On-chip silicon mode blocking filter employing subwavelength-grating based contra-directional coupler

YU HE, YONG ZHANG,* HONGWEI WANG, AND YIKAI SU

State Key Lab of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
*yongzhang@sjtu.edu.cn

Abstract: Mode blocking may be required in mode-division multiplexing (MDM) systems. We demonstrate a silicon mode blocking filter using a subwavelength grating-based contra-directional coupler. The device is capable of blocking the undesired mode channel without affecting the propagation of the other modes. As a proof-of-concept experiment, two mode blocking filters are experimentally demonstrated, which can block the TE0 mode and the TE1 mode, respectively. Low crosstalk (≤ 21.0 dB) and reasonable insertion losses (≤ 2.3 dB) are achieved for both the TE0-mode- and the TE1-mode blocking filters.

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1. Introduction

Space-division multiplexing (SDM) technology in optical fibers has been advancing rapidly to support the exponential growth of the optical transmission capacity [1,2]. As an integrated version of this technique, mode-division multiplexing (MDM) on silicon attracts much attention due to its compact footprint and the compatibility with the complementary-metal-oxide-semiconductor (CMOS) fabrication process [3–5]. Various MDM devices have been demonstrated on silicon-on-insulator (SOI) platform, such as mode (de)multiplexers [6–12], mode converters [13,14], multimode waveguide bends [15], and mode-selective switches [16–19]. In analogy to wavelength blockers, which have found applications in optical add-drop multiplexers (OADMs) [20–23], mode blocking filters could become a basic building block of the mode-division multiplexing (MDM) systems. As shown in Fig. 1, such a device is designed to block an undesired mode in the bus waveguide and let the other modes go through.

To date, only a few studies have been carried out to implement mode blocking. Mode blocking filters based on 1D photonic crystal [24], mode converters [25] and Mach–Zehnder interferometers (MZIs) [26] were proposed. However, these designs are difficult to block an
arbitrary mode channel while transparently passing other modes. Mode de-multiplexers with add-drop configurations [11,12] can also be seen as mode blocking filters by dropping undesired mode channels through asymmetrical mode coupling. In [27], we demonstrated a 3-channel mode (de)multiplexer using a subwavelength grating (SWG)-based co-directional coupler. However, these add-drop de-multiplexers cannot block the TE$_0$-mode channel, because all the modes in the bus waveguide are coupled out simultaneously due to the symmetrical mode coupling condition. It is highly desired to design an on-chip silicon mode blocking filter that is capable of blocking an arbitrary mode channel while transparently passing other modes.

In this paper, we propose and experimentally demonstrate a mode blocking filter using a SWG-based contra-directional coupler (contra-DC). The SWG is a periodic structure operating as a homogenous medium [28,29], it has been used in fiber-chip couplers [30], waveguide crossings [31], and MMI couplers [32]. Here, we use the SWG-based contra-DC to realize the function of mode blocking. The selected mode channel in the bus waveguide can be contra-directionally coupled to the SWG waveguide due to the periodic dielectric perturbations. Other modes in the bus waveguide, however, maintain the propagation without being affected. Our design can be applied to realize higher order mode blocking by simply adjusting the structural parameters of the SWG, thus offering high design flexibility. The device can block multiple modes by cascading more mode blocking filters with different structural parameters. As a proof-of-concept experiment, we demonstrate two mode blocking filters which can block the TE$_0$ mode and the TE$_1$ mode, respectively. For the TE$_0$-mode blocking filter, the insertion loss is lower than 1.4 dB and the crosstalk is lower than $-21.0$ dB in the wavelength range of 1535 nm $\sim$ 1570 nm. As for the TE$_1$-mode blocking filter, the insertion loss is lower than 2.3 dB and the crosstalk is below $-25.6$ dB, in the wavelength range of 1540 nm $\sim$ 1566 nm.

### 2. Device structure and operation principle

The schematic configuration of the proposed mode blocking filter is shown in Fig. 2. A SWG waveguide with a period of $\Lambda$ and a duty cycle of $\delta$, is placed along a strip bus waveguide, to form a contra-DC. The SWG structure provides the required dielectric perturbations and enables contra-directional coupling between the two waveguides under the phase matching condition [33]:

$$n_{bus} + n_{SWG} = \frac{\lambda}{\Lambda}$$  \hspace{1cm} (1)

where $n_{bus}$, $n_{SWG}$ are the effective indices of the waveguide modes in bus and SWG waveguides, respectively. $\lambda$ is the operation wavelength of the contra-DC. The period $\Lambda$ of the SWG and the widths of the bus and the SWG waveguides are properly designed, so that the selected mode in the bus waveguide can be contra-directionally coupled to the Bloch mode in the SWG waveguide. Other modes go through the bus waveguide due to the phase mismatch. To achieve a wide operation bandwidth of the mode blocking filter, a short coupling length and a narrow waveguide gap are required [33].

