Tunable Passband Flattened 1-from-16 Binary-Tree Structured Add-After-Drop Multiplexer Using SiON Waveguide Technology

C. G. H. Roeloffzen, F. Horst, B. J. Offrein, R. Germann, G. L. Bona, H. W. M. Salemink, and R. M. de Ridder

***Abstract*—A tunable, flat-passband, 1-from-16 add/drop multiplexer for wavelength-division-multiplexing networks is presented. The device is realized in high-index-contrast silicon-oxynitride waveguide technology and is based on cascaded resonant coupler filters in the form of a mirrored binary tree. Tunability is obtained using the thermo-optic effect. The isolation of the transit channels at the drop port is better than 18 dB, and the rejection of the drop channel at the output port is 26 dB.**

***Index Terms*—Add–drop, multiplexer, optical waveguide, resonant coupler, silicon–oxynitride, tunable, WDM.**

I. Introduction

WAVELENGTH-DIVISION multiplexing (WDM) is an efficient way to increase the capacity of an optical network. One of the key components to add and drop WDM channels in future ring and mesh topologies is a wavelength add–drop multiplexer (ADM). Various approaches are known to fulfill the add–drop function [1]. Dielectric filters and components based on fiber Bragg gratings are commercially available today. These devices are usually static, i.e., they cannot be tuned to other wavelengths. For applications in future networks, tunable devices may become of interest because they allow one to build reconfigurable networks.

Here, we present a tunable 1-from-16 ADM with cascading resonant coupler (RC) filter elements [2] in the form of a mirrored partial binary tree. The device is realized in high-index-contrast silicon–oxynitride (SiON) technology [3] and works in the 1550-nm wavelength window.

II. Binary Tree ADM

The ADM be presented here consists of one branch of a binary tree of cascaded even-odd channel-splitting optical filter elements ("slicers") [4], [5] as shown in Fig. 1. In the left half of the device, starting at the "in" port, the even and odd wavelength channels are separated in the first slicer. One half of the channels is directed to the next slicer having a double free spectral range (FSR), where they are split again. This continues until one channel, the "drop" channel, remains. In the right half of the device, the "add" channel with new data and the remaining channels are recombined, and transferred to the "out" port. Note that the in-to-drop and the add-to-out transfer function are equal, because the right half of the device is a mirrored copy of the left half.

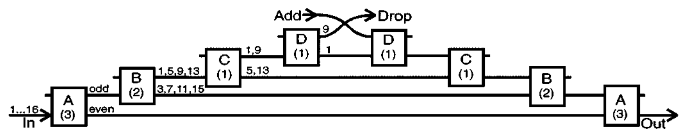

Fig. 1. Schematic drawing of the 1-from-16 add/drop multiplexer. The boxes represent the individual filter elements ("slicers"). The number in the box indicates the number of delay lines used for that slicer. The free spectral range for slicers A, B, C, and D is 3.2, 6.4, 12.8, and 25.6 nm, respectively.

One advantage of the binary-tree-based device layout is that the number of slicers, and thus the number of RC filter stages, grows only logarithmically with the number of wavelength channels in the communications system. For ADM devices based on a linear RC [6], [7], the number of filter stages grows linearly with the number of wavelength channels. A second advantage of the device layout results from the add-after-drop configuration of the device. This ensures extremely low add-to-drop crosstalk [8], [9], and the dropped wavelength is isolated from the output port in both the channel-splitting and combining sections of the device, leading to an improved suppression of the dropped wavelength at the output port.

III. Resonant-Coupler-Based Slicers

To maximize the usable bandwidth of an ADM filter, the shapes of the pass- and stopbands of the slicers should approach a square spectral response. This is not the case for the simplest slicing element, the asymmetric Mach–Zehnder Interferometer (MZI) filter, which has a cosine-shaped spectral response. It does not have a flat passband and it has a narrow stop-bandwidth of only 4% of the FSR at -25 dB suppression. Better results are achieved with multistage RC-type filters, as shown in Fig. 2.

A schematic drawing of a three-stage RC filter is shown in Fig. 3. It consists of four directional couplers with different coupling constants, and three delay lines, the second and third of which have twice the path length difference of the first one. This three-stage filter design features a flattened passband and a stop-bandwidth of 24% of its FSR at -25 dB suppression. The usable bandwidth for a slicer based on this three-stage RC filter will be 48% of the channel spacing.

