Widely Bandwidth-Tunable Broadband Optical Filter on Silicon

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We demonstrate an integrated silicon tunable band-pass filter with low in-band ripples of 0.3 dB, a high contrast of 55 dB, and no free-spectral range. A record bandwidth tuning from 788 to 117 GHz was achieved.

PACS numbers: (130.7408) Wavelength filtering devices; (350.2770) Gratings

Optical filters are essential components for optical communication applications such as wavelength-division multiplexing (WDM), signal processing, and dynamic bandwidth allocation [1]. These key devices are now needed in integrated photonic systems, in this case, on the silicon-on-insulator platform (SOI), to achieve the same functions as traditional discrete optical components such as diffractive grating spectrometers. Silicon photonics allows for CMOS compatible mass fabrication for low cost, high yield, and large-scale on-chip integration. Future high-capacity transmission systems, e.g., applying the super-channel technique, will require a dynamic channel bandwidth allocation over a few hundred gigahertz [2]. However, large bandwidth tunability is currently only available in bulky bench-top systems. Existing integrated tunable filters, e.g., using microring resonators and MZ interferometers, have relatively small tunable bandwidth (less than 200 GHz) [3]. Also, their free spectral ranges (FSRs) are small, typically less than 10 nm [3].

Contra-directional couplers(contra-DCs) are grating-assisted add-drop filters [4]. Analogous to waveguide Bragg gratings, the wavelength selectivity in contra-DCs are based on periodic dielectric perturbations. But instead of backreflections in the same waveguide, the selected wavelength in a contra-DC is dropped to another waveguide through contra-directional coupling. This allows add-drop operation without the need of a circulator. Contra-DCs have merits of compactness, flat-top response, flexible filter design (e.g, through apodization), and near-infinite FSR (in the case of first-order gratings). In particular, they allow for very high bandwidths (greater than 10 nm) and thus can support very-high-baud-rate super-channel signals [2]. In this paper, we demonstrate a broadband filter with a large tunability in both wavelength and channel bandwidth, using thermally controlled cascaded contra-DCs on a silicon chip. The filter has flat-top responses, low insertion loss, low in-band ripples, and high contrast between the pass-band and the stop-band.

The schematic of the proposed device is shown in Fig. 1. It consists of a pair of cascaded contra-DCs, each operating as an add-drop filter. The drop port of the first contra-DC is connected to the input port of the second contra-DC. Therefore, the finally dropped signal is determined by the product of the drop-port transfer functions of the two contra-DCs. The center wavelength of a contra-DC is determined by the phase-match condition: $\lambda_c = \Lambda(n_1 + n_2)$, where λ_c is the center wavelength of contra-directional coupling, Λ is the grating pitch, and n_1 and n_2 are the effective refractive indices of the first-order and second-order eigenmodes in the coupler. Assuming identical filter designs (i.e., same window functions and parameters) of the cascaded contra-DCs, the bandwidth of the finally dropped signal can be tuned by detuning their center wavelengths.

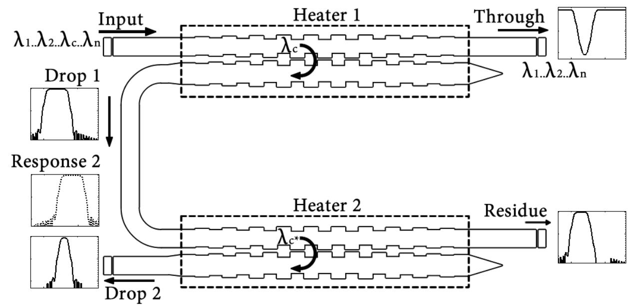

Figure 1. Schematic of the device. The dropped wavelength of the first contra-directional coupler is re-filtered in an identical component. Both contra-directional couplers are temperature-controlled with metal heaters. Plots show examples of spectrum at each port, on a logarithmic scale.

A broadband filter design for a coarse WDM on the 220-nm SOI platform [5] is adopted for individual contra-DCs. In each contra-DC, the widths of the waveguides are of 560 and 440 nm. This high asymmetry ensures a negligible forward coupling. The gratings are formed by sidewall corrugations in strip waveguides with a pitch of 312 nm. The spacing between the waveguides varies between 65 and 135 nm with a Gaussian profile as shown in Fig. 2 for efficient sidelobe suppression, for which details can be found in [5]. The spectral responses of each contra-DC is calculated using coupled mode theory, following the same procedure as in [4], with two additions: apodization and noise simulation.

