Athermal and flat-topped silicon Mach-Zehnder filters

QINGZHONG DENG,¹ LU LIU,¹ RUI ZHANG,¹ XINBAI LI,¹ JURGEN MICHEL,² AND ZHIPING ZHOU¹*

¹State Key Laboratory of Advanced Optical Communication Systems and Networks, School of Electronics Engineering and Computer Science, Peking University, Beijing 100871, China
²MIT Microphotonics Center, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
*zjzhou@pku.edu.cn

Abstract: Athermal and flat-topped transmissions are the two main requirements for a silicon WDM filter. A Mach-Zehnder (MZ) filter which simultaneously satisfies these two requirements has been experimentally demonstrated in this paper. A combination of strip waveguide and hybrid strip-slot waveguide is introduced for athermalization, and two-stage interference is utilized for flat-topped transmission. The temperature dependent wavelength shift is measured to be ~-5 pm/K while the best 1 dB bandwidth is 5.5 nm with 14.7 nm free spectral range (FSR). The measured minimum insertion loss is only 0.4 dB with a device dimension of 170 μm × 580 μm. Moreover, Such a MZ filter is compatible with the state-of-art CMOS-fabrication process and its minimum feature size is as large as 200 nm. © 2016 Optical Society of America

OCIS codes: (130.3120) Integrated optics devices; (130.2790) Guided waves; (130.7408) Waveband filtering devices.

References and links


1. Introduction

Silicon photonic wavelength division multiplexing (WDM) is widely anticipated to solve the bandwidth bottleneck problem in nowadays high-performance computing systems [1,2]. One main requirement of a WDM filter is the flat-topped transmission pass-bands and almost all kinds of silicon WDM filters have been modified to satisfy this requirement, such as cascade for ring resonators [3–6], multimode interference (MMI) assisted aperture for Arrayed Waveguide Gratings (AWGs) [7–10], multi-stage interference for Mach-Zehnder (MZ) filters [11–14]. All of these methods are efficient in flattening the pass-bands. For a silicon WDM filter, another main requirement is the athermal transmission spectrum since the large positive thermo-optic coefficient of silicon material (TOC $\sim 1.86 \times 10^{-4}$ K$^{-1}$) will cause considerable temperature dependent wavelength shift ($\sim$80 pm/K). Aiming at athermal filters, several methods have been reported, such as cladding with negative TOC materials [15–17], coupling with multiple structures [18, 19], and combination of multiple types of waveguide [20–25]. Constructing the arms of a MZ filter with the combination of multiple types of waveguide is the most promising athermal scheme, as summarized in [2], due to the merits of CMOS-compatible fabrication process and zero extra energy consumption. Therefore, MZ filters are the leading candidate to simultaneously satisfy the two main requirements. However, an athermal and flat-topped silicon MZ filter has not been experimentally demonstrated since the flat-top scheme is proposed only for the MZ with the same loss in the two arms while the athermal scheme makes the two arms hold significantly different losses.

In this paper, we expand the flat-top theory to the MZ with different losses in the two arms firstly. Then, an athermal and flat-topped MZ filter is experimentally demonstrated. We have presented some preliminary results in the 13th International Conference on Group IV Photonics [26], while the complete simulation and measurement results are analyzed here.
2. Flat-topped Mach-Zehnder filter

Two-stage interference [Fig. 1(a)] is utilized to flatten the pass-bands of a MZ filter. It consists of 3 directional couplers (DCs) and 2 phase shifters (PSs). \( \kappa_i \) denotes the cross-coupling coefficient of DC\(_i\) \((i = 1, 2, 3)\), and the self-coupling coefficient \((r_i)\) can be expressed as \( r_i = \sqrt{1 - \kappa_i^2} \) if the coupling loss is negligible. \( \Delta OL_{\text{eff}} \) denotes the optical path length difference of the two arms in PS\(_j\), while the value is \( 2\Delta OL_{\text{eff}} \) for PS\(_2\). \( a_1 \) denotes the optical field attenuation factor in the shorter arm of PS\(_1\), which means incident light with electric field amplitude of \( E \) will attenuate to \( a_1E \) after transmission through this waveguide, and \( a_2 \) corresponds to the longer arm. We define the relative attenuation factor of PS\(_1\) as \( a = a_2/a_1 \), and the value of PS\(_2\) will be \( a^2 \). Then, the transmission spectrum of Ch.1 \((T_{r_1})\) and Ch.2 \((T_{r_2})\) can be expressed as truncated Fourier series.