Manuscript received February 18, 2000; revised May 17, 2000.

C. G. H. Roeloffzen is with IBM Research, Zurich Research Laboratory, CH-8803 Rüschlikon, Switzerland and also with the University of Twente, Lightwave Devices Group, 7500 AE Enschede, The Netherlands.

F. Horst, B. J. Offrein, R. Germann, G. L. Bona, and H. W. M. Salemink are with IBM Research, Zurich Research Laboratory, CH-8803 Rüschlikon, Switzerland.

R. M. de Ridder is with the University of Twente, Lightwave Devices Group, 7500 AE Enschede, The Netherlands.

Publisher Item Identifier S 1041-1135(00)07445-0.

In the binary tree ADM, the first slicer (A in Fig. 1) determines the usable bandwidth and passband flatness of the total device because it has the smallest FSR, hence a three-stage filter is used here. Slicer B has a double FSR compared to A, thus a two-stage filter can be used. For slicers C and D, one-stage filters (MZI) are sufficient. This gives a total of 14 stages for the device. The transfer functions of the one-, two-, and three-stage RC-filters are given in Fig. 2. The design parameters and the stop-bandwidth at -25 dB suppression of the RC filters are given in Table I.

The length of couplers that should be longer than half the coupling length can be reduced to $L_{\mathrm{new}} = L_c - L_{\mathrm{old}}$ when all delay lines before the coupler are inverted/flipped. This has been used to reduce the length of the second coupler L_2 of the three-stage slicer shown in Fig. 3.

IV. Device Layout

The mask layout for the add–drop multiplexer is shown in Fig. 4. Because the cascade of couplers and delay lines contains many bend sections, a small radius of curvature is of high interest to keep the ADM device compact. Our silicon–oxynitride (SiON)-based structure has a relatively high refractive index contrast of 3.3% and a waveguide size of 2×3 μm^2 [3]. The strong guiding of the mode allows a minimum bending radius of only 1.5 mm without introducing noticeable bend or radiation losses and thus enables the cascading and folding of many stages into a compact device. Owing to the relatively high index contrast, the waveguide field is not matched to a standard single-mode fiber. However, fiber-to-chip losses of <0.7 dB per facet can be obtained using a short stretch of small-core fiber, fusion-spliced to the standard fiber and butt-coupled to the chip. The propagation losses of the waveguide are as low as 0.1 dB/cm at 1550 nm.

The length differences of the 14 delay lines in the design were chosen to result in a channel wavelength spacing of 1.6 nm (200 GHz) for the complete device. On one arm of each delay line a chromium heater film is deposited, which is used for tuning the ADM to different wavelengths. The heaters are also used to compensate for phase errors in the delay lines.

V. Measurements

The add–drop multiplexer can be tuned to any wavelength channel by properly addressing the individual heaters. To find the optimum heater settings for a given wavelength, one can use manual or automatic optimization procedures [9]. Examples of the designed and measured transfer functions are shown in Fig. 5, where the device is tuned to drop the ITU channels at a wavelength of 1547.7 nm (dashed lines) and 1555.8 nm (solid lines).

Fig. 5(c) shows the measured spectrum of the in-to-drop or add-to-out connection. (Owing to the mirror symmetry of the device, these connections can be interchanged.) The flat passband for the drop channel has width of ~0.7 nm at -0.1 dB. The measured TE-TM shift is smaller than 0.2 nm, resulting in a negligible bandwidth degradation. The isolation between the transit and the drop channels is better than 18 dB. The difference between designed and measured isolation is due to a small deviation of the coupling lengths of the fabricated couplers compared to the design. The on-chip loss for the in-to-drop connection is about 2 dB. The bends and directional couplers showed no measurable additional loss compared to a straight channel.

