Monolithic Silicon Photonic Few-mode Waveguide with Satellite Structures for Athermal Spectral Filtering

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Abstract: We propose a fully CMOS-compatible few-mode waveguide with "satellite" structures that exhibits thermally anomalous modal phase difference, and demonstrate the condition for athermal operation of spectral filtering from 20 to 50 ℃.

1. Introduction

Next generation datacom and computer-com would require dense wavelength-division multiplexed (DWDM) coherent optical communications between nodes. In such systems, integrated optical spectral filters play very important roles, for example, to extract (demultiplex) a target channel frequency, and to stabilize the laser frequency (the latter one is called as a wavelength locker). Silicon (Si) photonics enables dense integration of such optical functions on a chip. However, owing to its large thermo-optic (TO) coefficient, normally designed silicon photonics filters (such as arrayed waveguide gratings (AWGs), micro-ring resonators (MRRs), and so on) generally require active feedback control circuits for their stable operation, which limits reliable dense integration with electronics.

One of the methods to cancel out the large TO coefficient of Si is to co-integrate polymers having negative TO coefficient with the silicon waveguides [1]. However, the use of polymers would require non-CMOS-compatible process, and degradation of polymers would be a problem. Another method is to use specially designed passive structures, in which the use of asymmetric Mach-Zehnder interferometer (AMZI) with different waveguide widths has been proposed [2-3]. Although these methods are CMOS compatible, they cannot cancel out the local temperature fluctuations, *i.e.,* it cannot be athermal when two arms are exposed to two different temperatures, limiting them from co-packaging with electronics where temperature gradient is common. Although athermal AMZI with very close arms was demonstrated [4], it requires very small gap (100 nm) between silicon waveguides, which is difficult to be fabricated in silicon photonics fabs.

Here, we propose and experimentally demonstrate a few-mode waveguide with "satellite" structures. Here, the "satellite" structures mean two narrow-width Si structures placed at both sides of the central few-mode waveguide core intended to control the field distribution of the waveguide modes to realize an athermal condition. Because our proposed device is an AMZI filter based on a single waveguide, it is inherently tolerant to local temperature fluctuations. Moreover, our device is monolithic (using only Si and SiO_2) and fully CMOS compatible.

2. Operation principle

Figure 1 shows the principle of our device. The key part is the few-mode waveguide core with satellite structures as shown in Fig. 1(a). Here, the satellite structures are narrow-width (~200 nm) Si structures that do not have waveguiding modes themselves but are used to modify the index response of the modes to temperature changes. The core and the satellites are separated by clad material (SiO_2), with the gap of ~250 nm, for example. Here, as the core width is set so that two modes are allowed, both 0^{th} mode (indicated by blue lines in Fig. 1(a)) and 1^{st} mode (indicated by red lines) exist. Thanks to the existence of the satellites, the 1^{st} mode distributes off center, making considerable amount of light exist in the gap region. When the temperature rises, the Si core index increases much larger than that of SiO_2 cladding, making the effective indices of the two modes increase.

Figure 1(b) shows the simulated change rate of the effective indices for the 0^{th} and 1^{st} modes when the temperature rises by 1 K. We varied the core width w from 0.55 μm to 0.75 μm in this simulation, where the satellite width and gap value are fixed to 200 nm and 250 nm, respectively. As we can see from Fig. 1(b), the two curves intersect at a specific width (w ~ 0.67 μm), showing that the athermal condition $\partial n_0/\partial T = \partial n_1/\partial T$ is satisfied. Figs. 1(c) and (d) show the calculated $|E_x|^2$ field distribution for the two modes, where w is 0.6 μm (*i* in Fig. 1(b)) and 0.75 μm (*ii* in Fig. 1(b)), respectively. As we can see from these figures, the light existing in the clad (SiO_2) region (see, for example, the 1^{st} mode of Fig. 1(c)) moves into the core region (the 1^{st} mode of Fig. 1(d)). This increases the rate $\partial n/\partial T$ because Si has much larger TO coefficient than SiO_2. Furthermore, this effect is more sensitive in the 1^{st} mode than in the 0^{th} mode, thanks to the satellite structures. Therefore, we can satisfy athermal condition at a specific w value in Fig. 1(b).

