Single polarization transmission in pedestal-supported silicon waveguides

Jierong Cheng, Wei Zhang,* Qiang Zhou, Yu Wang, Yidong Huang, and Jiangde Peng

Tsinghua National Laboratory for Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing, 100084, China

**Corresponding author: zwei@tsinghua.edu.cn*

Received February 17, 2011; revised April 6, 2011; accepted April 12, 2011; posted April 14, 2011 (Doc. ID 142814); published May 6, 2011

In this Letter, properties of a pedestal-supported silicon waveguide are investigated, showing that it supports single polarization transmission. The pedestal is fabricated easily through a wet-etching process on strip waveguides. Theoretical analysis shows that this property is due to the leakage of quasi-TM mode when the pedestal width is small. A polarization extinction ratio larger than 20 dB at 1550 nm is measured in the pedestal waveguide sample, demonstrating single polarization transmission property experimentally. Thanks to its large single polarization transmission bandwidth, robustness in fabrication tolerance, and simple fabrication process, pedestal waveguides will have potential applications as simple silicon-integrated polarizers.

OCIS codes: 130.0130, 130.5440.

Integrated waveguide polarizers are important functional elements for integrated optoelectronic devices requiring polarization control, such as switches, interferometers, amplifiers, and receivers. To realize a high-quality waveguide polarizer, several schemes have been proposed based on modification of the waveguide's material and structure. Metal-clad waveguides [1] have been widely investigated as integrated polarizers, utilizing the single polarization transmission properties of surface plasma waves. In this scheme, the metal cladding should be carefully designed to avoid high excess loss of metal material. To realize an all-dielectric waveguide polarizer, usually large birefringence is introduced to the waveguide by large structural [2] or material asymmetry [3,4], leading to the cutoff of one polarization mode. Recently, combining waveguide birefringence and device structure design, such as Y junctions [5] and multimode interferometers [6], integrated polarization splitters are realized, which can also be used as polarizers.

In this Letter, the pedestal-supported silicon waveguide is investigated as a novel way to introduce large birefringence, which provides a simple way to realize a waveguide polarizer. The pedestal structure is commonly used in microcavities, such as microdisks [7] and the point defect cavity of a photonic crystal [8], serving as a mechanical support or a current channel. However, it is seldom used in waveguides [9]. Here, we introduce the pedestal to the silicon waveguide, making its quasi-TM modal field leak into the substrate. Thus, the pedestal waveguide can be used as an integrated waveguide polarizer.

Figure 1(a) is a schematic of the pedestal waveguide structure. The waveguide core is a silicon strip. Underneath the core is a SiO_2 pedestal supporting the waveguide. To simplify the simulation below, the cross section of the pedestal is viewed as a rectangle, whose dimensions are denoted by width W and height H. The fabrication process of the pedestal waveguide is simple and compatible with the traditional top-down fabrication. The silicon core is fabricated on a silicon-on-insulator wafer. The waveguide pattern is defined by electron beam (EB) lithography and then transferred into the silicon layer using inductively coupled plasma (ICP) dry etching. A SiO_2 cladding layer is deposited on the surface of the whole wafer through plasma-enhanced chemical vapor deposition (PECVD) to protect the strip waveguides. Then, the wafer is polished and cleaved so that both facets of the waveguide are exposed in order to couple with fibers. Until now, a basic strip waveguide was fabricated. Then, the buffered hydrofluoric acid (BHF) etching changes the basic strip waveguide into the pedestal waveguide if the wet-etching time is carefully controlled. The fabrication process shows good repeatability. Figure 1(b) shows a scanning electron microscope (SEM) image of a typical pedestal waveguide sample.