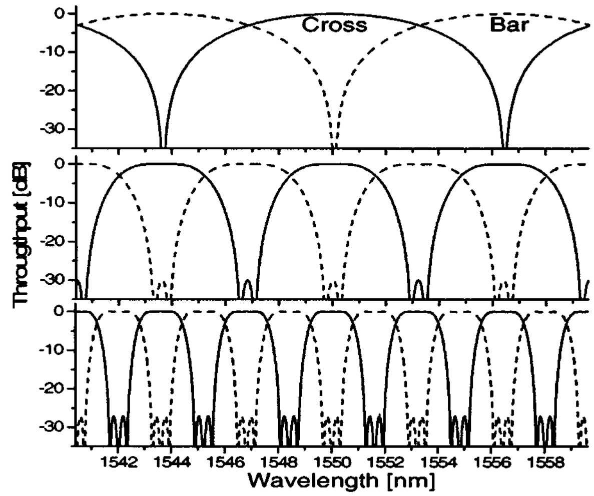

Fig. 2. Bar and cross transfer function of one-, two-, and three-stage resonant-coupler filters with free spectral ranges of 12.8, 6.4, and 3.2 nm, respectively (top to bottom).

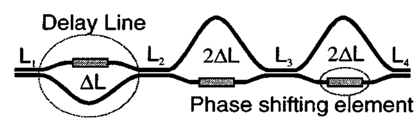

Fig. 3. Three-stage resonant-coupler layout. ΔL is the length difference of the delay line and L_n is the length of directional coupler.

TABLE I
LENGTHS OF THE COUPLERS RELATIVE TO ONE CROSS COUPLING LENGTH L_c, FOR ONE-, TWO-, AND THREE-STAGE FLATTENED PASSBAND FILTERS DESIGNED FOR -30 dB SUPPRESSION. WITHIN THE TOLERANCE BAND THE SUPPRESSION IS BETTER THAN -25 dB. THE LAST ROW GIVES THE ISOLATION BANDWIDTH RELATIVE TO THE FSR

	1 stage	2 stage	3 stage
L_1	0.50 ± 0.04	0.50 ± 0.02	0.50 ± 0.02
L_2	0.50 ± 0.04	0.34 ± 0.02	0.30 ± 0.02
L_3	–	0.18 ± 0.02	0.29 ± 0.02
L_4	–	–	0.09 ± 0.02
-25 dB BW	0.04 FSR	0.14 FSR	0.24 FSR

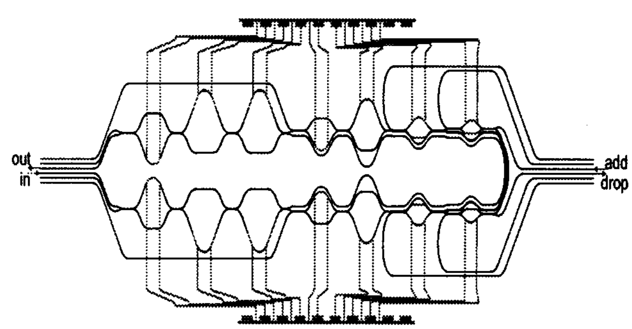

Fig. 4. Device layout of the 1-from-16 device. It consists of eight slicers and 14 delay lines. The input and output are the two center left waveguides and the add and drop are the two center right waveguides. The total device size is 65×14 mm^2.

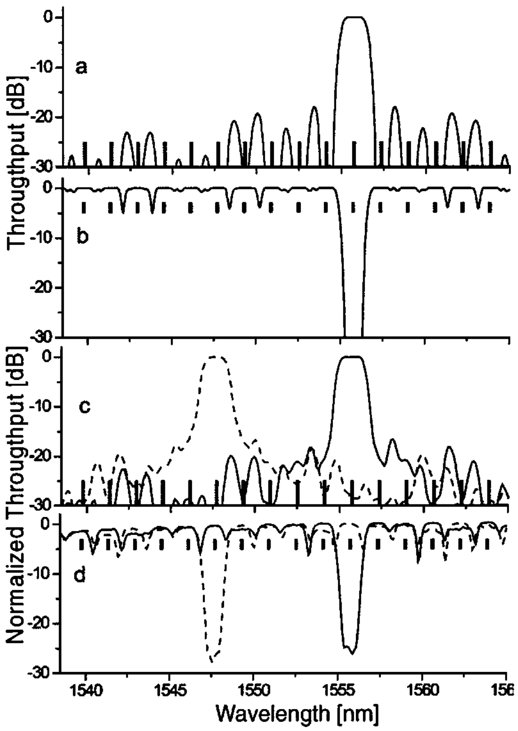

Fig. 5. Designed and measured spectra for 1-from-16 add-after-drop multiplexer (a) in-to-drop design, (b) in-to-out design, (c) in-to-drop measurement, (d) in-to-out measurement. Nonpolarized light was used in the measurements. The vertical markers indicate the positions of the wavelength channels, as given by a 200 GHz, or 1.6 nm, ITU grid.

