Fabrication strategies for filter banks based on microring resonators

C. W. Holzwarth,[a] R. Amatya, M. Dahlem, A. Khilo, F. X. Kärtner, E. P. Ippen, R. J. Ram, and Henry I. Smith
Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 19 June 2008; accepted 20 October 2008; published 1 December 2008)

Wavelength-division demultiplexers are a fundamental component needed for many proposed integrated photonic systems. By using filter banks based on microring resonators it is possible to create demultiplexers that are two orders of magnitude smaller and achieve better performance than the discrete component demultiplexers currently used. To create a filter bank out of microring resonators the resonant-frequency spacing must be controlled to within 1 GHz. This is achieved by controlling the electron-dose during scanning-electron-beam lithography in order to change the average ring waveguide width on the tens of picometer scale. Using this method a second-order twenty-channel dual filter bank (80 microrings) is fabricated with a average channel spacing of 83 GHz demonstrating the capability to make changes in the average ring waveguide width with an accuracy of 75 pm. It is shown that any frequency errors that remain after fabrication can be corrected using thermal tuning with integrated microheaters. The amount of power needed to correct for all frequency errors in the fabricated filter banks is 0.09 W, compared to the 2.4 W that is needed if no attempt is made to control the frequency spacing during fabrication. Also a temperature stabilization circuit is demonstrated that can stabilize the temperature of the filters to 80 mK (280 MHz). © *2008 American Vacuum Society.* [DOI: 10.1116/1.3021389]

I. INTRODUCTION

Advances in designs and fabrication techniques for strong-confinement microphotonic devices have made it possible to integrate on a single chip photonic systems that were previously comprised of relatively large discrete components. A wavelength-division demultiplexer is an essential component in integrated photonic systems such as ultrafast analog-to-digital converters and intrachip-communication networks. Currently, arrayed waveguide gratings are used as demultiplexers, but their size (on the order of 1 cm^2 in commercially available devices) is unattractive for integrated photonic systems. By using filter banks based on microring resonators it is possible to create demultiplexers that are two orders of magnitude smaller in size and achieve better performance. It has already been demonstrated that microring-resonator filters can achieve the low-loss and large free-spectral range (FSR) required for these applications.[1] It has also been demonstrated that precise copies of microring-resonator filters with the same dimensions, and therefore the same resonant frequency, can be fabricated using scanning-electron-beam lithography (SEBL) or 193 nm optical lithography.[1,2] However, methods for achieving frequency spacing accuracy better than 1 GHz to create filter banks have not previously been demonstrated. In this article, we present a combination of strategies for the fabrication of microring-resonator filter banks including: accurate resonant-frequency spacing control using SEBL, thermal tuning with microheaters, and thermal stability schemes that, when used together, enable frequency spacing accuracy and stability of better than 1 GHz with minimal power consumption.

The resonant frequency of microring-resonator filters is dependent on the optical path length of the microring, which is a function of the ring radius and the effective index of the ring waveguide. The radius of the microring can be easily controlled in the layout, but is limited to discrete jumps due to the discrete address grid of the SEBL system. The effective index of the ring waveguide can be controlled lithographically by changing its width and with postfabrication methods including thermal heating. Controlling the effective index lithographically is preferred over thermal tuning. However, achieving 1 GHz control of the resonant-frequency spacing would require control of the average ring waveguide width at the tens of picometer scale, more than two orders of magnitude finer than the 6 nm address grid of the SEBL system used (there are SEBL systems available with finer address grids, but none at the tens of picometer scale). Thermal tuning requires power during operation, which scales linearly with the number of microrings, and therefore is increasingly undesirable as the number of filters in a demultiplexer increases. Also sensitivity to external thermal perturbations means that the temperature of each microring must be stabilized to within ~250 mK to maintain a frequency spacing precision of 1 GHz.

