Inverse Designed Ultra-compact Broadband High-order Mode Filter

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Abstract. Utilizing the inverse design method of nonlinear direct-binary-search (DBS) optimization algorithm, we designed an ultra-compact broadband high-order mode filter on silicon-on-insulator wafer. The incident TE0 mode is prohibited to pass through the high-order mode filter while the TE1 mode can pass with low insertion loss. The footprint of this mode filter is only $1.56 \mu m \times 2.4 \mu m$. Numerical simulation shows that the insertion loss of this mode filter is lower than 0.26 dB and the extinction ratio is lower than 24.5 dB in the wavelength range from 1500 nm to 1600 nm. The insertion loss at the centre wavelength of 1550 nm is only 0.18 dB.

1. Introduction
In order to keep up with the increasing demand for the capacity of optical communication, mode-division multiplexing (MDM) on silicon-on-insulator (SOI) platform has attracted much more attention in the academic community due to its high performance, compact footprint and the compatibility with the complementary-metalsexide semiconductor (CMOS) fabrication process [1]. Analogous to wavelength filter, which is essential in the wavelength-division multiplexing (WDM) systems to filter out undesired wavelength [2], mode filter could become a basic component of the MDM systems. Mode filter is designed to eliminate undesired modes and only let the desired ones go through. Because of the weak confinement on high-order modes in multimode waveguides, there are many simple solutions for filtering out high-order modes while only leaving low-order modes, for example, tapering the waveguide to the cutoff width, or bending the waveguide to the appropriate radius. However, it is more difficult to filter the low-order mode in the multimode waveguide which are well confined in the waveguide. Up to now, only a few implementations of high-order mode filters have been studied. High-order mode filters based on 1D photonic crystal [3], mode converters [4], Mach–Zehnder interferometers (MZIs) [5], hyperbolic metamaterials [6], graphene-embedded waveguides [7], subwavelength-grating based contra-directional coupler [8] were proposed. However, these designs are complex in fabrication process or have large device sizes or have small operating bandwidths.

In contrast to previous high-order mode filter designs, we proposed a novel ultra-compact broadband high-order mode filter on SOI wafer in this paper. The device can be fabricated in only one-step etching process. Benefiting from DBS optimization algorithm, the footprint of this high-order mode filter is only $1.56 \mu m \times 2.4 \mu m$ while the insertion loss is lower than 0.26 dB and the extinction ratio is lower than 24.5 dB in the wavelength range of 1500 ~ 1600 nm. As far as we know, the high-order mode filter we designed is the smallest one ever demonstrated.
2. Structure and Principle

The schematic configuration of our proposed high-order mode filter is shown in Fig. 1. The device is designed based on a SOI substrate, in which the thicknesses of the buried oxide (BOX) layer is 3 μm and the top silicon layer is 220 nm. After etching process, we deposited 2 μm silicon dioxide cladding layer on top. Silicon dioxide cladding layer can protect the chip and provide better mode field symmetry to improve the device performance. The mode filter is composed of input waveguide, input taper, inverse design region, output taper and output waveguide. To reduce the transmission loss and eliminate undesired high-order modes, adiabatic tapers from 600 nm to 900 nm are designed to access the input/output waveguides with the inverse design region. The inverse design region with an ultra-compact footprint of only 1.56 μm × 2.4 μm is digitized into 13 × 20 pixels. One pixel is in the shape of square with a side length of 120 nm. Each pixel has two possible states: ‘0’ represents a fully etched hole with radius of 45 nm in the centre of the square, and ‘1’ represents that the pixel is all-silicon structure without hole etched. As a result, the inverse design region can be exclusively described by a binary matrix. The minimum of feature size in our designed mode filter is the radius of the hole (90 nm), and it ensures that the entire device including the hole in inverse design region can be readily achieved with electron-beam lithography process.

![Fig.1 (a) Initial structure of high-order mode filter (b) Optimal structure of high-order mode filter.](image)

When light enters the input waveguide, the adiabatic input taper will access to the inverse design region and expand its spot, then the light wave is scattered by a number of pixels etched with circle hole in the inverse design region. Adiabatic output taper is used to collect the output light from the inverse design region and eliminate undesired high-order modes via the cutoff width. By optimizing the arrangement and distribution of holes in the inverse design region, the designed mode filter only allows high-order mode (TE1) to pass while the low-order mode (TE0) is prohibited.

