Optics Communications 285 (2012) 4368–4371

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

CMOS—compatible reconfigurable microring demultiplexer with doped silicon slab heater

Kang Xiong, Xi Xiao, Xianyao Li, Yingtao Hu, Zhiyong Li, Tao Chu, Yude Yu, Jinzhong Yu*

State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Sciences, P.O. Box 912, Beijing 100083, PR China

ARTICLE INFO

Article history:
Received 26 April 2012
Received in revised form
13 June 2012
Accepted 30 June 2012
Available online 13 July 2012

Keywords:
CMOS
Demultiplexing
Micro-resonator
Reconfigurable
Silicon-on-insulator (SOI)
Wavelength division multiplexing (WDM)

ABSTRACT

We present a 1×4 reconfigurable demultiplexer based on cascaded silicon microring resonators. The device is fabricated on a 0.18 μm complementary metal oxide semiconductor (CMOS) process. A homogeneous doped silicon slab heater is proposed and fabricated directly on the slab region of the microring resonator for thermal tuning. The flows of the heating currents in the heaters are parallel to the ring waveguide through the heavily doped slab regions located on both sides of the ring waveguide without through the waveguide core regions. The proposed doped heaters are experimentally verified with low-voltage operation and tuning efficiency of ~77 pm/mW. Without any tuning or trimming, predicted average channel spacing distribution in the whole free spectral range (FSR) is demonstrated. Full reconfigurability is also demonstrated in the demultiplexer with channel spacing of 2 nm (250 GHz) and 1 nm (125 GHz), corresponding to channel isolation of less than −21 dB and −16 dB, respectively. Such a low-voltage operation and reconfigurable demultiplexer is suitable for on-chip optical interconnect.

1. Introduction

Silicon-on-insulator (SOI) microphotonics has become an attractive technology for chip-scale optical interconnect due to its compatibility with standard CMOS technology at high reliability and low cost [1]. Microring resonators are ultra-compact fundamental SOI structures which have been proved to be especially suitable for wavelength filtering and routing [2–4]. Several multi-channel SOI microring resonator devices have been demonstrated [5–8] for wavelength division multiplexing (WDM) application. However, SOI microring resonators are extremely sensitive to fabrication imperfections and ambient temperature fluctuations, which make it very challenging to precisely control the desired resonance wavelength of a microring resonator and achieve the desired channel spacing between adjacent microring resonator channels. Fortunately, the thermally tunable silicon microring resonators can provide effective and large range tuning of the resonance wavelength. Furthermore, the resonance wavelength of each microring can be thermally tuned individually and simultaneously, so it is available to the reconfiguration and the flexible controlling of both the resonance wavelength and channel spacing in silicon microring WDM devices.

In general, there are two main kinds of thermal heater in silicon tunable microring resonator: one is the metal heater on the top of the silicon microring resonator isolated from the cladding layer (commonly a SiO_2 layer) [6–8]; and the other is directly integrated by the heater onto the slab region of the rib waveguide by doping the silicon rib waveguide as a p–i–n resistor [9–11] or alloying the silicon slab to form a nickel silicide (NiSi) resistor [12]. Among these, doped silicon technology is the fundamental process in the established commercial CMOS manufacturing without introducing extra materials and special processes, hence, doped silicon slab heater is employed here in order to fully compatible with the standard CMOS process.

In this paper, we have demonstrated a 1×4 reconfigurable silicon microring demultiplexer, which was fabricated on a commercial 0.18 μm CMOS process. A novel homogeneous doped silicon slab heater was proposed and employed to tune resonance wavelength in every channel with low-voltage operation and tuning efficiency of ~77 pm/mW. Without any tuning or trimming, the demultiplexer was demonstrated with predicted average channel spacing distribution in the whole FSR. Full reconfigurability was also demonstrated with channel spacing of 2 nm (250 GHz) and 1 nm (125 GHz), channel isolation of less than −21 dB and −16 dB, respectively.