In this study we demonstrated a method capable of controlling the average ring waveguide width on the tens of picometer scale by varying the electron-beam dose for each microring.[3] Using this method we fabricated a twenty-channel second-order dual filter bank (80 total rings) that demonstrated a control of the average ring waveguide width of 75 pm. This method was also used to reduce resonant-frequency errors that occur due to intrafield distortion and proximity effects from backscattered electrons. In addition to

[a]Electronic mail: cwh@mit.edu.

directly fabricating the filter banks this SEBL technique can be used to create photomasks to be used by optical lithography tools, which have already demonstrated their ability to create highly precise microring resonators, to create filter bank structures.[2]

Resistive heaters were fabricated above the microring resonators and used to thermally correct any frequency errors still present after fabrication. Also by using a thermal-stability circuit we show that the filter temperature can be stabilized to within 80 mK, even in the presence of an outside thermal perturbation. The thermal power needed to correct for frequency-spacing errors in the twenty-channel dual filter bank was 0.09 W, significantly less than the 2.4 W that would be needed if no effort was made to control the resonant-frequency spacing.

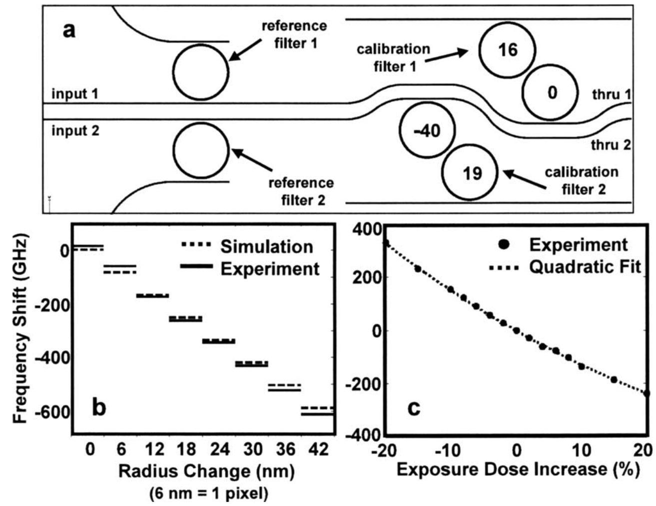

FIG. 1. (a) Device layout for frequency calibration experiments. The numbers inside the calibration filter rings denote their relative frequency mismatch. (b) Frequency dependence on changes in ring radius. (c) Frequency dependence on percent change in exposure dose.

II. EXPERIMENT

A. Filter fabrication

The basic building blocks of the fabricated filter bank are second-order microring-resonators with silicon-rich silicon nitride (SiN_x) as the high-index core (n=2.18 at 1550 nm). The filters are designed to have a 16 nm FSR and a 3 dB bandwidth of 25 GHz. This allows for a filter bank with 20 channels spaced by 80 GHz.

The fabrication of the filters begins by thermally growing a 3 μm thick SiO_2 undercladding layer on a silicon wafer. Next, 400 nm of SiN_x was deposited using low-pressure chemical-vapor deposition. A layer of polymethyl methacrylate (PMMA), an electron-beam resist, and Aquasave, a conducting polymer from Mitsubishi Rayon, were spun on to the wafer. SEBL was then used to write the features in the PMMA. The Aquasave layer was removed first with deionized water and then the PMMA was developed in a solution of three parts methyl isobutyl ketone: one part isopropyl alcohol. Next, a nickel hard mask was formed using electron-beam evaporation and a lift-off process. The pattern was then transferred through the SiN_x using reactive-ion etching in CHF_4/O_2. The nickel was then removed using a commercial nickel etchant. Next, the 2 μm thick overcladding layer was formed out of hydrogen silsesquioxane (HSQ) using an optimized annealing technique.[4] The annealing was optimized so that the HSQ had nearly the same optical properties as SiO_2 as well as excellent gap filling and self-planarization. After the overcladding layer was formed, resistive titanium heaters were fabricated on the HSQ above the microrings using contact lithography and a lift-off process. The sample was then cleaved to expose the end facets of the waveguides for optical testing.

B. Frequency control

Using a two-dimensional cylindrical mode solver it was possible to calculate the dimensional sensitivity of the resonant frequency for changes in radius and average-ring-waveguide width where these are 87 and 200 GHz/pixel, respectively (1 pixel is equal to 6 nm). To achieve spacings between resonant frequencies that were not a simple linear combination of these two numbers, a variation of the electron-beam dose was used to change the average ring waveguide width. This could be done with a precision two orders of magnitude smaller than the SEBL address grid. The point-spread function of an electron beam is closely approximated by a double Gaussian. By increasing the exposure dose, the width of the ring waveguide could be increased in a finely controlled manner.

