Monolithic Integration of a Multiplexer/Demultiplexer With a Thermo-Optic VOA Array on an SOI Platform

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Abstract—In this letter, a nine-channel 100-GHz arrayed waveguide grating multiplexer/demultiplexer is monolithically integrated with a Mach–Zehnder interferometer thermo-optic variable optical attenuators (VOAs) arrayed on a silicon-on-insulator platform. The on-chip transmission loss is ∼6 dB and the crossstalk is less than −25 dB for the transverse-electric mode. The maximum modulation depths of different thermo-optic VOAs are similar, ∼15 dB with 2.7-V bias. The frequency response of our device is fast (≥100 kHz) for thermo-optic effect devices. The maximum power consumption of a single VOA is less than 35 mW.

Index Terms—Arrayed waveguide grating (AWG), monolithic integration, multiplexer/demultiplexer, silicon-on-insulator (SOI), thermo-optic variable optical attenuator (VOA).

I. INTRODUCTION

RECENTLY, wavelength-division-multiplexing (WDM) networks have attracted much attention and have been quickly deployed for optical communication [1]. Arrayed waveguide grating (AWG) is a critical optical component to increase the transmission capacity in WDM systems, and is extensively used as the multiplexer/demultiplexer. Generally, optical signal power levels in WDM systems are different for the wide wavelength range because of the intrinsic nonflat gain profiles of erbium-doped fiber amplifiers. Thus it also exhibits dependence of optical signal levels on the network configuration. In order to improve the optical signal-to-noise ratio for long-distance transmission with the WDM networks, it is important to preserve the power uniformities across all signal channels. Variable optical attenuator (VOA) or power equalizers can effectively realize the power balance of WDM channels. Thus it is expected that the integration of AWG-VOA can not only achieve wavelength blocking and equalizing, but can also enhance the reliability and reduce the cost.

Previously, a few AWG-VOA integration structures have been reported, such as an eight-channel AWG integrated with microelectromechanical systems VOA [2], a 16-channel AWG integrated with Mach–Zehnder interferometer (MZI) VOA [3], [4], and a 40-channel AWG integrated with polymer VOA [5]. Although the performances of integrated devices were good, those based on silica or polymer material were difficult to be monolithically integrated with other functional devices. In addition, their processes are not compatible with complementary metal–oxide–semiconductor (CMOS) technology. As a result, the devices based on silica or polymer materials are prohibited from mass production due to the high cost, large size, high power consumption, and low frequency response.

In this letter, we report a monolithically integrated circuit comprised of a nine-channel 100-GHz AWG multiplexer/demultiplexer and a four-channel MZI thermo-optic VOA array on silicon-on-insulator (SOI) using the compatible process with CMOS. We designed and fabricated the devices with rib waveguides of 2.0-μm widths, which were formed by partially etching the 2.0-μm top silicon layer to a depth of 1.4 μm. The size of the integrated AWG-VOA device is ∼10 × 9 mm².

II. DESIGN AND EXPERIMENTS

Recently, ultrasmall AWG formed on SOI using a single etch process has been reported. However, the performance is generally poorer than ideal [6]. More complex structures and fabrication schemes must be added for improved performance, such as a double-etch process and a special coupling converter [7]. To reduce the cost and simplify the process, we designed the integrated device on the SOI wafer with a rather thick top-Si layer (2.0 μm). In order to minimize the process sensitivity on AWG performance, the feedback structure was adopted. A single AWG is used as the multiplexer as well as the demultiplexer. The schematic diagram of the integrated devices is shown in Fig. 1. This device consists of a nine-channel 100-GHz AWG as the multiplexer/demultiplexer, and four thermo-optic effect VOAs. Besides the through channel, it has four drop-channels and four add-channels. The uppermost is the through channel; the second to the fifth in output/input port are the drop/add channels, and the sixth to the ninth connect the multiplexer and demultiplexer through thermo-optic VOAs. The signal with wavelengths of λ₁ − λ₀ from input through channel is split first into nine output channels by AWG (as a multiplexer). The signal with wavelengths of λ₁ − λ₀ is dropped out by drop channels, respectively. λ₅ − λ₀ will pass through the VOA array, and then pass through the AWG (as a multiplexer) to be combined into the output through channel. The add-signal λ₆ − λ₀ launched from the relative add channels can also be combined into the output through channel by AWG. The VOA array can modulate the optical intensity of λ₆ − λ₀.