2. Design and fabrication

In a silicon microring demultiplexer configuration, cascaded microring resonators are coupled to a common through-port waveguide and respective drop-port waveguides that routing

* Corresponding author.
E-mail address: jzyu@semi.ac.cn (J. Yu).

0030-4018/$ - see front matter Crown Copyright © 2012 Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2012.06.085

the corresponding wavelength. The resonance wavelength of a microring resonator is dependent on the resonator's perimeter (optical path), thus the perimeters of the cascaded microring resonators can be slightly varied to divide among the resonance wavelengths of different channels. In order to achieve average distribution of four channels in the whole FSR, the resonance wavelength shift $\Delta\lambda$ is designed to be FSR/4. The wavelength shift depends on $\Delta\lambda = \lambda_0 n_{eff} \Delta P/(n_g P)$ [5], and the FSR depends on $FSR = \lambda_0^2/(n_g P)$. Hence, we can get the change of the resonator's perimeter$\Delta P = \lambda_0/(4n_{\mathrm{eff}})$, where P and ΔP are the resonator's perimeter and the change of the resonator's perimeter, λ_0 is the resonance wavelength, n_{eff} and n_g are the effective index and the group index of the silicon waveguide, respectively.

As shown in Fig. 1(a), a four channel demultiplexer was fabricated on the SMIC commercial 0.18 μm CMOS process [13] with 340-nm-thick top silicon layer and 2-μm-thick buried dioxide layer. The microring resonator of every channel is designed as a racetrack-shaped microring. The bend portions of the racetrack are kept constant at 9 μm and coupled to the through- and drop-port waveguides while the lengths of the straight portions of the racetrack are slightly varied to change the resonator's perimeter. The perimeters of the cascaded microring resonators are of around 20π μm. The slab height is 80 nm and the waveguide width is 450 nm for both the bus and racetracks. The distance between adjacent resonators is 100 μm, which can be reduced for a more compact design. The gaps between the racetracks' bends and the coupling through- and drop-port waveguides are fixed at 200 nm. Based on the former discussion, at the wavelength of 1550 nm, $\Delta P = \sim 140$ nm, i.e., the length change of the racetrack's straight waveguides is $\sim$70 nm to achieve average channel spacing in the whole FSR.

A novel doped silicon slab heater is firstly proposed and employed in the tunable resonator by homogeneous doping of the slab region of the microring to thermally tune the resonance wavelength. The schematically illustrated architecture and microscope picture of the integrated doped silicon slab heater are shown in Fig. 1(b) and (c), respectively. Both sides of the slab of the microring are heavily n-doped with a doping density of 1×10^{19} cm^{-3} and the n$^+$ doped areas are 700 nm away from the edge of the ridge. Aluminum wires and pads are fabricated on a 1 μm silicon dioxide cladding. Interleaved positive and negative metal contacts are embedded in the doped areas, which forms multiple doped silicon resistors surrounding the microring in parallel with resistances of several ten ohms to obtain chip-compatible low-voltage operation. When applied voltages are applied onto the electrodes, current flows are flowed through the slab doped areas of the microring along the rib waveguide, and the heat generated from doped silicon is transferred to the microring through the slab, and the microring is heated up leading to effective refractive index increase, and subsequently the resonance wavelength is red shifted.

3. Experimental demonstration

To characterize the fabricated 1×4 demultiplexer, grating couplers are integrated on the input and the output terminals of the waveguide to achieve convenient fiber-to-chip light coupling on the measurements. The measured spectrum of the four channel wavelength demultiplexer is shown in Fig. 2. Around the wavelength of 1550 nm, the demultiplexer has a FSR of $\sim$9.4 nm, and thus the average channel spacing should be $\sim$2.35 nm. In Fig. 2, within two FSR, the channel resonance wavelengths are 1542.83 nm, 1545.15 nm, 1547.45 nm, 1549.86 nm, 1552.24 nm, 1554.54 nm, 1556.85 nm, 1559.37 nm, indicating the channel spacings of 2.32 nm, 2.30 nm, 2.31 nm, 2.38 nm, 2.30 nm, 2.31 nm, 2.52 nm, respectively. They agree reasonably well with the designed average distributed channel spacing. The device exhibits high extinction ratio (>26 dB) on the drop-port spectrums along with high adjacent channel isolation (<-22 dB). The measured -3 dB bandwidth of the drop-port spectrums are 0.26–0.32 nm and the measured channel dropping losses are very small ($\sim$1 dB).