Empirical calibration experiments were performed to establish the relationship between resonant frequency and electron-beam dose. For these experiments both a single-ring reference filter and a second-order calibration filter were fabricated in close proximity, sharing the same thru-port, as shown in Fig. 1(a). The reference and calibration filters allow one to factor out all frequency shifts due to factors other than the input change in ring radius or electron-beam dose, which include the temperature drift during optical testing, drift of the electron-beam current of the SEBL system, and thickness variation of the SiN_x. By comparing the relative frequency shifts of each calibration filter with respect to the reference filter for many variations in input ring radius and exposure dose it was possible to find the frequency dependence on both, as seen in Fig. 1(b) and 1(c). Figure 1(b) showed that only discrete frequency jumps were possible by changing the ring radius due to the 6 nm address grid of the SEBL system. Alternatively, Fig. 1(c) showed that the frequency dependence on dose can be varied continuously allowing for any desired frequency shift. However, one cannot vary the electron-beam dose by too much because this can result in underexposing or overexposing the electron-beam resist. Thus, it is best to use a combination of changes in ring radius, for large coarse shifts, and changes in electron-beam dose, for smaller shifts, to achieve the desired spacing between resonant frequencies.

For the fabrication of a twenty-channel second-order dual filter bank, with 80 GHz spacing between resonant frequencies, each ring pair must have a radius increase of 6 nm (1 pixel) and an electron-beam dose decrease of 0.6% of the optimum electron-beam dose. By using the changes in radius and dose together it was possible to fabricate the whole filter bank without deviating from the optimum electron-beam dose by more than 5.7%. Similarly, using this method it was calculated that the electron-beam dose never needs to be varied by more than 6.3% to achieve any desired resonant-frequency spacing.

C. Intrafield distortion and proximity effects

During the calibration experiment it was noticed that the four rings of the two calibration filters located in the same write field had consistent frequency mismatches, as labeled in Fig. 1(a). These resonant-frequency mismatches are due to a combination of proximity effects from backscattered electrons (pattern-dependent errors) and intrafield distortion of the SEBL write field (location-dependent errors).[5] As shown in the calibration experiments the resonant frequency depends on the electron-beam dose. Therefore, if the two rings in the same filter have different surroundings they will have a different electron-beam dose due to the contribution of backscattered electrons from nearby patterns to the total dose. This was confirmed in the calibration experiments, where the top most and bottom most rings had higher resonant frequencies corresponding to their lower effective doses (fewer surrounding features). It is possible to correct for this pattern-dependent frequency mismatch due to proximity effects by increasing the electron-beam dose accordingly for rings with higher resonant frequencies.

Due to the symmetry of the calibration layout, the frequency mismatch should be the same for both filters since the proximity effects are the same. However, by averaging over 60 filters it is found that the mismatch in the lower left filter is 59 GHz and the mismatch in the upper right filter is 16 GHz. This difference shows that there is an additional contribution to the frequency mismatch that is location dependent. The location dependent term is due to small deformations in the ring shape caused by the intrafield distortion of the SEBL write field. Intrafield distortion is due to the fact that the address grid of a SEBL write field is not a perfect Cartesian grid. These deviations of the address grid from a Cartesian grid distort the shape of the microring and shift the resonance frequency. This contribution to the frequency mismatch is location dependent and therefore as long as the rings are always written in the same place of the write field it will remain constant. Once the frequency shifts due to proximity effects and intrafield distortion are known they can be corrected by changing the electron-beam dose appropriately.

III. RESULTS

A. Filter bank measurements

A top-view optical micrograph, cross-sectional scanning-electron micrograph and the optical measurements of a fabricated twenty-channel dual filter bank (80 total microrings) are shown in Fig. 2. The average channel spacing of the filter