First, the pedestal waveguide is investigated by the finite element method. The indices for silicon and SiO_2 are set to 3.46 and 1.44, respectively. The dimensions of the silicon core are fixed to 400 nm × 220 nm in the cross section, and the pedestal height H is fixed to 250 nm. These parameters are chosen as those of the waveguide sample tested in the experiment. The effective indices (n_{eff}) of quasi-TE and quasi-TM modes of the pedestal waveguide are calculated under different pedestal widths W and wavelengths λ, shown in Fig. 2. The results clearly indicate that n_{eff} for the two polarization modes decline as W reduces. This trend is obvious as air takes growing proportion in the cladding with the reduction of W. Moreover, since the width of the core is larger than its height, this cross-sectional profile determines that the modal

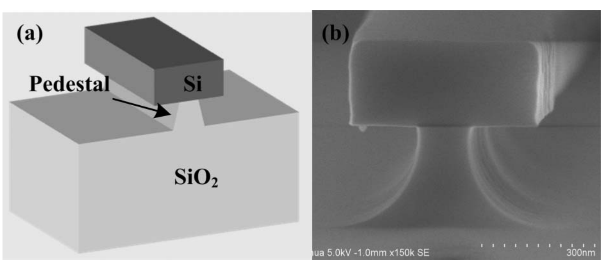

Fig. 1. (a) Schematic of the pedestal-supported silicon waveguide. The dimensions of the pedestal are denoted as width W and height H. (b) SEM image of a typical pedestal waveguide sample.

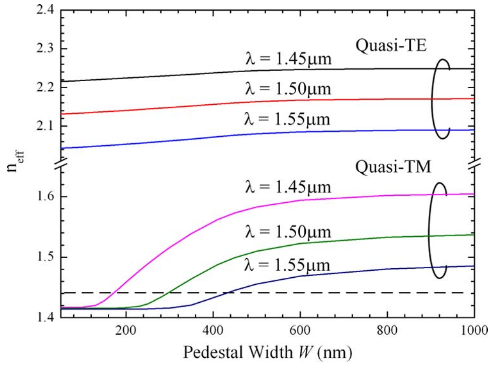

Fig. 2. (Color online) n_{eff} of the quasi-TE and quasi-TM modes under increasing pedestal width W at different wavelengths.

distribution of the quasi-TM mode is more extended to the upper and lower surfaces, leading to a smaller n_{eff} than that of the quasi-TE mode. With the decrease of W, the n_{eff} of the quasi-TM mode goes below the index of SiO_2, which is shown by the dashed line in Fig. 2. Quasi-TM mode, whose n_{eff} goes below the dashed line, will leak into the substrate through the pedestal. Under these conditions, the pedestal waveguide supports only single quasi-TE mode transmission. For a specific wavelength, there exists a critical pedestal width for single polarization transmission when n_{eff} of quasi-TM mode is equal to 1.44. From Fig. 2, it can be seen that the critical width grows with the increase of wavelength. When the pedestal width is much smaller than the critical width, the quasi-TM modal distribution is mainly down to the substrate, thus the calculated n_{eff} converges to a fixed value with the decrease of pedestal width.

When quasi-TM mode is a leaky mode, n_{eff} has an imaginary part, corresponding to the leaky loss. Figure 3 shows the calculated leaky loss spectra of the quasi-TM mode under different pedestal widths W. It can be seen that the loss is negligible in the short-wavelength band, where the quasi-TM mode is a guided mode. However, the loss increases dramatically in the long-wavelength band, indicating that the quasi-TM mode changes into a leaky mode. This trend of the leaky loss spectrum shows the cutoff property of the quasi-TM mode. At wavelengths larger than 1450 nm, the single quasi-TE mode transmission can be realized within 1 mm in length when the pedestal width is located in the range of 50 to 200 nm, showing enough fabrication tolerance and large bandwidth in practical application.

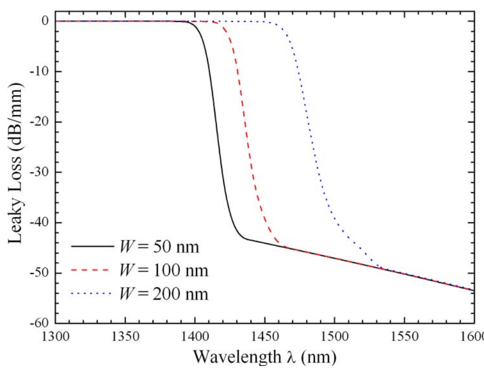

Fig. 3. (Color online) Leaky loss of the quasi-TM mode as a function of wavelength under different pedestal widths.