In order to ensure that the waveguide is single mode and is easy to couple with the optic fiber, the rib waveguide is used. Etching depth is 1.4 μm and the width of each arrayed waveguide is 2.0 μm, with a minimum radius of 300 μm.
schematic diagram of the waveguide cross section is shown in inset 1 of Fig. 1. The device was designed to operate at the grating order of 150, with a path length difference of 53.89 μm for transverse-electric (TE) mode, and the free propagation region (FPR) focal length is 2015 μm. The minimum pitch between the neighboring waveguides is 8 μm at the fan-out section. Taper structures are used between output/arrayed waveguides and FPR, as shown in the insets of Fig. 1. To reduce the insertion loss nonuniformity of the device, the free spectral range of 11 nm is chosen, more than the minimum required spectral range of 7.2 nm. The structures of these VOAs are identical, consisting of the 1 × 2 multimode interference (MMI) splitter/combiner and two phase arm waveguides, as shown in Fig. 1. According to the self-image theory, the width and length of the MMI splitter/combiner are 16 and 293 μm, respectively. The distance between the two phase arm waveguides is 8 μm. The phase arms are 1200 μm long and the heater length is 900 μm above the arms. The tapers are used to connect the single-mode waveguide with the MMI waveguide to reduce the loss. High-resistance Ta metal is used in the heater element on the phase arms waveguides, and low-resistance Al metal is used in connecting electrodes.

The SOI wafers used in this experiment have a 2.0-μm-thick top silicon layer (n = 3.45) over a 2-μm-thick buried oxide (n = 1.45). The oxide thickness of 2 μm is sufficient to reduce the optical leakage into the substrate. The waveguide structures were patterned with 248-nm-deep ultraviolet lithography and directly etched into the top silicon layer with the inductive coupled plasma-reactive ion etching. The silicon etching depth is 1.4 μm. In order to reduce the sidewall roughness of the rib waveguides, a 200-nm-thick SiO2 layer was thermally grown on the etched Si-structure. Before depositing the 100-nm-thick Ta metal for the heater, another SiO2 layer was deposited by low-pressure chemical vapor deposition in order to further reduce the optical leakage from waveguides into the metal film. Finally, a 700-nm-thick Al metal layer was deposited and etched. The total size is 10 × 9 mm². Fig. 1 also shows the scanning electron microscope (SEM) images of the AWG/MMI output section.

III. RESULTS AND DISCUSSION

The device was polished to reduce the coupling loss with the optical fiber. We used the single-mode lens fiber to couple to the device. It was measured using a tunable laser source and an optical spectrum analyzer. Fig. 2 shows the TE mode spectral response of the integrated device. There are nine peaks in the spectra, measured at the through port and each of the four drop ports. One is the through signal, including λ1, which only passes through the demultiplexer, and λ0−λ9 modulated signals which pass through the demultiplexer, thermo-optic VOA, and multiplexer. The others (λ2−λ5) are the drop signals. The on-chip transmission loss and the crosstalk of AWG are about 6 and −25 dB, respectively. The channel spacing is 0.8 nm ±0.02 nm, which is close to the designed target. The polarization-dependent wavelength is about 0.13 nm. The loss difference between the signals λ3 and the signals λ0−λ9 shows that the total propagation loss of AWG and the thermo-optic VOA is ~8.5 dB. As a result, the propagation loss of thermo-optic VOA is 2.5 dB. The add-signals are like the drop signals. The central wavelength is 1545 nm, shifting 1.8 nm from the designed wavelength. The shift is mainly caused by the difference between the measurement temperature and the designed temperature on AWG, and partially caused by process deviation. The deep etch can effectively reduce the size, but the contribution of the sidewall roughness to the propagation loss increases with the etch depth. This is the dominant loss mechanism. For the small rib waveguide, the etch depth is difficult to control and the small deviation could cause obvious loss, especially for the MMI structure.

Fig. 3 shows the modulation of the thermo-optic VOA for TE mode. The maximum modulation depth is ~15 dB under a bias of 2.7 V. The maximum power consumption of a single VOA is less than 35 mW. We use the finite-element analysis method (COMSOL) to simulate the temperature field under the experimental condition with operating a phase difference of π. The result shows that there is a temperature difference of ~5 K between the two phase arms under the operating π phase difference condition. This simulated result is in reasonable agreement with the result obtained using a modified one-dimensional analytical treatment of the heat flow [8]. Using the equation from [8], we can obtain ~4.7 K temperature difference between two phase arms for our VOA device. To minimize the temperature field effect caused by the heated arm, the space between VOA and AWG is more than 2000 μm. The thermal effect on other
The frequency response of our device is compensated by the power consumption of the thermo-optic VOA. The maximum dissipation is about 25 dB for TE mode. When one VOA is being modulated, the inset of Fig. 5. Inside the 25-dB transmission bandwidth for TE mode, the dispersion of integrated device varies from 60 to 60 ps/nm.

IV. CONCLUSION

The monolithic integration of a feedback nine-channel 100-GHz multiplexer/demultiplexer with thermo-optic VOA array on the SOI platform is demonstrated. The device shows good performance: the transmission loss is about 6 dB and crosstalk is less than 25 dB for TE mode. The maximum modulation depth is about 15 dB, and the response time is less than 10 μs. The power consumption of the thermo-optic VOA is very small (<35 mW). When one VOA is being modulated, the effect on neighboring device is negligible.

REFERENCES