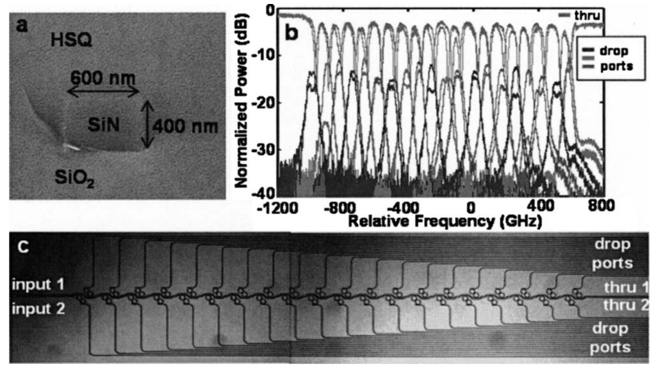

FIG. 2. (a) Scanning-electron micrograph of SiN_x waveguide cross-section with HSQ overcladding. (b) Transmission response and (c) top-view optical micrograph of twenty-channel second-order dual filter bank.

bank is 83 GHz compared to the target channel spacing of 80 GHz. This corresponds to a dimensional precision of the relative change in the average ring waveguide widths of 75 pm. The standard deviation of the resonant-frequency spacing is 8 GHz corresponding to a random variation of the average ring waveguide widths of approximately 210 pm. The ~5 dB variation in the drop-ports is due to different amounts of frequency mismatches between the two rings of each filter.

The frequency mismatch between the two rings in the same filter is now 27 and 31 GHz on the average, with a standard deviation of 8 GHz, for the top and bottom filters, respectively. This compares with the mismatches of 59 and 16 GHz for the top and bottom filters, respectively, that were present before varying the electron-beam dose to compensate for intrafield distortion and proximity effects. The fact that the frequency mismatch is close to the same for the two filters is evidence that the change in dose is effective in correcting for intrafield distortion. However, since the mismatch is not zero there is still a pattern dependent frequency mismatch due to proximity effects. This is not a surprise since the pattern had to be changed slightly from the calibration experiment to accommodate for the drop ports of the 19 additional channels. This highlights the importance of making the pattern the same for the calibration experiment and the filter-bank fabrication.

B. Thermal tuning and stability

As is evident in the optical measurements, there are still some small random frequency errors in the resonant-frequency spacing and frequency mismatch between two rings of the same filter. These errors can be corrected with postfabrication thermal tuning with integrated microheaters, taking advantage of the temperature dependence of the index of refraction. By fabricating independently controlled heaters above each microring it is possible to correct for any frequency mismatch between the rings in the same filter, as demonstrated in Fig. 3. Likewise, the frequency of both rings of the filter can be tuned at the same time to shift the resonant frequency to fix any errors in the resonant-frequency spacing. Using an optimized heater design the SiN_x filters

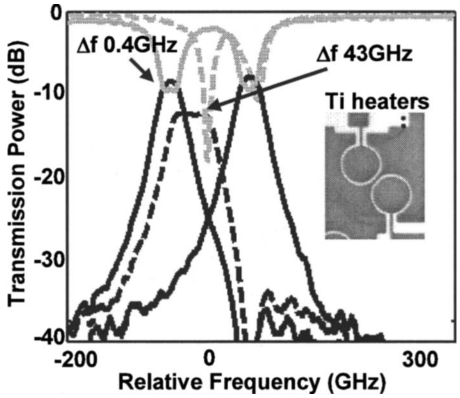

FIG. 3. Transmission response of a two-channel second-order microring-resonator filter bank. The second filter in the bank (the response on the left) had a 43 GHz frequency mismatch before tuning (dotted line) that was reduced to 0.4 GHz after tuning (solid line). The first filter in the bank (the response on the right) had a much smaller mismatch of 20 GHz before tuning that was reduced to 0.6 GHz after tuning (only the after tuning drop response is shown). The inset is an optical micrograph of the integrated titanium heaters located above the microrings.

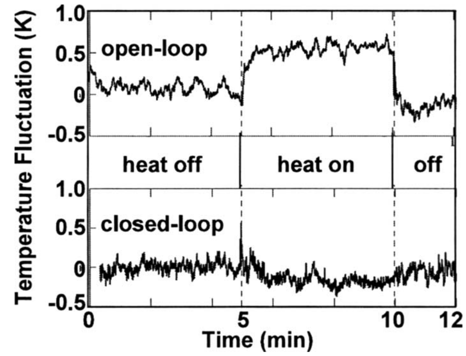

FIG. 4. Temperature stability measurements of a microring-resonator filter in the presence of an external temperature perturbation when using a resistive temperature stability circuit in an open-loop (top) and closed-loop (bottom) setup.