The resonance wavelength of each microring in the fabricated demultiplexer can be independently thermally tuned with the doped silicon slab heater. The resistance of the doped silicon heater is designed to be of several ten ohms, which can obtain high heating powers with chip-compatible low applied voltages. We test and characterize the heating capability of the heater by measuring the transmission spectra of one drop port with different applied voltages (heating powers). As different voltages from a voltage source are applied onto the heater in one of the four channels, the drop-port spectra are shown in Fig. 3(a). Fig. 3(b) exhibits the I–V curve of the doped silicon heater and sequentially the thermal resistance is $\sim$30 Ω. Fig. 3(c) shows the thermal tuning efficiency for the doped silicon heater demonstrated here and is estimated to be $\sim$77 pm/mW. When the applied voltage is $\sim$2.06 V, the tuning power in terms of wavelength shift per FSR is $\sim$125 mW. A wavelength tuning of one FSR

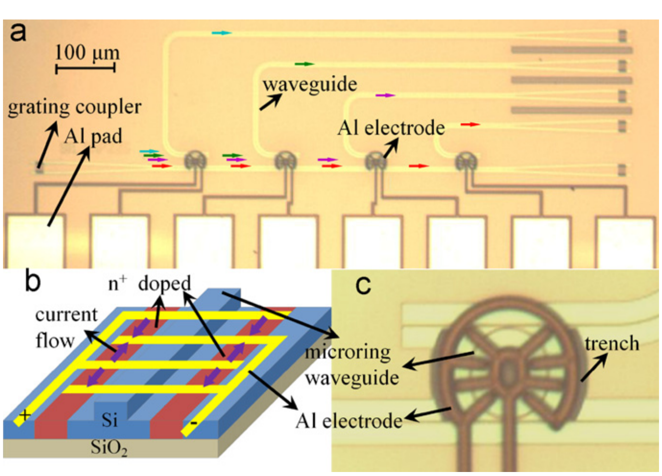

Fig. 1. Micrographs of the fabricated 1×4 reconfigurable demultiplexer: (a) microscope picture of the whole demultiplexer; (b) schematically illustrated architecture and (c) microscope picture of the doped silicon slab heater.

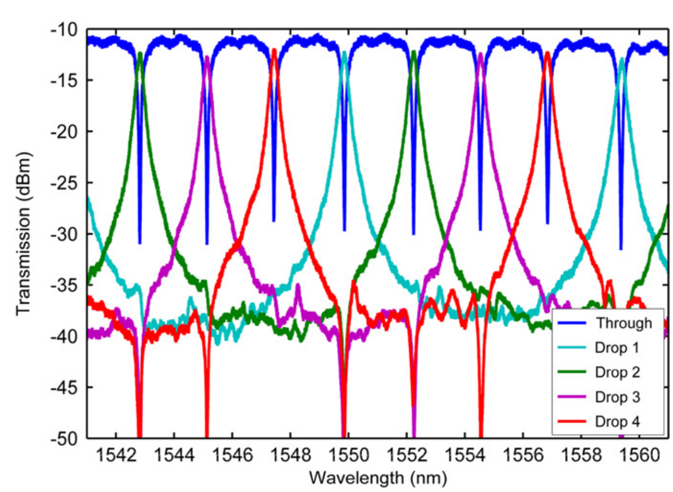

Fig. 2. The through spectra (blue) and drop spectrums of the 1×4 wavelength demultiplexer without any thermal tuning. Drop1 to Drop4 represents the drop ports of the four cascaded microring resonators.