Compact Optical Add-Drop De-Multiplexers with Cascaded Micro-Ring Resonators on SOI *

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A four-channel integrated optical wavelength de-multiplexer is experimentally illustrated on a silicon-on-insulator (SOI) substrate. With the aid of cascaded micro-ring resonators, the whole performance of the wavelength de-multiplexer is improved, such as 3 dB bandwidth and channel crosstalk. Based on the transform matrix theory, a four-channel wavelength de-multiplexer with average channel spacing 4.5±0.5 nm (3 dB bandwidth ∼ 2 ± 0.5 nm) is demonstrated at telecommunication bands. For each channel, the extinction at the adjacent channel is below −39 dB and the out-of-band rejection ratio is up to 40 dB. The channel dropping loss is below 5 dB in the five FSR spectral response periods (near 100 nm).

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Low-cost highly integrated wavelength division multiplexing/de-multiplexing[1−5] systems provide an effective approach to increase the capacity of the fiber communication system and play an important role in photonic integrated circuits. Thanks to the high-index contrast, silicon-on-insulator (SOI) platforms allow low-loss single-mode propagation and micron-sized bending radii, offering an attractive technology to shrink photonic integrated circuits down to micrometer-scale size.[1] To obtain excellent filtering performance in a single channel of a wavelength de-multiplexing system, such as high out-of-band rejection and wide and flat passband, high-order resonator-based filters on SOI platforms have been widely reported.[6−12] However, for the multi-channel micro-resonators-based[5−7,13] wavelength de-multiplexer, to our best knowledge, it usually has a 3 dB bandwidth of about 1 nm and channel crosstalk of about 30 dB (for the best case).[1,14,15] Here, to improve 3 dB bandwidth and crosstalk, we demonstrate a four-channel wavelength de-multiplexer consisting of cascaded micro-resonator arrays on SOI. The individual resonance wavelength of each high-order micro-resonators in the array is shifted by changing its perimeter. To divide the free spectral range (FSR) of the micro-ring resonators into four channels, we change the perimeter of micro-resonators in a uniform step of 132 nm, and demonstrate a four-channel resonator arrays in telecommunication bands. We measure the spectral responses of four drop-ports and the through port over the S and C bands (1465 nm–1560 nm). The four-channel dropping filters have a free spectral range of 18 nm, an average channel spacing of 4.5 nm, an ultra-wide 3 dB bandwidth of about ∼ 2 ± 0.5 nm, a high out-of-band rejection ration ∼40 dB, a low channel cross talk ⩽ −39 dB and a low channel dropping loss < 5 dB.

We choose micro-ring-resonators for analysis, fabrication and characterization, as shown in Fig. 1. In a silicon micro-ring de-multiplexer configuration, high-order micro-ring resonators are coupled to a common bus waveguide, and the respective channel routes the corresponding wavelength through the drop-port waveguide. The resonance wavelength of a micro-ring resonator is dependent on the resonator's perimeter (optical path), thus the perimeter of cascaded micro-ring resonators can be slightly varied to divide among the resonance wavelength of different channels. As the silicon waveguide has very large dispersion, the effective index varies with the resonance wavelength. Then, the master equations of the two resonators illustrated in Fig. 1 are

$$\begin{aligned} m\lambda_0 &= n_{\text{eff}}^{\lambda_0} P, \\ m(\lambda_0 + \Delta\lambda) &= n_{\text{eff}}^{\lambda_0+\Delta\lambda}(P + \Delta P), \end{aligned} \tag{1}$$

where m is the resonance order (which is an integer), λ_0 is the resonance wavelength, P is the perimeter of the micro-ring, and n_{eff} is the effective index of the micro-ring. The resonance wavelength changes with the perimeter of the ring, also for the effective index.

From the above equation and definition of group index ($n_{\text{g}}^{\lambda_0} = n_{\text{eff}}^{\lambda_0} - \lambda_0 \frac{dn_{\text{eff}}^{\lambda_0}}{d\lambda}$), we obtain

$$\Delta\lambda = \frac{\lambda_0 n_{\text{eff}} \Delta P}{n_{\text{g}} P}. \tag{2}$$

Therefore, the resonance wavelength of the ring is proportional to its perimeter. In the case of the ring, we can slightly change the radius of the ring to shift

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the resonance wavelength for routing different lights to functionalize the wavelength de-multiplexer.