Then, we demonstrate the single quasi-TE mode transmission property of the pedestal waveguide in the experiment. To begin, the transmission properties of basic strip waveguides with different lengths on a wafer sample, obtained after EB, ICP, and PECVD processes, are measured as a reference. Then, the BHF etching is carried out on the same wafer sample to fabricate pedestal waveguides, which are measured by the same measurement system. The measurement system has a CW laser source with a wavelength of 1550 nm and a polarization controller (Agilent, 11896A) to adjust the polarization of the incident light wave for the measured waveguide. The light wave is coupled into and out of the waveguide by two tapered fibers (focal length of 4.5 μm and mode radius of 0.7 μm), which is realized by a high-precision autoalign system (SURUGA SEIKI C7214-9015) with a resolution of 50 nm. The output light from the waveguide is detected by a Power Meter (Agilent, 81624A) and recorded in the computer.

The insertion losses of strip waveguides are measured and shown in Fig. 4. It can be seen that both quasi-TE (stars) and quasi-TM (circles) modes can be guided in strip waveguides. After linearly fitting the measured losses of strip waveguides with different lengths, transmission losses of −1.97 and −3.28 dB/mm are obtained for quasi-TE and quasi-TM modes, respectively. However, for pedestal waveguides, the losses of the quasi-TM mode, shown by the squares in Fig. 4, increase by more than 30 dB compared with that in strip waveguides. Since the losses of the quasi-TE mode after wet etching (triangles) remain the same, we can conclude that the coupling condition and the sidewall roughness do not change dramatically in the wet-etching process. The increased loss of 30 dB for the quasi-TM mode is mainly due to the leaky loss introduced by the pedestal structure. Comparing the insertion losses of quasi-TE and quasi-TM modes in the pedestal waveguides, a polarization extinction ratio (PER) of more than 20 dB is obtained in the experiment. It is worth noting that the real PER may be larger than the measured value since it is limited by the PER of the incidence light wave, which is about 20 dB, measured by a PER meter (Santec Inc. PEM-320). Moreover, since the insertion losses of quasi-TE modes in the strip waveguide and the pedestal waveguide are

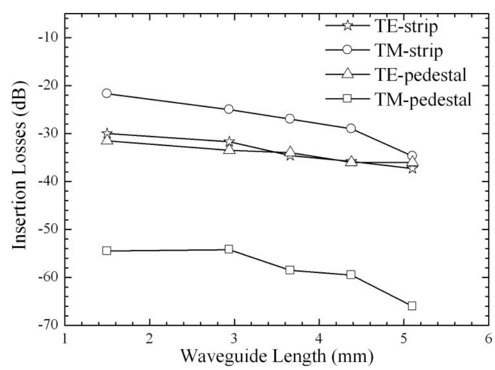

Fig. 4. Measured insertion losses for two polarization modes in strip waveguides and pedestal waveguides. Stars, quasi-TE modes in strip waveguides; circles, quasi-TM modes in strip waveguides; triangles, quasi-TE modes in pedestal waveguides; squares, quasi-TM modes in pedestal waveguides.

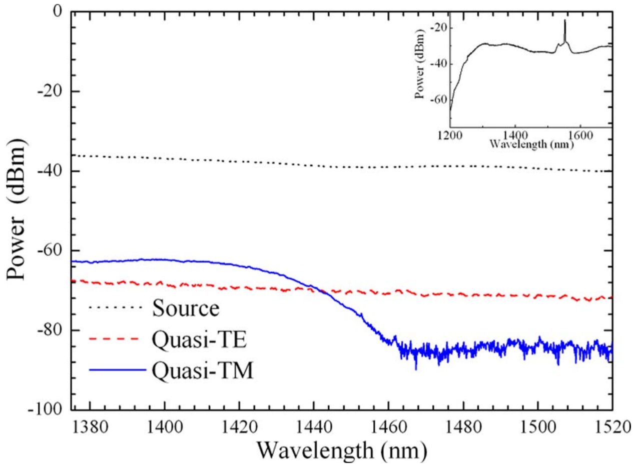

Fig. 5. (Color online) Transmission spectra of two polarization modes in the pedestal waveguide of 1.6 mm in length. Inset: the whole spectrum of the SC source. Dotted curve, spectrum of SC source; dashed curve, output spectrum of quasi-TE mode; solid line, output spectrum of quasi-TM mode.

nearly the same (stars and triangles in Fig. 4), the pedestal structure has negligible excess loss.