While an unapodized (uniform) grating can be simulated with only two transfer matrices , S_1 and S_2 [4], an apodized one needs both of these matrices for each

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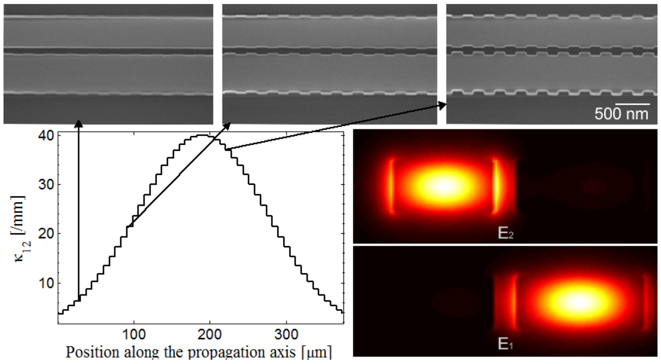

Figure 2. (Top)SEM photography of a part of the grating. The contra-directional coupler consists of two close waveguides of different width with periodic sidewall corrugations. (Bottom Left) Apodization profile of the grating. A larger coupling requires larger corrugations. (Bottom right) Average electric field in both waveguides.

step along the propagation, to match the change of coupling. The first change is thus to modify the transfer matrix of the system to the product of all the grating elements along the propagation axis. This calculation ideally takes shape in an infinite sum, but for computation simplicity, we use a finite number of steps with different couplings that still approximates the apodization profile with enough accuracy. Our simulations uses steps of constant length $z_i - z_{i-1} = z_c$. The total response of a contra-DC $C(z_0, z_n)$ is calculated using the transfer-matrix method, where $E(z_0) = C(z_0, z_n)E(z_n)$.

$$[!h]C(z_0, z_n) = \prod_{i=1}^{n} \mathrm{e}^{S_{1,i}(z_i - z_{i-1})}\mathrm{e}^{S_{2,i}(z_i - z_{i-1})} \qquad (1)$$

It is possible to easily add phase noise to the transfer matrix solution by adding random noise to the $\Delta\hat{\beta}$ propagation constants. The frequency distribution of the noise will thus match the quantization steps of the matrices, but since the response noise is dependent of both the amplitude and frequency of the sidewall roughness [6],we can match the simulation to the experiment by choosing the right noise amplitude.

On top of each contra-DC sits a metal strip acting as a microheater for thermal tuning. The refractive index of silicon has a temperature dependence of $1.87\times10^{-4}\mathrm{K}^{-1}$ at room temperature for wavelengths around 1550 nm [7]. Without electrical input, the optical responses of the two filters are identical (neglecting fabrication uniformities) resulting in a sharp transition from the pass-band to the stop-band. Applying independent electrical currents on the heaters, we can shift the spectra of the contra-DCs simultaneously or differentially for wavelength or bandwidth tuning. In the ideal case, each contra-DC should be uniformly heated so that the apodization profile does not change as the temperature varies.

The device was fabricated using a CMOS-compatible technology with electron-beam lithography. Fiber grating couplers were used as optical IOs in the measurement. Fig. 3 shows the measured drop port response of the cascaded contra-DC filters. The measurements were normalized using the response of a pair of directly connected fiber grating couplers on the same chip.

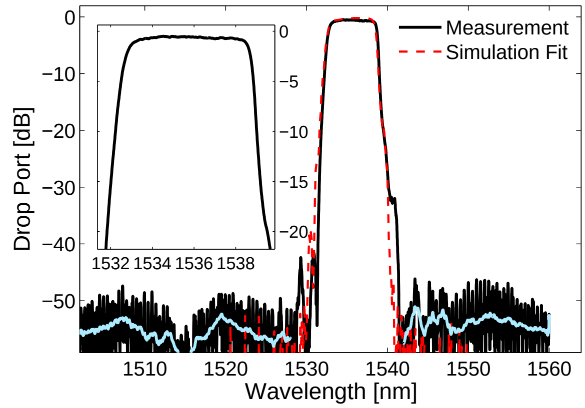

Figure 3. Spectral response of the cascaded filters without heating: 1-dB BW is 733 GHz, 3-dB BW is 788 GHz, 10-dB BW is 868 GHz, and 20-dB BW is 990 GHz. The red line shows the averaged noise floor.

The device exhibits a high side-lobe suppression ratio (SLSR) of over 40 dB and a high contrast of about 55 dB between the pass-band and the stop-band. The insertion loss is very low, less than 0.5 dB (i.e., 0.25 dB per contra-DC), with small ripples of less then 0.3 dB within the 1-dB passband over 5.8 nm (733 GHz). The edge roll-off rate is 19 dB/nm on the left side and 24 dB/nm on the right side. Further work could optimize the grating structure using the inverse layer peeling algorithm[8] since the mathematics of the contra-directional coupler are similar to those of Bragg gratings.

By changing the temperature of a single contra-DC, we offset the phase-match condition of a filter, resulting in a smaller band overlap between the two contra-DCs and thus a narrower passband in the drop port, as shown in Fig. 4. Due to the wavelength detuning, the stop-band edges are only determined by the single filters. As a result, the side-lobes suppression degrades for small bandwidths but is still better than 15 dB. A continuous tuning of the 3-dB bandwidth from 788 GHz down to 117 GHz (i.e., over 670 GHz or 5.4 nm) is experimentally observed as the on-chip temperature increases by 70 degrees. The smallest bandwidth measured in this case was limited by the maximal power delivered before the metal heaters (300-nm-thick, 2-μm-wide Al strips) were damaged. A smaller bandwidth below 50 GHz should be feasible if more robust heaters are used. The power efficiency of the bandwidth tuning is about 24 mW/nm, which can significantly improved by optimizing the heater design, e.g., using smaller heater features and thermal isolation [9].