\[
\begin{align*}
T_{r_1} &= a_1^6 \left[ \kappa_1 \kappa_2 r_3 - r_1 r_2 r_3 a e^{-j\phi} + \kappa_1 \kappa_2 \kappa_3 a^2 e^{j2\phi} + r_1 \kappa_2 \kappa_3 a^3 e^{j3\phi} \right] \\
T_{r_2} &= a_1^6 \left[ \kappa_1 \kappa_2 \kappa_3 - r_1 r_2 r_3 a e^{-j\phi} - \kappa_1 \kappa_2 r_3 a^2 e^{-j2\phi} - r_1 \kappa_2 \kappa_3 a^3 e^{-j3\phi} \right] \\
\phi &= \frac{2\pi}{\lambda}; \quad r_i = \sqrt{1 - \kappa_i^2} \quad (i = 1, 2, 3)
\end{align*}
\]

In the form of Eq. (1), \( a_1 \) contributes to the insertion loss only. Therefore, we fix \( a_1 = 1 \) in the following theoretical analysis for the flat-top performance. If the loss difference in the arms are neglected \((a = 1)\), designing the coupling coefficients to satisfy \( \kappa_1^2 = 0.50 \), \( \kappa_2^2 = 0.29 \), and \( \kappa_3^2 = 0.08 \) will simultaneously make Ch.1 and Ch.2 flat-topped [Fig. 1(b)] [11]. We mark the value of \( \kappa_i \) under this condition as \( \kappa_i \) \((i = 1, 2, 3)\) for the convenience of statement.

According to Eq. (1), we find that the flat-top feature of Ch.1 can be maintained by modifying the coupling coefficients as Eq. (2) for the case of \( a \neq 1 \). After such modifications, the whole spectrum will scale down with the decrease of \( a \) while the shape of the spectrum are kept unchanged. As shown in Fig. 2(a), the insertion loss increases with the decrease of \( a \) while the 1 dB bandwidth is independent with \( a \). Similarly, Eq. (3) can keep the flat-top feature for Ch.2 as shown in Fig. 2(b).

For Ch.1: 
\[
\begin{align*}
\kappa_1^2 &= \frac{a^2 \kappa_1^2}{1 - (1 - a^2)K_1^2}; \quad \kappa_2^2 = \kappa_2^2; \quad \kappa_3^2 = \frac{a^2 \kappa_3^2}{1 - (1 - a^2)K_3^2}
\end{align*}
\]

For Ch.2: 
\[
\begin{align*}
\kappa_1^2 &= \frac{a^2 \kappa_1^2}{1 - (1 - a^2)K_1^2}; \quad \kappa_2^2 = \kappa_2^2; \quad \kappa_3^2 = \frac{a^2 \kappa_3^2}{1 - (1 - a^2)K_3^2}
\end{align*}
\]
Comparing between Eqs. (2) and (3), one can find that the required coupling coefficients of Ch.1 and Ch.2 are different only in $\kappa^2$ [Fig. 2(c)]. Moreover, the required $\kappa^2$ of the two output ports differ slightly when $a$ close to 1. Therefore, Eq. (4) is utilized when the two ports need to be considered simultaneously [Fig. 2(d)]. Even though the spectra are not strictly scaled down, the 1 dB bandwidths are not significantly degenerated.

For Ch.1 and Ch.2:

$$\kappa^2 = \frac{a^2 K_1^2}{1-(1-a^2)K_1^2}; \ \kappa^2 = \kappa^2_2; \ \kappa^2 = K_3^2$$

(4)

3. Athermalization with hybrid strip-slot waveguide

To achieve athermal performance, two types of waveguides are utilized to construct the arms of the phase shifters [Fig. 3(a)]. The effective thermo-optic coefficient ($\partial n_{eff} / \partial T$) and the waveguide length ($\Delta L$) of the two waveguide types are designed to satisfy the athermal condition,

$$\frac{\partial n_{eff}^I}{\partial T} \cdot \Delta L^I = \frac{\partial n_{eff}^II}{\partial T} \cdot \Delta L^II.$$

(5)

Under athermal condition, the free spectral range (FSR) of this filter can be expressed as

$$\text{FSR} = \frac{\lambda^2}{\Delta OL_g}$$

$$\Delta OL_g = n_g \cdot \Delta L_T^I \cdot \left[1 - \frac{TO_g^I}{TO_g^II} \right]; \ \ TO_g^I = \frac{\partial n_{eff}^I}{\partial \lambda} \cdot \left(\frac{\partial \lambda}{\partial T} \right)^I \ (i = I, II)$$

