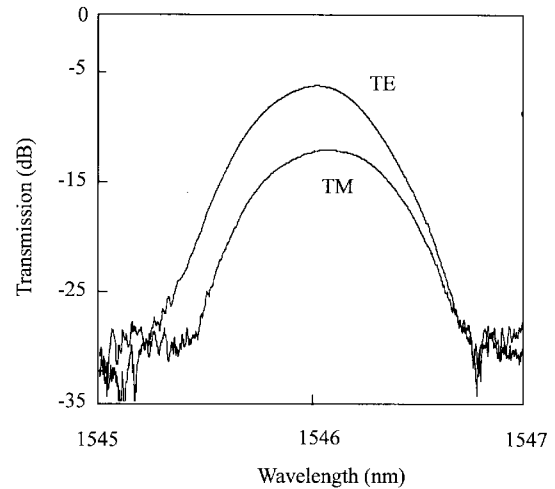
Fig. 3. Measured wavelength response of four output channels at 1.55 μm wavelength.

4469 μm . The grating array consists of 30 waveguides and the input/output waveguide pitch is 25 μm .

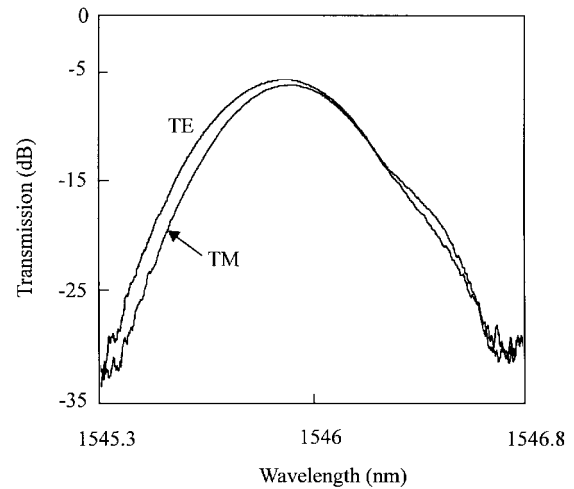
Fig. 2 shows a photograph of the fabricated device. A 90° grating geometry was chosen to minimize the chip area. This geometry also minimizes variations in effective unit path length, $n\Delta L$, due to bends. The device size is $2.7 \times 2.7 \text{ cm}^2$ with a conservative 2-cm waveguide bend radius. The multiplexer was fabricated on a bond and etchback silicon-on-insulator (BESOI) wafer having a 5- μm -thick Si on top of a 1- μm SiO₂ layer. After photolithography and pattern formation, the device was etched to a rib height of 2 μm using a two step reactive ion etching (RIE) process [12]. The first SF₆ etch was performed at 100 mTorr with 250 W RF power for 6 min. This was followed by a SF₆/O₂:85 mTorr/15 mTorr etch at 250 W RF power for 2 min. The two step etch was developed in order to avoid problems associated with polymerization of the photoresist.

III. RESULTS AND DISCUSSION

Fig. 3 shows the measured wavelength response of four output channels at 1.55- μm wavelength. We use the broad-band



(a)



(b)

Fig. 4. (a) TE-TM polarization dependence of SOI phased-array wavelength multiplexer with a rib height of 2 μm . (b) TE-TM polarization dependence of multiplexer with deeper waveguide etch with a rib height of 3 μm .

spontaneous emission from an erbium-doped fiber amplifier (EDFA) covering 1520–1570-nm wavelength range as the input source. We experimentally established that the coherence length of this source is sufficiently long for characterization of our filter. The light source is coupled into the center input channel through a polarizing fiber and collected at the four output channels by a cleaved single-mode fiber. The spectrum is measured using an HP optical spectrum analyzer with 0.1 nm wavelength resolution. The measured FSR is 7.6 nm and the channel spacing is 1.9 nm (237 GHz). The transmission peaks have the Gaussian profile with –3-dB bandwidth of 0.72 nm corresponding to a 38% bandwidth/channel spacing ratio. The adjacent channel crosstalk is less than –22 dB measured as the signal to noise ratio within a channel. The on chip loss is <6 dB and the output nonuniformity is less than 2 dB.

Fig. 4(a) shows polarization sensitivity measurements. A TE–TM shift of approximately 0.04 nm is observed. This, to the best of our knowledge, is the lowest polarization shift observed in any waveguide technology without compensation techniques. The insertion loss is higher for TM with respect

to TE as a result of higher propagation loss of TM mode compared to TE. The polarization sensitivity in integrated waveguides stems primarily from two sources: 1) The stress in the waveguiding layer and 2) the cross-sectional geometry of the waveguide. Unlike silica (glass) waveguides, SOI films do not have intrinsic stress. Therefore, we believe that the residual spectral sensitivity of 0.04 nm and the observed difference in the propagation loss of TE and TM modes is due to the asymmetry of the rib geometry, and in principle, should not be present in deeply etched rib waveguides which resemble a symmetric channel waveguide geometry. We have confirmed this hypothesis by increasing the rib height to 3 μm . The result shown in Fig. 4(b) shows a negligible TE/TM spectral shift of 0.02 nm, and nearly identical propagation loss for the two modes. Therefore, the TE-TM dependence can be nearly eliminated with a deep waveguide etch. However, there is a limit to the rib height as too deep an etch could result in multimode waveguiding and the concomitant distortion of the spectrum. This effect can be seen as the small shoulder on the right flank of the passband in Fig. 4(b). The multimode propagation also affects the crosstalk which was increased to < -15 dB in the deeply etched device.

IV. CONCLUSION

We have successfully demonstrated a four-channel phased-array waveguide grating wavelength multiplexer operating at 1.55 μm in SOI technology. The device exhibits low on-chip loss of < 6 dB and crosstalk of < -22 dB. It has extremely low-polarization dependence. In principle, the filter can be made very compact due to the tight optical confinement possible in the SOI structure. The results demonstrate the potential of the SOI waveguide technology as a platform for realization of low cost, high performance, and reliable WDM components that are truly compatible with the silicon IC technology. The combination of silicon integrated optics, VLSI circuits, and even micromechanics could lead to high performance and reliable microsystems with vast capabilities.

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