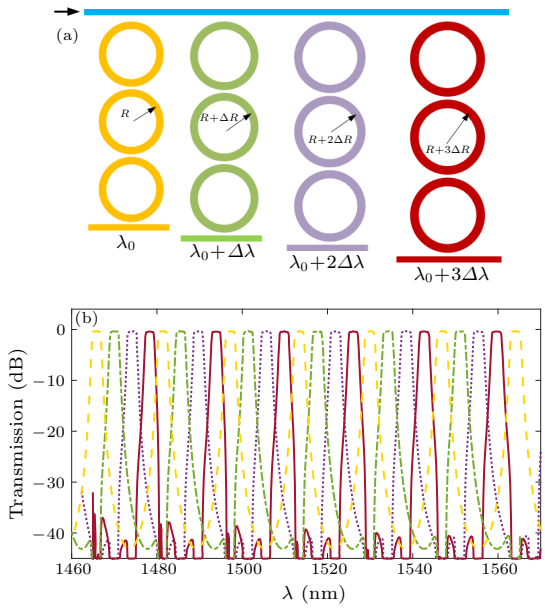

Fig. 1. (a) Theoretical model of the four-channel wavelength de-multiplexer, which changes the resonator's perimeter to shift its resonating wavelength. (b) Simulation results of four-channel wavelength de-multiplexer using the transfer-matrix method. The yellow line corresponds to the first channel as indicated in (a) with radius R. Similarly, the green/violet/red line refers to the second/third/fourth channel of the de-multiplexer.

To achieve average distribution of four channels in the whole FSR, the resonance wavelength shift is designed to be FSR/4. From Eq. (2) and $FSR = \lambda_0^2/(n_g P)$,[5] we have

$$\Delta P = \lambda_0/4n_{\text{eff}}. \tag{3}$$

As shown in Fig. 2(a), a four-channel wavelength de-multiplexer was fabricated on the SOI wafer with a 340-nm-thick top silicon layer and a 2-μm-thick buried dioxide layer. The slab height is 130 nm, and the widths of waveguide and ring are 450 nm and 600 nm, respectively. To achieve a wide 3 dB bandwidth in each channel, we choose the power coupling coefficients between waveguide-to-resonator and inter-resonators to be 0.45 and 0.09, respectively. Using 3D finite difference time domain, we calculate the gaps between waveguide-to-resonator and inter-resonators, which are 22 nm and 96 nm, respectively, to meet the coupling requirements. Based on the former discussion, at the wavelength of 1550 nm, $\Delta P = 132$ nm, i.e., the radius change of the ring is 21 nm to achieve average channel spacing in the whole FSR. Figure 1(b) is the simulation results of the four-channel wavelength de-multiplexer using the transfer-matrix method where the material dispersion is considered. As we can see, the four-channel drop ports occupy one fourth of the FSR separately.

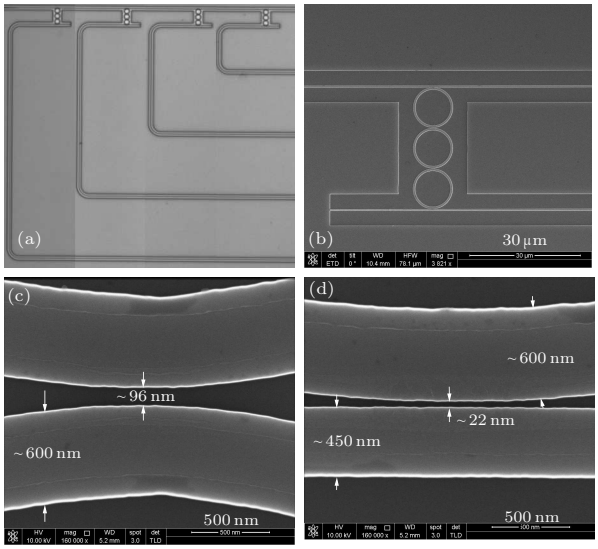

Fig. 2. (a) Micrograph image of the fabricated four-channel wavelength de-multiplexer. For high resolution, we map three parts together into a picture. (b)–(d) Scanning-electron-micrograph images of one fabricated micro-ring resonators channel dropping filter with the coupling region between inter-resonators and waveguide-to-resonator.