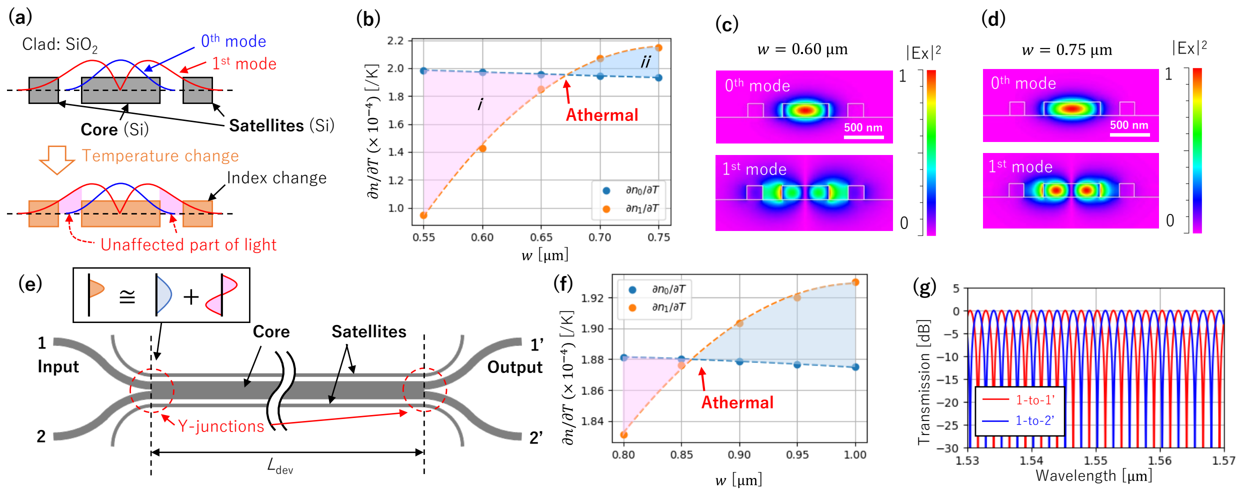

Fig. 1. (a) Schematic of the proposed waveguide structure. (b) Calculated $\partial n/\partial T$ for the two modes. (c), (d) Calculated E-field distributions for $w = 0.6$ μm and 0.75 μm, respectively. (e) Proposed AMZI filter structure. (f) Calculated $\partial n/\partial T$ for rib-type structures. (g) Calculated spectral response of the AMZI filter.

One of the devices that can be constructed using the above proposed structure is an AMZI filter or an interleaver as schematically depicted in Fig. 1(e). In this figure, the central part (length of L_{dev}) has the structure of Fig. 1(a) where the athermal condition is satisfied. Attached to the both edges are Y-junctions which are connected to single-mode waveguides (1, 2 for the inputs, and 1', 2' for the outputs). When we input light only from port 1, the left Y-junction is excited by the upper half part, as shown in the inset of Fig. 1(e). As shown in the inset, it resembles the summed field of both 0th and 1st modes of the few-mode core, thus the light excites both modes equally. After travelling the length L_{dev}, the two modes acquire different phases, $\phi_i = (2\pi n_i/\lambda)L_{\mathrm{dev}}$ where i = 0 or 1, as the two modes have different effective indices n_i. Depending on the phase difference at the output edge, $\Delta\phi = \phi_1 - \phi_0$, the light is directed to either port 1' or 2'. This is considered as an AMZI filter where the two arms correspond to the two modes. Because the athermal condition $\partial n_0/\partial T = \partial n_1/\partial T$ is satisfied, the phase difference is insensitive to the temperature, making the spectral response athermal.

Silicon photonics waveguides are sometimes realized using rib-type structure where Si slab regions are half-etched. We note that we can also obtain athermal conditions for the rib-type structure. The calculated $\partial n/\partial T$ values for the rib-type structures with the core height of 220 nm, half-etching depth of 110 nm (slab height of 110 nm), satellite width of 200 nm, gap value of 530 nm are plotted in Fig. 1(f) where the athermal condition is satisfied at $w \sim 860$ nm. We simulated the spectral response of the rib-type structure as shown in Fig. 1(g). The length of the few-mode core, L_{dev}, is 3.5 mm. From the results in Fig. 1(g), periodic (interleaved) transmission peaks (dips) are observed.

3. Experimental demonstration

We have fabricated the rib-type periodic spectral filter in AIST Super Cleanroom (SCR), which is a 300-mm SOI wafer process line equipped with ArF immersion lithography. The micrographic images of the fabricated chip are shown in Fig. 2(a). The waveguide structure is the same as the above simulation, where we prepared three gap values: 430 nm, 480 nm, and 530 nm. The magnified images of the Y-junction, the few-mode waveguide, and a grating coupler, are shown in the insets of Fig. 2(a). The device is designed for transverse electric (TE)-like mode. We input TE-polarized amplified spontaneous emission (ASE) light from the port 1 through a single-mode fiber (SMF) and measured the output spectra from port 1' and 2' using an optical spectrum analyzer. The results are shown in Fig. 2(b) for the gap value of 530 nm. Here, the spectrum of the grating coupler was subtracted from the raw results. From the Fig. 2(b), we can see that the periodic filter spectra were observed, which resembles Fig. 1(e). We changed the substrate temperature from 20 °C to 50 °C by using a temperature controller and measured the transmission spectra as shown in Fig. 2(c). The dip wavelengths, as indicated by diamond mark, were plotted as functions of temperature in Fig. 2(d) for the gap values of 430 nm, 480 nm, and 530 nm. We further fitted the results of Fig. 2(d) and extracted the slopes for each center wavelength. The results are plotted in Fig. 2(e), together with fitted lines. As shown in this figure, athermal conditions (*i.e.*, zero temperature dependence of the spectral dips, as shown in red dashed line) are satisfied at each corresponding wavelength for the gap values of 430 nm, 480 nm, and 530 nm. Therefore, we can conclude that by changing the structure, the athermal wavelength can be arbitrarily adjusted.