To show the characteristics of pedestal waveguides more clearly, we also measure the transmission spectrum of a pedestal waveguide sample of 1.6 mm in length by a broadband super continuum (SC) source. The SC source is based on a passive mode-locked fiber laser, the light pulses of which passing through a piece of highly nonlinear fiber (fabricated by OFS Inc.) to generate SC. Its spectrum is shown in the inset in Fig. 5. Using the SC as the incidence light of the pedestal waveguide, we measure its output spectrum through an optical spectral analyzer (OSA, Agilent 86142B). The experimental results in Fig. 5 show that the transmission spectrum of the quasi-TE mode is almost unchanged under different wavelengths, showing that the quasi-TE mode is a guided mode in the whole wavelength range we measured (1375–1520 nm). The insertion loss is about 31.5 dB mainly due to the coupling loss between the waveguide and fibers since no taper structures are designed in the ends of the waveguide. On the other hand, quasi-TM mode shows a clear cutoff property. At wavelengths larger than 1420 nm, the output power declines dramatically until it is below the noise background of the OSA. The trend of the quasi-TM spectrum agrees well with the theoretical analysis (dashed curve in Fig. 3), and the pedestal width in the sample is estimated to be around 100 nm from the spectrum. It is worth noting that, by introducing an UV lithography process before BHF etching, the pedestal structure can be fabricated in a small section of the strip waveguide in various integrated optical devices, operating as a simple integrated polarizer.

In conclusion, properties of silicon waveguide supported by an SiO_2 pedestal are investigated. Theoretical analysis shows that if the pedestal width is small enough, its quasi-TM mode will convert to a leaky mode under certain wavelengths, with an n_{eff} that has a real part lower than the index of SiO_2 and an imaginary part showing obvious leaky loss. This property is demonstrated experimentally by the transmission characteristics comparison between the common strip silicon waveguides and pedestal waveguides. Experimental results shows a clear single polarization transmission property of the tested pedestal waveguide sample, with a PER larger than 20 dB at the wavelength of 1550 nm. The output spectrum of the pedestal waveguide sample shows a clear cutoff property in the quasi-TM mode, which agrees well with the theoretical analysis. Thanks to its large single polarization transmission bandwidth, robustness in fabrication tolerance, and simple fabrication process, it may have wide applications in silicon photonics as a simple integrated silicon polarizer.

This work is supported in part by the National Natural Science Foundation of China (NSFC) under grant 60777032, the 973 Program of China under contracts 2010CB327600 and 2011CBA00303, and the Tsinghua University Initiative Scientific Research Program.

References

1. E. M. Garmire and H. Stoll, IEEE J. Quantum Electron. **8**, 763 (1972).
2. C. H. Chen, L. Pang, C. H. Tsai, U. Levy, and Y. Fainman, Opt. Express **13**, 5347 (2005).
3. O. Watanabe, M. Tsuchimori, A. Okada, and H. Ito, Appl. Phys. Lett. **71**, 750 (1997).
4. K. Baba, T. Iden, and M. Miyagi, Electron. Lett. **36**, 1461 (2000).
5. H. Fukuda, K. Yamada, T. Tsuchizawa, T. Watanabe, H. Shinojima, and S. Itabashi, Opt. Express **14**, 12401 (2006).
6. Y. F. Ma and D. W. Huang, in *IEEE/LEOS International Conference on Optical MEMS and Nanophotonics* (2007) p. 121.
7. S. L. McCall, A. F. J. Levi, R. E. Slusher, S. J. Pearton, and R. A. Logan, Appl. Phys. Lett. **60**, 289 (1992).
8. H. G. Park, S. H. Kim, S. H. Kwon, Y. G. Ju, J. K. Yang, J. H. Baek, S. B. Kim, and Y. H. Lee, Science **305**, 1444 (2004).
9. A. D. Chaudhari, L. C. West, C. W. Roberts, and Y. Lu, IEEE Photon. Technol. Lett. **7**, 526 (1995).