can be tuned with an efficiency of 80 μW/GHz.[6] The heaters are located 1.6 μm above the filters preventing any significant loss due to absorption by the metallic heaters. The crosstalk between heaters for different rings in the same filter is below 5% and the crosstalk from heaters of the adjacent filter is less than 0.1%. It is possible to use thermal tuning alone to create filter banks with accurate frequency spacing, but even with heaters optimized for tuning efficiency it would consume too much power. By controlling resonant frequencies through changes in radius and electron-beam dose the power needed for thermal tuning is greatly reduced. For example the power needed to fix all frequency errors in the fabricated twenty-channel dual filter bank is 0.09 W, significantly less than the 2.4 W needed if all filters are fabricated exactly the same and then thermally tuned to the desired frequencies.

Since the resonant frequencies of microring-resonator filters are dependent on temperature it is important to integrate some temperature stabilization circuit to protect the system from outside temperature fluctuations. Temperature stabilization is achieved by constructing Wheatstone bridge circuits to monitor the resistance of each titanium heater.[6] This circuit exploits the predicable change of electrical resistance of titanium with temperature, creating a resistance temperature detector. When the temperature changes due to an outside thermal perturbation the change in resistance is measured and the power supplied to each heater is adjusted correspondingly. The thermal stability of the resonant frequency in the presence of a 1 K chip-level thermal fluctuation is measured using a two-color lock-in method both in an open-loop and closed-loop configuration. These measurements demonstrate that in the presence of an outside thermal perturbation the temperature of the ring is stabilized to within 80 mK, which translates to a frequency stability of 280 MHz (Fig. 4). This temperature control method is adequate for chip temperature fluctuation of less than 30 K since the heaters cannot reduce the power below 0 mW and suffer failure above 40 mW. If greater fluctuations are expected a two stage thermal stability scheme using a thermoelectric cooler to reduce the magnitude of the temperature fluctuation could be used. The level of stabilization can be further improved by using a material for the resistive heater that has a higher temperature dependence, such as platinum or polysilicon.

IV. CONCLUSION

We have shown that using slight changes of the electron-beam dose we are able to fabricate filter banks with accurate frequency spacings that are not limited by the discrete address grid of the SEBL system. Using this method we fabricated a twenty-channel dual filter bank with an average channel spacing of 83 GHz, demonstrating the ability to change the average ring waveguide width with a precision of 75 pm. Furthermore, we showed that it is possible to correct for any frequency errors that are present after fabrication using thermal tuning. We were able to achieve tuning efficiency of 80 μW/GHz for the microring resonators. The power needed to correct for all the frequency errors in the twenty-channel dual filter bank is calculated to be 0.09 W compared to the 2.4 W that would be necessary if no attempt had been made to control the resonant-frequency spacing during fabrication. Lastly, we showed by using the heaters as resistance temperature detectors we are able to stabilize the resonant frequency to 280 MHz in the presence of external thermal perturbations. By combining these methods it is possible to fabricate a filter bank with a desired channel spacing that is stabilized to better than 1 GHz.

[1]M. A. Popovic, T. Barwicz, M. R. Watts, P. T. Rakich, L. Socci, E. P. Ippen, F. X. Kärtner, and H. I. Smith, Opt. Lett. **31**, 17 (2006).
[2]S. K. Selvaraja, W. Bogaerts, D. Van Thourhout, and R. Baets, *Proceeding of the 14 European Conference on Integrated Optics (ECIO)*, Eindhoven, the Netherlands (2008).
[3]C. W. Holzwarth, T. Barwicz, M. A. Popovic, P. T. Rakich, E. P. Ippen, F. X. Kärtner, and H. I. Smith, J. Vac. Sci. Technol. B **24**, 6 (2006).
[4]C. W. Holzwarth, T. Barwicz, and Henry I. Smith, J. Vac. Sci. Technol. B **25**, 6 (2007).
[5]J. G. Goodberlet, J. T. Hastings, and Henry I. Smith, J. Vac. Sci. Technol. B **19**, 6 (2001).
[6]R. Amatya, C. W. Holzwarth, Henry I. Smith, and R. J. Ram, IEEE Photonics Technol. Lett. **20**, 20 (2008).