![Fig. 2. Schematic configuration of the proposed mode blocking filter.](image)
As an example, we design a TE₀-mode blocking filter which can block the TE₀ mode and let the TE₁ mode pass through. The schematic configuration is shown in Fig. 3(a). The design process is described as follows: we calculate the effective indices of the TE₀ mode in the bus waveguide and the Bloch mode in the SWG waveguide. Here, we approximate the SWG to a homogenous waveguide with an equivalent material refractive index [34]:

\[ n_{Eq}^2 = \delta \cdot n_S^2 + (1 - \delta) \cdot n_{Clad}^2 \]  

(2)

where \( n_{Eq} \), \( n_S \), and \( n_{Clad} \) are the refractive indices of the equivalent material, silicon and cladding, respectively. The widths of the bus waveguide and the SWG waveguide, are chosen to be \( w_{bus} = 0.6 \) μm and \( w_{SWG} = 0.8 \) μm, respectively.

The calculated effective indices of the guided modes with the phase-matching condition are shown in Fig. 3(b). Here we plot the left part (purple solid line) and the right part (blue dotted line) of Eq. (1) as a function of the wavelength. The phase-matching condition is satisfied at the cross-point of these two curves, where the TE₀ mode in the bus waveguide can be contra-directionally coupled to the Bloch mode in the SWG. The large differences between the effective indices of the eigen-modes and the Bloch mode result in significant phase mismatching, and therefore the co-directional coupling is suppressed. The duty cycle \( \delta \) of the SWG waveguide is 60%. The gap is 50 nm and the coupling length is 10 μm to achieve a wide operation bandwidth. To allow the contra-directional coupler operating at the central wavelength of 1550 nm, the period of the SWG \( \Lambda \) is calculated to be 323 nm to satisfy the phase-matching condition, as shown in Fig. 3(b). We use the 3D finite-difference time-domain (3D-FDTD) method to simulate the propagation of the optical field in the proposed mode blocking filter structure. The period is optimized to be 315 nm through iterative 3D-FDTD simulations to minimize the deviation caused by the index approximations.

The calculated propagating Re{E_y} field distributions for the TE₀ and TE₁ mode inputs are shown in Figs. 3(c) and 3(d), respectively. The insets show the Re{E} fields at the cross sections of the input and output ports. The dotted lines in Figs. 3(c) and 3(d) illustrate the waveguide walls but do not represent the actual sizes of the SWG waveguides. When the TE₀ mode is launched into the Input port, the light is coupled and converted to one contra-directional propagating mode in the SWG waveguide. While for the TE₁ mode, the injected
signal propagates through the bus waveguide and outputs from the *Thru* port. Therefore, the TE_0 mode in the bus waveguide is blocked, while the TE_1 mode transmission is unaffected. There may be some optical reflection at the end facet of the SWG waveguide, which can be eliminated by adding a tapered structure at the end of the SWG. Note that there is a weak coupling between the TE_1 mode in the bus waveguide and the co-directional propagating Bloch mode in the SWG waveguide, which results in excess loss of the TE_1 mode at the *Thru* port. We attribute it to the weak confinement of the TE_1 mode and the narrow gap between the waveguides. This co-directional coupling can be suppressed by using a larger gap, at the cost of a narrower operation bandwidth of the device.

To verify the scalability of our proposed structure, we also demonstrate a TE_1-mode blocking filter which can block the TE_1 mode, and allow the TE_0 and TE_2 modes in the bus waveguide to propagate, as shown in Fig. 4(a). Structural parameters of the TE_1-mode blocking filter are described as follows: the widths of the bus waveguide and the SWG waveguide, are chosen to be \( w_{\text{bus}} = 1.0 \ \mu\text{m} \) and \( w_{\text{SWG}} = 0.7 \ \mu\text{m} \), respectively. The duty cycle \( \delta \) is 60%. Figure 4(b) shows the phase-matching condition of the TE_1-mode blocking filter. The SWG period \( \Lambda \) is firstly calculated to be 338 nm and then adjusted to 330 nm through iterative simulations, so the contra-directional coupler operates at the central wavelength of 1550 nm. Short coupling length (20 \( \mu\text{m} \)) and narrow waveguide gap (50 nm) are adopted to achieve a wide operation bandwidth. Simulated propagating Re{\( E_y \)} field distributions for the TE_0, TE_1 and TE_2 inputs are shown in Figs. 4(c)-(e), respectively. The insets show the Re{\( E \)} fields at the cross sections of the input and output ports. The dotted lines in Figs. 4(c)-(e) illustrate the waveguide walls but do not represent the actual sizes of the SWG waveguides. When the TE_1 mode is injected, it is contra-directionally coupled to the Bloch mode in the SWG waveguide. The TE_0 mode and the TE_2 mode are confined in the bus waveguide and output from the *Thru* port without coupling. Note that there is a weak co-directional coupling between the TE_2 mode in the bus waveguide and the Bloch mode in the SWG waveguide, due to the weak confinement of the TE_2 mode in the bus waveguide and the narrow gap. This co-directional coupling can be suppressed by using a larger gap, at the cost of a narrower operation bandwidth.