3. Design and Simulation

In order to evaluate the performance of the device in the inverse design process, the figure-of-merit (FOM) is defined as:

\[
FOM = T_{11} - n^* (T_{00} + T_{01} + T_{10})
\]

where \(T_{xy}\) is the average transmission efficiencies in the wavelength range of 1500 ~ 1600 nm when the input mode is TEx and the output mode is TEy. For example, \(T_{11}\) is the average transmission efficiencies in the wavelength range of 1500 ~ 1600 nm when the input mode is TE1 and the output mode is TE1. \(T_{11}\) represents the insertion loss of the high-order mode filter while \(T_{00}, T_{01}, T_{10}\) all represent the extinction ratio. \(n\) is a weighted coefficient for extinction ratio. In this paper, \(n\) is set to 1 in order to achieve the balance between the insertion loss and the extinction ratio. For an ideal high-order mode filter, \(T_{11}\) is 1 and \(T_{00}, T_{01}, T_{10}\) are all 0, so the ideal FOM is 1.

We applied the DBS optimization algorithm to design the local optimum arrangement and distribution of holes in the inverse design region. DBS optimization algorithm is an iterative search algorithm which has been previously used to design different devices, such as polarization beam
splitter [9], polarization rotation [10], multimode waveguide crossing [11], power splitter [12-13], mode converter [14], mode (de) multiplexer [15] and bending waveguide [16]. Different from other global optimization algorithm such as particle swarm algorithm and genetic algorithm, DBS optimization algorithm can only find the local optimal solution but it is much more effective in time consumption. In any case, DBS optimization algorithm has the advantage that it is guaranteed to converge to a solution. We used the 3D finite-difference time-domain (FDTD) method to calculate the FOM by commercial software (Lumerical FDTD Solutions). At the beginning, we set the inverse design region as all-silicon initial structure without circle hole, that means all the pixels’ state is ‘1’. Then, we switch the state of each pixel in turn, and numerically calculate the FOM using 3D FDTD. If the FOM increases, then the reversed pixel state will be retained. If not, the pixel goes back to the original state and the algorithm proceeds to the next pixel. A single iteration ends up while scanning a whole round of all 260 pixels. When using the DBS optimization algorithm to calculate the state of each pixel in the inverse design region, the row scan and column scan are alternately used. When scanning by row, it goes from left to right in the horizontal direction and from bottom to top in the vertical direction; when scanning in the column, it goes from bottom to top in the vertical direction and from left to right in the horizontal direction. If the increase of FOM is less than 0.5% after one iteration, we think the optimization process has converged and the whole design is end.

The calculated FOMs in the iteration process are illustrated in Fig.2. The FOM increases very quickly in the first two iterations, and then it gradually slows down. The FOM converges after the sixth iteration. Simulated spectra transmission of the optimal designed mode filter is illustrated in Fig.3. As we can see, the insertion loss is lower than 0.26 dB and the extinction ratio is lower than 24.5 dB in the wavelength range of 1500 ~ 1600 nm. At the centre wavelength of 1550 nm, the insertion loss is only 0.18 dB. The magnetic field distributions at 1550 nm for TE0 input and TE1 input are illustrated in Fig.4 (a) and 4 (b), respectively. Detailed magnetic field distributions in the inverse design region are also showed in Fig.4. When TE1 mode is incident, the light field is first separated into two parts and then combine at the end of the inverse design region, so the TE1 mode can pass the mode filter with low insertion loss. When the TE0 mode is incident, part of the light is scattered outside the waveguide, and part of the light is converted into TE3 mode which will be filtered out in the output taper with the cutoff width, so the TE0 mode cannot pass through the high-order mode filter.
4. Conclusion

To conclude, we have demonstrated a novel ultra-compact broadband high-order mode filter on silicon-on-insulator wafer. By optimizing the arrangement and distribution of holes in the inverse design region, TE1 mode can pass through the mode filter with low insertion loss while TE0 mode is prohibited. The footprint of this mode filter is only $1.56 \mu m \times 2.4 \mu m$. The insertion loss for TE1 mode is lower than 0.26 dB and the extinction ratio is lower than 24.5 dB in the wavelength range of 1500 ~ 1600 nm. Furthermore, the device does not need extra fabrication steps and has great potentials in MDM systems. Fabrication of the proposed high-order mode filter will be realized in future work.

Acknowledgments

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