# Wavelength Tunable 1-from-16 and Flat Passband 1-from-8 Add–Drop Filters

B. J. Offrein, F. Horst, G. L. Bona, H. W. M. Salemink, R. Germann, and R. Beyeler

*Abstract*— **Tunable add–drop filters for wavelength-division multiplexing networks are presented. The compact devices are realized in high-index-contrast silicon-oxynitride planar waveguide technology and are based on the resonant coupler principle. The first device selects one wavelength channel from a comb of up to eight wavelengths and exhibits a flat passband. Scalability of the filter concept to a larger number of wavelength channels is illustrated with a 1-from-16 add–drop filter. Tunability is obtained using the thermo-optic effect and chromium heater stripes. The devices show negligibly small polarization sensitivity. The isolation of the transit channels to the drop port is between 15 and 20 dB and the rejection of the drop channel ranges from 18 to 23 dB. The design and scalability trade-offs are discussed.**

*Index Terms*—**Add–drop, optical waveguide, silicon-oxynitride, tunable, WDM.**

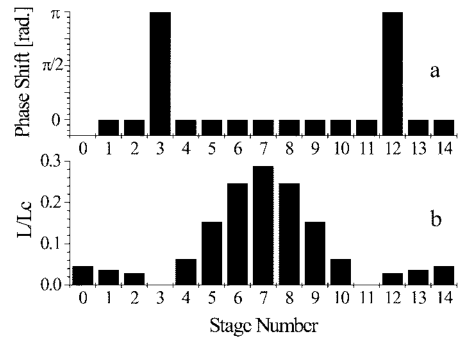


Fig. 1. (a) Delay line phase shift and (b) coupler length distribution for the 14-stage 1-from-8 add–drop design. L is the coupler length and Lc the coupling length for complete power transfer.

## I. Introduction

The increasing demand for high-bandwidth communications has driven the deployment of wavelength-division multiplexing (WDM). The ability to add and drop WDM channels is a very attractive feature because it is a passive filter function that allows the detection and retransmission of one wavelength channel while passing through all other channels. Various approaches are known to fulfill the add–drop function [1]. Dielectric filters and fiber Bragg gratings are commercially available and are now being deployed in the field. These devices are usually static, i.e., they cannot be tuned to other wavelengths. Tunability is of interest for various reasons. First, it allows a flexible application of the add–drop filters and, second, it offers the possibility to build reconfigurable networks. Reconfigurability enhances the functionality and flexibility of future WDM networks. Here, we report the realization of tunable add–drop components operating in the 1550-nm window. The devices are able to select a single wavelength channel from a comb of up to 8 and up to 16 channels, respectively, and are realized in high-index contrast silicon-oxynitride planar waveguide technology.

## II. Device Design

The add–drop components are of the resonant coupler (*RC*) type, a cascade of directional couplers and optical delay lines [2], [3]. The optical delay line consists of a unit length, which is the same for all stages, and a phase shift. The unit arm length difference sets the free-spectral range (FSR) of the response. The additional delay line phase shift and the directional coupler parameters determine the filter response within one FSR. The number of delay line stages increases with the required fine structure in the spectral response of the filter. Standard finite impulse response techniques [4] and the procedure described in [5], [6] were used to design the devices. As reported earlier, the realization of a 1-from-4 add–drop filter with a flat passband requires 7 stages [7], [8]. The 1-from-8 and 1-from-16 filters reported here have a higher finesse, which requires more stages. The wavelength channel spacing is 1.6 nm (200 GHz) in both cases. Note that the device design itself is independent of the channel spacing. The unit arm length difference sets the FSR and scales the response to the required spectral span. Hence the same designs as reported below can also be used for a channel spacing of e.g., 50 GHz, but the unit arm length difference has to be increased by a factor of 4. The response of the *RC* add–drop filter devices is periodic, hence a 1-from-m add–drop filter can also be used as a 2-from-2m, 3-from-3m, etc., where m is the number of WDM channels in the system.

### *A. 1-From-8 Add–Drop Filter*

The design parameters of the 1-from-8 filter are given in Fig. 1 and are comparable to the 15-stage design presented in [9]. The coupler length distribution shows a sinc-like behavior, and the delay line arms induce a phase shift of $\pi$ at the stage numbers where the coupler length approaches zero.