Fig. 5(d) presents the transmission spectrum for the in-to-out connection. The dropped wavelength is isolated by at least 26 dB. The notch width of the drop channel is 0.7 nm at -24 dB isolation. Between the through channels small notches are visible which are due to multipath interference between the four paths leading from the drop to the add section of the device. Because these paths are made equally long, the interference only leads to additional losses. These become significant only outside the flat passband ranges of the first slicer. Therefore, each of the through channels has, like the drop channel, a usable bandwidth of 0.7 nm. The on-chip loss for the in-to-out connection is about 3 dB. The add-after-drop configuration resulted in a homo-wavelength crosstalk from the add to the drop port of less than -55 dB.

VI. Conclusion

We presented a tunable flattened passband 1-from-16 add–drop multiplexer based on resonant-coupler elements and fabricated in high-refractive-index-contrast SiON technology. A binary tree method of cascading filter elements was used. As the number of required filters grows only logarithmically with the number of wavelength channels, scaling to a larger number of channels can easily be done. The isolation of the transit channels to the drop port is better than 18 dB, and the rejection of the drop channel is better than 26 dB. The on-chip loss is about 3 dB.

Acknowledgment

The authors gratefully acknowledge the invaluable contributions of the technology staff, in particular those of R. Beyeler, U. Drechsler, M. Tschudy, and fruitful discussions with D. Wiesmann.

References

[1] G. E. Keiser, "A review of WDM technology, and applications," *Opt. Fiber Technol.*, vol. 5, pp. 3–39, 1999.

[2] H. H. Yaffe, C. H. Henry, M. R. Serbin, and L. G. Cohen, "Resonant couplers acting as add-drop filters made with silica-on-silicon waveguide technology," *J. Lightwave Technol.*, vol. 12, pp. 1010–1014, 1994.

[3] G. L. Bona, W. E. Denzel, B. J. Offrein, R. Germann, H. W. M. Salemink, and F. Horst, "Wavelength division multiplexed add/drop ring technology in corporate backbone networks," *Opt. Eng.*, vol. 37, pp. 3218–3228, Dec. 1998.

[4] B. H. Verbeek, C. H. Henry, N. A. Olsson, K. J. Orlowsky, R. F. Kazarinov, and B. H. Johnson, "Integrated four-channel Mach–Zehnder multi/demultiplexer fabricated with posphorous dped SiO_2 waveguides on Si," *J. Lightwave Technol.*, vol. 6, pp. 1011–1015, 1988.

[5] K. Oda, N. Takato, T. Kominato, and H. Toba, "A 16-channel frequency selection switch for optical FDM distribution systems," *IEEE J. Select. Areas Commun.*, vol. 8, pp. 1132–1140, Aug. 1990.

[6] B. J. Offrein, F. Horst, G. L. Bona, H. W. M. Salemink, R. Germann, and R. Beyeler, "Wavelength tunable 1-from-16 and flat passband 1-from-8 add-drop filters," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 1440–1442, Nov. 1999.

[7] M. Kuznetsov, "Cascaded coupler Mach–Zehnder channel dropping filter for wavelength-division-multiplexed optical systems," *J. Lightwave Technol.*, vol. 12, pp. 226–230, Feb. 1994.

[8] C. G. H. Roeloffzen, R. M. de Ridder, K. Wörhoff, and A. Driessen, "Crosstalk reduction of a Mach–Zehnder based add-drop multiplexer," in *Proc. Symp. IEEE/LEOS Benelux Chapter*, Nov. 1999.

[9] B. J. Offrein, R. Germann, F. Horst, H. W. M. Salemink, R. Beyeler, and G. L. Bona, "Resonant coupler-based tunable add-after-drop filter in silicon-oxynitride technology for WDM networks," *IEEE J. Sel. Topics Quantum Electron.*, vol. 5, pp. 1400–1406, Sept./Oct. 1999.