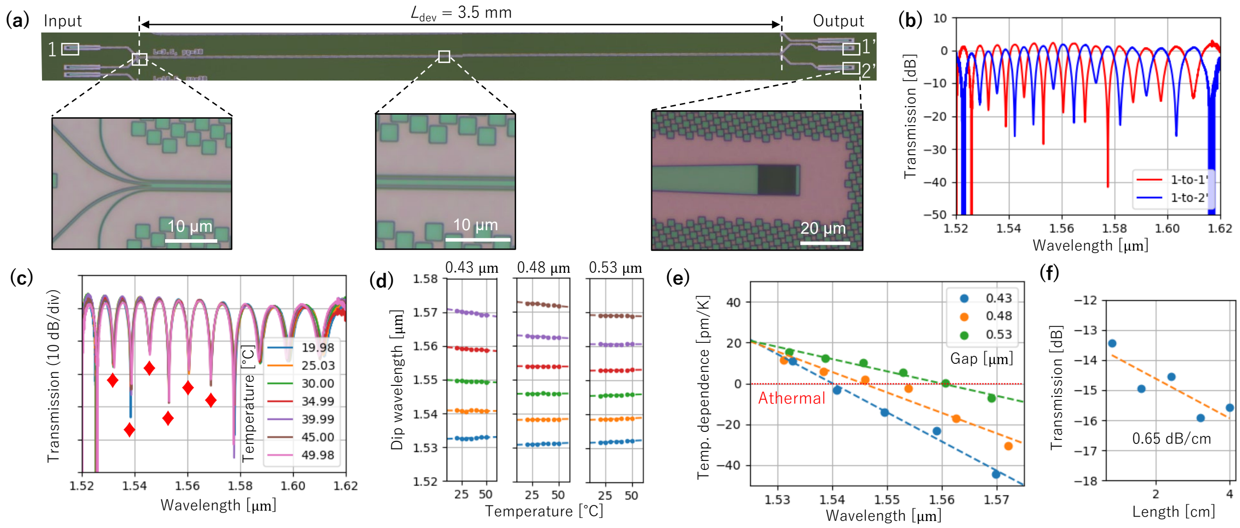

Fig. 2. (a) Microscopic image of the fabricated chip. (b) Measured transmission spectra where the grating spectrum was excluded. (c) Measured transmission with different temperatures. (d) Extracted dip wavelengths and (e) temperature dependence for three gap values. (f) Results of the cutback measurement.

The spectra of Fig. 2(b) are obtained by subtracting the transmission spectrum of the single-mode waveguide with the same length. Therefore, the *y*-axis is considered as an on-chip loss, including the loss of two Y-junctions and the loss difference between the few-mode waveguide and the single-mode waveguide. The results showed that there is no significant loss because the peak values are approximately zero. We note that some peaks in Fig. 2(b) exceeds 0 dB, which we consider are originated from fluctuations in fiber-to-chip coupling loss. We also fabricated samples to measure the waveguiding loss of the few-mode waveguide through a cutback measurement. In these samples, we injected light to the 0th mode of the few-mode waveguide using a taper structure from a single-mode waveguide. We measured the averaged transmission power from 1540 nm to 1600 nm for the samples with various lengths, and the results are shown in Fig. 2(f). From this figure, we obtained the loss value of 0.65 dB/cm, indicating ~0.23 dB waveguiding loss at the 3.5 mm few-mode waveguide section.

4. Discussion

One of the applications of athermal spectral filters is a wavelength locker, in which transmission power change of the filter corresponding to wavelength change of a laser source is detected by balanced power monitors and fed back into the laser to stabilize the wavelength. Integrated athermal filters would be of importance in next generation optical systems toward coherent and DWDM optical transmission systems. According to our simulation, the locking slope of approximately 50 dB/nm can be obtained using channel-type structures as shown in Fig. 1(a). We can further obtain larger locking slope by designing longer waveguide. However, longer waveguide results in larger chip size. Therefore, realization of bent waveguides would be important to realize compact devices in the future. We note that future WDM multiplex / demultiplex filters would also be obtained by cascading the proposed filters with different FSRs.

5. Conclusion

We proposed and demonstrated athermal spectral filtering operation based on a few-mode waveguide with satellite structures. We further discussed the use of our device to DWDM applications. We believe that our results will lead to next-generation silicon photonics devices that is co-packaged with electronics.

6. References

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