Because the directional couplers 3 and 11 have an amplitude coupling ratio of less than 0.3%, they can be ignored with only a minor influence on the filter response. As a result, the 14-stage design can be implemented as a 12-stage *RC* device with the delay lines of stages 3 and 10 exhibiting the double arm

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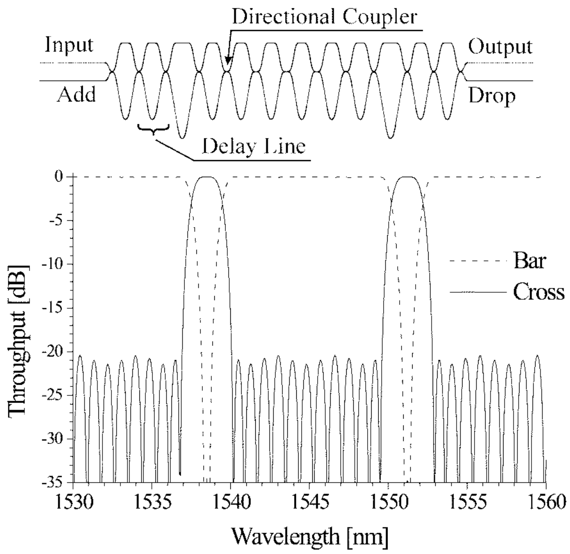


Fig. 2. Device layout (top) and design spectral response (bottom) of the 12-stage 1-from-8 device.

length difference. This saves space and decreases the number of heater elements. The FSR is $8 \times 1.6 = 12.8$ nm (1.6 THz). Fig. 2 shows the device layout and the theoretical filter response. The designed isolation of the transit channels to the drop port is 20 dB (input-to-drop path or cross response).

The flat passband design results in a broadened notch in the bar response with a width greater than 0.7 nm at an isolation level of 20 dB. This makes the design tolerant to detuning effects of the laser wavelength and relaxes the tuning control of the add–drop filter itself.

### *B. 1-From-16 Add–Drop Filter*

A 1-from-16 add–drop filter was designed that consists of 16 stages. The designed side-lobe level in the cross response is at $-20$ dB and the passband is of the standard type without flattening [2]. The FSR is $16 \times 1.6 = 25.6$ nm (3.2 THz).

## III. Implementation

The $RC$ layout generally leads to long devices owing to the large amount of bends. In fiber-matched waveguides where the minimum bending radius is about 15–20 mm this is a problem because only a small number of stages can be cascaded in line on a 4-in wafer. For applicable device functions it is important that a larger number of stages can be cascaded. Therefore we developed a high-index-contrast planar waveguide technology based on silicon-oxynitride [10]. The SiON waveguides show propagation losses below 0.15 dB/cm in the 1550-nm wavelength region [11], and are polarization insensitive owing to careful control of the processing parameters. The allowable bending radius is 1.5 mm, i.e., a factor of 10 smaller than in fiber-matched technologies. The device size of both components is $65 \times 6$ mm$^2$ including the heater contact lines and bonding pads. Low-loss packaging of such waveguide devices to standard single-mode fibers (SMF's) can be obtained using lensed fibers or mode converters [12]. Another promising approach is the use of high-index-contrast fibers for butt-coupling to the optical chip. Efficient coupling can be achieved because the modal field profiles of such fibers are well matched to that of our waveguides. It is known that such high NA fibers can be spliced to standard single-mode fibers with losses of less than 0.3 dB, i.e., by using the thermally expanded core technique (TEC) [13].

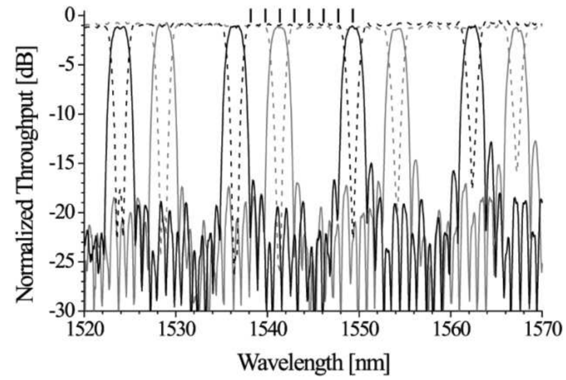


Fig. 3. Measured 1-from-8 add–drop filter response tuned to two add–drop wavelengths. Bar (dashed lines) and cross (solid lines) are shown over a range spanning of three FSR's. The vertical stripes indicate the eight WDM channel positions.

## IV. Measurements

As phase errors in the delay line arms may lead to a distortion of the filter response, every heater is individually addressable. This permits both compensation of the phase errors and tuning of the add–drop filter. This technique has been applied successfully in a 1-from-4 add-after-drop configuration [7]. The heater power optimizations have to be performed only once for a series of add–drop wavelengths that span at least one FSR. The heater settings are stored and can be read back to tune the device to another add–drop wavelength channel. The thermooptic response time is in the submillisecond regime. The measured coupling length in the directional couplers is within a few percent of the design value, and hence no trimming mechanism is required here.