By applying the same temperature variation on both

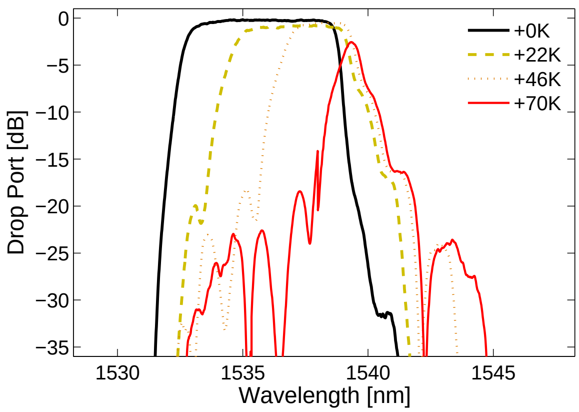

Figure 4. Spectral response of the device for different temperatures applied to only one contra-DC: 1-dB BW tuned down to 65 GHz, 3-dB BW to 117 GHz. The temperatures are obtained from simulation fit.

contra-DCs, the center wavelength can be tuned without affecting the filter shape. As shown in Fig. 5, when the center wavelength is continually changed over 4 nm by varying the on-chip temperature, the filter shape is maintained with sharp edges. Actually, slight detuning between the cascaded contra-DCs may be used to compensate for band-edge distortions due to fabrication errors for a more symmetric filter shape. The power efficiency of the wavelength tuning is about 44 mW/nm, which is about twice the power consumption of the bandwidth tuning since two contra-DCs are heated simultaneously.

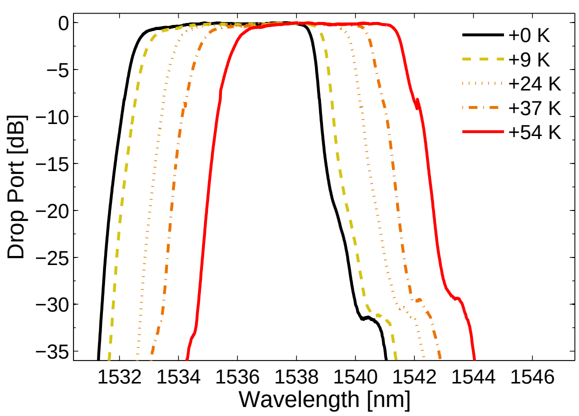

Figure 5. Spectral response with the heat applied to both contra-DCs: the central wavelength is tuned from 1535 nm to 1539 nm continuously; the temperatures are calculated by comparison to simulation.

An other important parameter to monitor is the group delay of the device. An uneven delay can cause distortion during detection of the signal, just like dispersion. The simulation and measurements seen in Fig. 6 both show a group delay difference of less then 10 ps.

In summary, we have demonstrated a bandwidth tunable filter with a low insertion loss of less then 0.5 dB, low ripples of less than 0.3 dB, a large maximal bandwidth of greater than 750 GHz, and high contrast of 55 dB. Compared to other devices based on microring resonators and MZIs, it enables a much larger maximal passband and does not suffer from small FSRs. A large bandwidth tuning range over 670 GHz has been achieved, which, to the best of our knowledge, is the widest ever demonstrated on a silicon chip. This ultra-wide bandwidth tunability makes the device very attractive for next-generation ultrahigh baud-rate applications (e.g., high-capacity superchannel transmissions) and flexible optical networking.

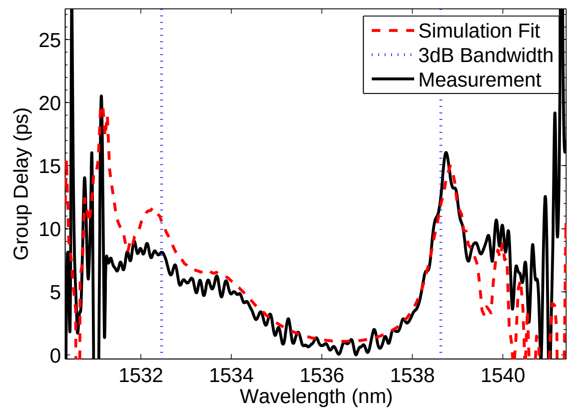

Figure 6. Group delay response of the tunable filter at the drop port. The delay stays within 12 ps between any two points in the band. The out of band results are noisy due to the weak signal.

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Table I. Recent results with multi-element on-chip silicon filters

Publication	Filter type	BWmax / FSR	Tunable BW	On-chip loss	Contrast
Ding (2011)	MRs + MZI	55 GHz / 1 THz	28-55 GHz	3.6 dB	30 dB
Orlandi (2012)	MRs + MZI	173 GHz / 200 GHz	23-173 GHz	0.46-1.06 dB	15-34 dB
Ong (2013)[3]	Cascaded MRs	125 GHz/ 0.9 THz	11.6-125 GHz	0.25 dB	50-100 dB
This work	Cascaded contra-DC	778 GHz / Unlimited	117-778 GHz	0.5 dB	55 dB

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