![Fig. 4.](image-url)
3. Device fabrication and experimental results

We fabricated the devices on a SOI wafer with a 220-nm-thick silicon on top of a 3-μm silica buffer layer. The devices were firstly defined using E-beam lithography (Vistec, EBPG-5200+) and inductively coupled plasma (ICP, SPTS) etching. A 1-μm-thick SiO₂ cladding layer was then deposited on top of the devices by plasma-enhanced chemical vapor deposition (PECVD, Oxford). TE grating couplers with an etching depth of 70 nm were employed for vertical coupling between the optical fibers and the silicon chip. The period of the grating is 630 nm and the filling factor is 48%. The coupling loss of the TE-polarized grating coupler is 7.0 dB/port at the central wavelength of 1550 nm. A tunable continuous wave (CW) laser (Keysight 81960A) and an optical power meter (Keysight N7744A) were used to characterize the devices.

Fig. 5. (a) Microscope image and (b) scanning electron microscope (SEM) images of the fabricated TE₀-mode blocking filter; (c) microscope image and (d) SEM images of the fabricated TE₁-mode blocking filter. The insets show the magnified micrographs of the coupling regions.
Figures 5(a) and 5(c) show the microscope photos of the fabricated TE₀- and TE₁-mode blocking filters, respectively. A number of filters were fabricated on the same wafer to measure the transmission responses for different mode (TE₀, TE₁, and TE₂) inputs, respectively. We have labeled each device as #1 – #10 for easy identification. To characterize the performances of the proposed mode blocking filters, mode multiplexers [11] are introduced as input devices, which can couple the injected fundamental modes to high-order modes (TE₁, TE₂) and then launch them to the Input ports of the corresponding mode blocking filters. The widths of the access/bus waveguides of the TE₁-, TE₂-mode multiplexers are 0.416/0.927 μm and 0.480/1.325 μm, respectively. Low insertion losses of 0.7 dB and 1.3 dB are achieved for the TE₁-, TE₂-mode (de)multiplexers, respectively. Adiabatic tapers with a ∼0.8° angle are used to smoothly connect the bus waveguides of the mode (de)multiplexers and the mode blocking filters with different widths [11]. The taper lengths used in device #1, #2, #5, #6, #7 are 6.4 μm, 10.0 μm, 21.1 μm, 4.7 μm, 12.1 μm, respectively. De-multiplexing stages are cascaded after the mode blocking filters to convert the output high-order mode signals back to the TE₀ modes for analysis. The scanning electron microscope (SEM, ZEISS) photos of the fabricated TE₀- and TE₁-mode blocking filters are shown in Figs. 5(b) and 5(d), respectively. The insets show the magnified micrographs of the coupling region.

Fig. 6. Measured and simulated transmission responses of (a) the TE₀-mode blocking filter, and (b) the TE₁-mode blocking filter, respectively. The dashed curves represent the simulated responses of the mode blocking filters by 3D-FDTD methods.

The measured and simulated transmission responses of the fabricated TE₀-mode and TE₁-mode blocking filters are shown in Figs. 6(a) and 6(b), respectively. The transmission spectra of mode blocking filters with different inputs are normalized to that of the corresponding input devices, as shown in Figs. 5(a) and 5(c). The imperfection of the mode (de)multiplexers can be eliminated through the normalization process. For the TE₀-mode blocking filter, the TE₁ mode goes through the bus waveguide with an insertion loss lower than 1.4 dB, and the injected TE₀ signal can be blocked with an extinction ratio of ≥21.0 dB, in the wavelength range of 1535 nm ~1570 nm. For the TE₁-mode blocking filter, the insertion losses of the TE₀ and TE₂ modes at the Thru port are 1.0 dB and 2.3 dB, respectively, and the injected TE₁ light...
is blocked with an extinction ratio of 25.6 dB, in the wavelength range of 1540 nm ~1566 nm. The relatively higher insertion loss of the TE₂ mode in the short wavelength can be attributed to the co-directional coupling between the TE₂ mode in the bus waveguide and the Bloch mode in the SWG waveguide. This can be optimized by increasing the gap between two waveguides at the cost of a narrower operation bandwidth. Compared to the simulated results, the larger bandwidth and the lower crosstalk value of the TE₁-mode blocking filter in the experiment can be attributed to the narrower waveguide gap caused by the fabrication process.

4. Summary

We propose and experimentally demonstrate a mode blocking filter using a SWG-based contra-DC. The device can block multiple modes by cascading various mode blocking filters with different structural parameters. As a proof-of-concept experiment, we demonstrate two mode blocking filters which can block the TE₀ mode and the TE₁ mode respectively. For the TE₀-mode blocking filter, the insertion loss is lower than 1.4 dB and the crosstalk is below −21.0 dB in the wavelength range of 1535 nm ~1570 nm. For the TE₁-mode blocking filter, the insertion loss is lower than 2.3 dB and the crosstalk is below −25.6 dB, in the wavelength range of 1540 nm ~1566 nm. These mode blocking filters may find applications in MDM systems.

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