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Guan, Xiaowei; Ding, Yunhong; Frandsen, Lars Hagedorn

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Ultra-compact broadband higher order-mode pass filter fabricated in a silicon waveguide for multimode photonics

XIAOWEI GUAN,* YUNHONG DING, AND LARS H. FRANDSEN

Department of Photonics Engineering, Technical University of Denmark, Ørsteds Plads Building 345A, 2800 Kgs. Lyngby, Denmark
*Corresponding author: xgua@fotonik.dtu.dk

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An ultra-compact and broadband higher order-mode pass filter in a 1D photonic crystal silicon waveguide is proposed and experimentally demonstrated. The photonic crystal is designed for the lower order mode to work in the photonic band gap, while the higher order mode is located in the air band. Consequently, light on the lower order mode is prohibited to pass through the filter, while light on a higher order mode can be converted to a Bloch mode in the photonic crystal and pass through the filter with low insertion loss. As an example, we fabricate a ∼15-μm-long first-order-mode pass filter that filters out the fundamental mode and provides a measured insertion loss of ∼1.8 dB for the first-order-mode pass signals. The extinction ratio is measured to be around 50 dB (with a variation of ±10 dB due to the detection limitation of the measurement setup) in the measured wavelength range from 1480 to 1580 nm. Additionally, calculations predict the extinction ratio to be larger than 50 dB in a 170 nm broad bandwidth. © 2015 Optical Society of America

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In order to keep up with the ever-increasing demands for higher capacity in optical communication systems, transmitting signals with multiple modes in a few-mode fiber (FMF) has recently been suggested as a promising technique [1–3]. Being an integrated version of this technique, multimode photonics in silicon waveguides has attracted substantial attention [4–7] to exploit the already matured single-mode silicon photonic devices and silicon’s complementary metal–oxide–semiconductor (CMOS) compatibility. For devices applied in the silicon multimode photonics, various functionalities have been achieved including (de)multiplexing [8–11], bending [12], converting [13], and resonating [14] multimode signals. Additionally, mode filtering is also foreseen as an essential functionality in silicon multimode photonics for mode-division multiplexing (MDM), resembling wavelength filtering for wavelength-division multiplexing (WDM). Filtering out a higher order mode in a waveguide is not a tough problem due to its weaker confinement. Simple solutions can be implemented, e.g., tapering the waveguide down to the cut-off width of the higher order mode or stripping the higher order mode in an appropriately designed waveguide bend [15]. In both cases, signals carried on the higher order mode are naturally lost. However, a higher order-mode pass filter, which can keep a signal on a higher order mode but filter out light on the lower order mode, is not straightforward to produce. Meanwhile, for on-chip applications, mode filters are supposed to have a compact size without compromising insertion loss (IL) and extinction ratio (ER). To the best of our knowledge, there have been no reports in literature on ultra-compact higher order-mode pass filters. Although an add/drop configuration can be seen as a higher order-mode pass filter, it still encounters the drawback of having a large footprint (e.g., ∼40 μm for adding and dropping the transverse electric first-order-mode [16]).

In this Letter, we propose and experimentally demonstrate an ultra-compact higher order-mode (HOM) pass filter using a 1D photonic crystal (PhC) in a silicon (Si) multimode waveguide. The 1D PhC has previously been used in a silicon single-mode waveguide to accomplish a 9-μm-long polarization filter with an ER of 27 dB [17]. Here, the 1D PhC is applied in a silicon multimode waveguide to achieve a HOM pass filter, and the ER is measured to be around 50 dB with a filter length ∼15 μm.

Figure 1 shows the 3D view of the proposed HOM pass filter with a 1D PhC in a silicon waveguide. The PhC is comprised of a periodic corrugation of the silicon waveguide with period $L_p$ and width $w_c$ of the connecting nanobridge. To reduce the insertion loss originating from the mode mismatch for the HOM, adiabatic tapers are designed to access the PhC with the silicon waveguides, the width of which, $w_{ac}$, is larger than 500 nm to support multimodes as shown by the cross-section of the inset in Fig. 1.