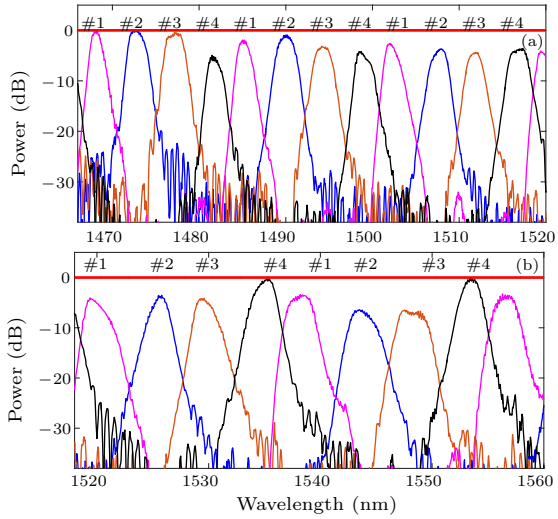

Fig. 3. Spectral responses of four drop-ports of the wavelength de-multiplexer as shown in Fig. 2. We demonstrate five FSR spectral response periods (FSR∼18 nm), covering over the S and C bands. For a clear view, the full spectral response is divided into two parts plotted in (a) for 1465–1520 nm and in (b) for 1520–1560 nm. The channel number is denoted as $\#n$ (n = 1, 2, 3 and 4). In all the figures, the red line indicates the 0 dB reference line.

We use third-order micro-resonators instead of a single one to yield a filtering response with high out-of-band rejection, wide 3 dB bandwidth and flat pass-band etc., which are essential for WDM systems. To characterize the fabricated four-channel wavelength de-multiplexer, grating couplers are integrated on the input and output terminals of the waveguide to achieve convenient fiber-to-chip light coupling. The measured spectral responses of the four drop-ports are illustrated in Fig. 3, where the same color represents one port. The filter's response repeats for

five times. The channel center wavelength increases at an average step of 4.5 nm to longer wavelengths from drop-port #1 to drop-port #4. The channel parameters of the four dropping channels in the third FSR are listed in Table 1. Around the wavelength of 1510 nm, the designed wavelength de-multiplexer has an FSR of 18 nm, and thus the average channel spacing should be 4.5 nm. As we can see, the measured FSR is around 18 nm, which agrees well with the designed value. The measured non-uniform channel spacing is not perfectly matched with the design due to fabrication imperfections (the air gap between waveguide and resonator is so narrow (around 22 nm) that the fabrication imperfection is large). The device exhibits high extinction ratio (>40 dB) on the drop-port spectrum. The measured dropping loss is mostly less than 5 dB, and in the best case it can be 0.03 dB. The measured 3 dB bandwidth of the drop-port spectrum is around 2 nm, which is wider than the reported wavelength de-multiplexer using high-order micro-ring resonators to the best of our knowledge, and such a high 3 dB bandwidth allows for accommodating large optical signal bandwidth and temperature variations in on-chip environment.[8,16] The large fluctuations in the 3 dB bandwidth is mainly attributed to the deviation of designed power coupling coefficients. The shape factor, defined as the ratio between 3 dB bandwidth and 20 dB bandwidth, is around 0.4, indicating a fast rolling-off response. The adjacent channel isolation is influenced by the fluctuations in the dropping loss. In most cases, the adjacent channel isolation[17] is below −39 dB owing to third-order resonators, which is truly improved.

Table 1. Channel parameters for the four dropping channels around 1510 nm.

Channel	#1	#2	#3	#4
1 dB bandwidth (nm)	0.85	1	1.1	1.6
3 dB bandwidth (nm)	1.5	2	1.85	2.45
20 dB bandwidth (nm)	4.75	5	5	5.55
Shape Factor	0.32	0.4	0.37	0.44
Center wavelength (nm)	1502	1507.85	1511.9	1516.95
Dropping loss (dB)	−2.586	−3.68	−4.373	−3.682
Spacing (nm)	5.85 (#1, 2)		5.05 (#3, 4)	
	4.05 (#2, 3)			
Isolation (dB)	< −39 dB (#1, 2)		< −37 dB (#3, 4)	
		< −33 dB (#2, 3)	< −33 dB (#4, 1)	

In conclusion, we have demonstrated a four-channel silicon wavelength de-multiplexer for WDM applications. To obtain a good passband response for WDM signal processing, third-order filters are adopted, where each channel is composed of three coupled micro-ring resonators. The demonstrated four-channel wavelength de-multiplexer has an FSR near 18 nm and a non-uniform channel spacing around 4.5 nm. For all the drop channels in the five FSR spectral response periods, the dropping loss is below 5 dB, the adjacent channel isolation is below −39 dB, and the 3 dB bandwidth is enlarged to 2 nm. The broadened 3 dB bandwidth and the improved channel isolation mean this device can handle high-speed data transmission with negligible signal degradation.

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