(6)

where $n_g = n_{eff} - \lambda \cdot \partial n_{eff} / \partial \lambda$ is the group refractive index. Equation (6) indicates that larger difference in $TO_g$ of the two waveguide types will produce shorter phase shifters for a certain
FSR, which means more compact device. Due to the large difference with the strip waveguide in $TO_g$, shown in Fig. 3(b), the hybrid strip-slot waveguide is introduced to combine with normal single-mode waveguide (strip waveguide with $W = 450$ nm) for athermal performance. To ease the fabrication process, the total width of the hybrid strip-slot waveguide is chosen to be $W = 600$ nm so that the minimum feature size of the filter can be kept as large as 200 nm. The optical mode profiles of the two waveguides are displayed in Figs. 3(c) and 3(d) where mode mismatch can be observed. To overcome this mode mismatch, a multimode interference (MMI) based waveguide mode converter [Fig. 3(e)] is utilized to connect the waveguides [27, 28]. The device fabricated by Singapore A*STAR Institute of Microelectronics (IME) Multi-Project Wafers (MPW) is shown in Fig. 3(f) where $\Delta L^1 = 400$ $\mu$m, $\Delta L^2 = 553$ $\mu$m and the coupling length of the three DCs are 10.5 $\mu$m, 7.0 $\mu$m and 2.4 $\mu$m respectively.

Designing the filter in Fig. 3(a) to have flat-top pass-bands, characterization for the relative attenuation factor ($a$) is essential according to the analysis in the previous section. The mode converter is cascaded for measurement as described in [28] while the hybrid strip-slot waveguide and strip waveguide are constructed into rings to measure the attenuation factor with the method in [29]. The measured optical field attenuation factors are listed in Table 1. Based on the measured $a$, the required coupling coefficients for top-flat performance can be calculated with Eq. (4), shown in Table 2. Moreover, the coupling coefficients of the DCs in the fabricated filter are characterized and listed in Table 2 also. Comparing the two sets of values, one can find that the fabricated one satisfy the requirements roughly.
Therefore, this filter is expected to have athermal and flat-topped transmission spectra. The measured transmission spectra under different temperature are plotted in Fig. 4: (i) the temperature-dependent wavelength shift is only ~5 pm/K around 1550 nm wavelength which has been prominently improved when compared with traditional MZ filters (~80 pm/K); (ii) the device has flat pass-bands with 1 dB-bandwidths of 5.5 nm for Ch.1 and 5.0 nm for Ch.2 while the FSR is 14.7 nm; (iii) the cross talk between the two channels is ~13.6 dB; and (iv) the insertion loss is 0.4 dB (Ch.1) and 1.4 dB (Ch.2). It is worth to mention that even though the athermal performance is characterized in the temperature range of 25–45 °C, the proposed filter is expected to hold the athermal performance in a wider temperature range since the athermal condition [Eq. (5)] is not sensitive to temperature fluctuations.

### Table 1. The measured optical field attenuation factors.

<table>
<thead>
<tr>
<th>Mode converter</th>
<th>553 μm hybrid strip-slot waveguide (a&lt;sub&gt;ac&lt;/sub&gt;)</th>
<th>400 μm strip waveguide (a&lt;sub&gt;ST&lt;/sub&gt;)</th>
<th>Relative attenuation factor (a = a&lt;sub&gt;ac&lt;/sub&gt;²a&lt;sub&gt;SL&lt;/sub&gt;/a&lt;sub&gt;ST&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.97 ± 0.01</td>
<td>0.88 ± 0.03</td>
<td>0.98 ± 0.01</td>
<td>0.84 ± 0.03</td>
</tr>
</tbody>
</table>

### Table 2. The required and the fabricated DC coupling coefficients.

<table>
<thead>
<tr>
<th>κ&lt;sup&gt;1&lt;/sup&gt;</th>
<th>κ&lt;sup&gt;2&lt;/sup&gt;</th>
<th>κ&lt;sup&gt;3&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required</td>
<td>0.41 ± 0.02</td>
<td>0.29</td>
</tr>
<tr>
<td>Fabricated</td>
<td>0.38 ± 0.02</td>
<td>0.25 ± 0.02</td>
</tr>
</tbody>
</table>

Fig. 4. The measured transmission spectra of the fabricated athermal flat-topped MZ filter.

### 4. Conclusion

In this work, a MZ filter which simultaneously satisfies the two main requirements for a silicon WDM filter, athermal and flat-topped transmission, has been experimentally demonstrated. Combination of strip waveguide and hybrid strip-slot waveguide is introduced for athermalization, and two-stage interference is utilized for flat-topped transmission. The designing theory for flat-topped filter is expanded to the MZ with different losses in the two arms so that it can be applied to an athermal MZ filter. The athermal performance is measured to be ~5 pm/K while the 1 dB bandwidth is 5.5 nm for Ch.1 and 5.0 nm for Ch.2 (@ 14.7 nm FSR). The measured minimum insertion loss is 0.4 dB with a device dimension of 170 μm × 580 μm. Such a MZ filter can be easily fabricated with the state-of-art CMOS-fabrication process since its minimum feature size is as large as 200 nm. Furthermore, the device can be scaled up to multi-channel WDM filters by taking the proposed filter as the fundamental building block and cascading like a binary tree [11].

### Funding

National Natural Science Foundation of China (NSFC) (61120106012).