### *A. 1-From-8 Add–Drop Filter*

Fig. 3 shows the filter response tuned to the add–drop ITU wavelengths at 1541.35 and 1549.32 nm. The filter response is normalized to the transmission of a straight waveguide. The left-hand part of the spectrum shows excellent agreement with the theoretical response curves. For larger wavelengths, side lobes appear up in the cross response. The latter is caused by the wavelength dependence of the coupling length of the directional couplers. The coupling length decreases by about 12% from 1530 to 1570 nm, which is in agreement with the effect on the filter response in this wavelength region. On the lower wavelength side, the opposite occurs and the side lobes decrease. Hence, the total operating window of the device is at least 40 nm. In this range the isolation of the transit channels to the drop port is better than 18 dB and the drop wavelength is rejected from the output port by at least 22 dB.

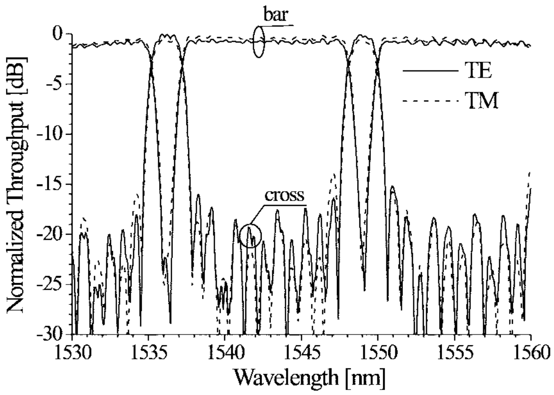


Fig. 4. Add–drop filter response measured for TE and TM polarized light.

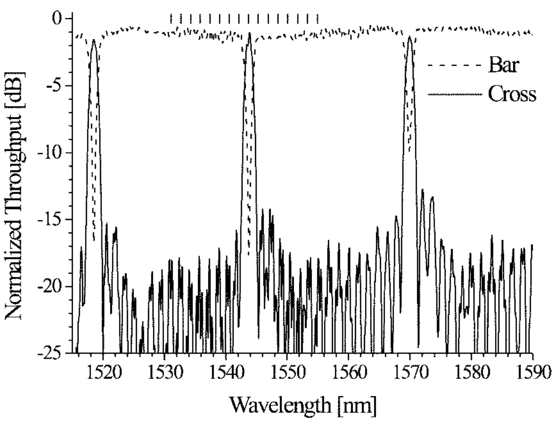


Fig. 5. Measured 1-from-16 add–drop filter response across two FSR's. The vertical lines indicate the eight WDM channel positions.

A small increase of the directional coupler lengths will shift the operating regime into the 1550 nm window. The total electrical power change required to tune the device to the adjacent WDM channel is 900 mW. The polarization sensitivity of this component is very small as shown in Fig. 4, and the on-chip losses at 1550 nm are about 1.5 dB.

### *B. 1-From-16 Add–Drop Filter*

Fig. 5 shows the spectral response normalized to the transmission of a straight waveguide after optimization of the individual heater powers. The isolation of the transit channels from the drop path ranges from 15 to about 20 dB (cross), and the rejection of the drop channel from the transit port is 17 dB (bar). The on-chip losses at 1550 nm are about 2 dB. The total electrical power change to tune to the adjacent add–drop channel is 600 mW.

The $-20$-dB bandwidth of the 1543-nm passband is narrow enough and the FSR is wide enough to permit this device to be used as a 1-from-16 add–drop filter. Improvements such as a better isolation or a flat passband can be obtained by introducing more stages. The homo-wavelength crosstalk issue can be eliminated using an add-after-drop configuration [7]. The yield on the wafer containing the 1-from-8 and 1-from-16 add–drop filters was seven well-functioning devices out of a total of eight.

## V. Conclusion

We presented a 1-from-8 and a 1-from-16 add–drop filter based on the *RC* concept. The 12- and 16-stage devices demonstrate its scalability to a large number of stages. The required number of stages increases with the finesse of the filter response. Moreover, design improvements such as a flat passband or better isolation lead to more stages. The high-index-contrast SiON technology is ideally suited to implement such devices as it combines excellent waveguiding properties with a small bending radius of 1.5 mm. Chromium heaters on the delay line arms allow compensation of phase errors and tuning of the filter response.

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