It is well known that a higher order mode in a silicon wire has a weaker confinement than a lower order mode (e.g., as indicated by the mode profiles of the TE$_0$ and the TE$_1$ modes in Fig. 2) and, therefore, the higher order mode has a lower...
where $\lambda$ tor $0.5$, and the lower and higher order modes, respectively, to realize a length in order to be far away from the cut-off condition, which should also be quite smaller than half the central wavelength in Eq. (1), but the optical path length for the higher order mode in the designed filter satisfy the Bragg grating equation in Eq. (2). Not only should the effective indices of the lower order modes in the nanobridge and teeth of the grating, the fundamental mode and the first-order mode in the access multimode waveguides with a width of 800 nm. Here, the wavelength $\lambda_0 = 1550$ nm, and the refractive indices of Si $n_{Si} = 3.478$ and the surrounding silica ($SiO_2$) $n_{SiO_2} = 1.444$ are calculated from the Sellmeier formula [18]. By choosing the width of the access waveguides $w_{ac} = 800$ nm and the width of the nanobridge $w_b = 140$ nm, we obtain a grating period of $\sim 410$ nm, in which the optical path length of the TE$_1$ mode is $\sim 0.636$ $\mu$m and smaller than half a wavelength (0.775 $\mu$m). Here, $n_0$ of the higher order (TE$_1$) mode used in Eq. (2) is approximately 1.444 as the TE$_1$ mode is not supported in the nanobridge with a width of 140 nm and therefore will be distributed in the surrounding SiO$_2$.

Using a 3D finite-difference time-domain (3D FDTD) method, the band diagram of the PhC can be obtained, and the grating period $L_p$ is optimized to be 370 nm to center 1550 nm in the band gap for the TE$_0$ mode, as shown in Fig. 3. At the wavelength of 1550 nm, the wavevector ($k$) of the TE$_1$ Bloch mode is 6.928 $\mu$m$^{-1}$ and the corresponding effective index ($n_{eff}$) is 1.709 according to the equation $k = (2\pi/\lambda)n_{eff}$. From this value and Fig. 2, we choose a waveguide width of the taper ($w_t$) of 575 nm to mode (index)-match the TE$_1$ Bragg mode in the access waveguide to the TE$_1$ Bloch mode in the PhC.

Figure 4(a) shows the calculated normalized transmissions for the TE$_0$ (red) and TE$_1$ (blue) modes in the designed TE$_1$-mode pass filter with a period number $N = 20$. Here, the taper length $L_t$ is 4 $\mu$m, i.e., the total length of the filter is $\sim 15$ $\mu$m. One can find that the transmission for the TE$_0$ mode is very low ($\sim 50$ dB) from 1450 nm to 1620 nm. In contrast, the transmission for the TE$_1$ mode has very low loss ($\sim 3$ dB) in the same wavelength range. Specifically, the transmissions at $\lambda_0 = 1550$ nm are $-60.7$ dB and $-1.3$ dB for the TE$_0$ and TE$_1$ modes, respectively. Figures 4(b) and 4(c) show the simulated electrical fields of light propagation at the central wavelength $\lambda_0 = 1550$ nm for the TE$_0$ and the TE$_1$ modes, respectively, and clearly picture the pass filter functionality.

The designed TE$_1$-mode pass filters were fabricated on a silicon-on-insulator wafer with 250-nm silicon on top of a HOM TE$_1$ pass filter. Figure 2 shows the effective indices $n_{eff}$ calculated using the finite-element method implemented in the software package COMSOL for different TE modes and different widths of the silicon waveguide having a height of 250 nm. Here, the wavelength $\lambda_0 = 1550$ nm, and the refractive indices of Si $n_{Si} = 3.478$ and the surrounding silica ($SiO_2$) $n_{SiO_2} = 1.444$ are calculated from the Sellmeier formula [18]. By choosing the width of the access waveguides $w_{ac} = 800$ nm and the width of the nanobridge $w_b = 140$ nm, we obtain a grating period of $\sim 410$ nm, in which the optical path length of the TE$_1$ mode is $\sim 0.636$ $\mu$m and smaller than half a wavelength (0.775 $\mu$m). Here, $n_0$ of the higher order (TE$_1$) mode used in Eq. (2) is approximately 1.444 as the TE$_1$ mode is not supported in the nanobridge with a width of 140 nm and therefore will be distributed in the surrounding SiO$_2$.

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The designed TE$_1$-mode pass filters were fabricated on a silicon-on-insulator wafer with 250-nm silicon on top of a
3-μm buried-oxide (BOX) layer. Fully etched grating couplers [19] were used to couple light between the fibers and the silicon waveguides. Electron-beam lithography was utilized to pattern the chip and followed by an inductive plasma-etching process [13]. Finally, the whole chip was covered with a 1-μm SiO2 layer. Figure 5 (bottom) shows the scanning electron micrograph (SEM) image of the fabricated filter with period number \( N = 20 \) (\( \lambda_0 = 1550 \text{ nm} \)).

In order to efficiently couple between the TE\(_1\) mode in the silicon multimode waveguide and the TE\(_0\) mode in the silicon single-mode waveguide, phase matching should be satisfied, i.e., the effective indices should be equal for the two modes. From Fig. 2, one can find that a width of 383 nm for the single-mode waveguide would secure phase matching to the multimode waveguide with the effective indices being \( \sim 2.28 \). Figure 6(a) shows the measured coupling efficiency for the two-waveguide-coupling system with a coupling length of 15 μm and a gap of 200 nm as shown by the inset SEM image. Taking into account the measurement inaccuracy of \( \sim 0.2 \text{ dB} \), the coupling efficiency is \( \sim 0.3 \text{ dB} (\sim 93\%) \) at 1550 nm and larger than \( -2 \text{ dB} (\sim 63\%) \) from 1490 nm to 1580 nm. With this waveguides configuration, we measured the normalized transmissions of the TE\(_0\) and the TE\(_1\) modes for the proposed filter with period number \( N = 20 \) as shown in Fig. 6(b), in which the calculated transmissions from Fig. 4(a) in the measured wavelength range are also given for comparison. The waveguides used for normalization have the same configuration but without the filter. One can see that for the whole measured wavelength range from 1480 to 1580 nm, the measured transmission of the TE\(_0\) mode is as low as \( -50 \text{ dB} \). The

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**Fig. 4.** Calculated normalized transmissions (a), and light propagation for the TE\(_0\) (b) and the TE\(_1\) (c) modes of the designed filter with \( N = 20 \) (\( \lambda_0 = 1550 \text{ nm} \)).

**Fig. 5.** (Top) Microscope image of the waveguide configuration for characterizing the proposed filter. (Bottom) SEM image of the fabricated HOM pass filter.

**Fig. 6.** (a) Measured coupling efficiency from TE\(_0\) mode in a waveguide with width 383 nm to the TE\(_1\) mode in a waveguide with width 800 nm. Inset shows the SEM image of the coupled waveguides. Here, due to a measurement inaccuracy of \( \sim 0.2 \text{ dB} \), the measured and normalized coupling efficiency is slightly larger than 0 dB when it is close to full coupling around 1540 nm. (b) Measured and normalized transmissions (solid lines) of the TE\(_0\) and the TE\(_1\) modes for the proposed filter with \( N = 20 \). Here the calculated transmission spectra (dashed lines) from Fig. 4(a) are also given for comparison.
variation of ±10 dB is due to the absolute measured power (≈ −80 dBm) being close to the noise floor of our optical spectrum analyzer. The measured transmission level of the TE1 mode is larger than −5 dB for the whole measured wavelength range. Thus, ERs of ≈50 dB can be achieved in the 100-nm band. At 1550 nm, the ER for the fabricated TE1-mode pass filter is 48 dB, and the IL is 1.8 dB. From the figure, it is also seen that we obtain good agreement between measured and calculated values.

We also measured the normalized transmissions of the TE0 and TE1 modes at 1550 nm for the proposed TE1-mode pass filter with different PhC period number \( N \), as shown in Fig. 7. For all periods, one can find that the transmission of the TE1 mode is always larger than −3.5 dB. On the other hand, the transmission of the TE0 mode initially decreases linearly and starts to fluctuate when the transmission reaches below −50 dB (\( N > 15 \)), i.e., being close to the detection limit of the setup. Therefore, one can reasonably expect a higher ER for the proposed filter using a setup with higher sensitivity.

In summary, we have proposed and demonstrated an ultra-compact and broadband higher-order-mode pass filter based on a 1D PhC and fabricated in a silicon waveguide. The 1D PhC is designed for the lower order mode to work in the band gap so that light on the lower order mode will be prohibited entering the PhC with high reflection and scattering. In contrast, the PhC supports a Bloch mode for the higher order mode so that light on the higher order mode can propagate through the filter with low loss. As an example, we designed and fabricated a TE1-mode pass filter rejecting the TE0 mode. The fabricated TE1-mode pass filter has an ER of ≈48 dB and an IL of −1.8 dB at 1550 nm when the period number of the PhC grating is 20. The corresponding length of the filter is only 15 μm, including tapers and a ≈7 μm-long PhC part. For the complete measured wavelength range of 100 nm, ERs of −50 dB are achieved, which are limited by the detection limitation of our measurement setup. We believe one can cascade such filters to get a higher order-mode pass filter of any order. For example, a TE2-mode pass filter can be realized by cascading one filter filtering out the TE0 mode (keeping the TE2 and the TE1 modes) and one pass-filtering out the TE1 mode (keeping the TE2 mode). Thus, the present design provides a promising option to achieve an on-chip higher-order-mode pass filter for higher order modes with any order and simultaneously having ultrahigh extinction ratios and broad band operation.

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