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Highly Efficient Fiber Coupling Structure for Si Wire Waveguide Using Standard CMOS Compatible SiN Waveguides

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Abstract

We propose and design a highly efficient fiber coupling structure for Si wire waveguides consisting of a Si inverted taper and a CMOS-compatible SiN waveguide. A small SiN waveguide with a 310 nm-square core can provide low-loss and low-polarization-dependent fiber-SiN coupling and SiN-Si mode conversion.

1. Introduction

Si photonics technology is attracting attention for promoting developments in high-density photonic and photonic-electronic integrations [1,2]. For example, optical interconnects based on this technology have a potential to solve critical problems such as bandwidth restriction, integration density, and power consumption of electronic devices. Moreover, the fabrication process is highly compatible with complementary metal-oxide semiconductor (CMOS) and applicable to a high-volume production technology with superior cost performance [3].

As an issue that should be solved in implementing Si photonic integrated circuit, there is a large coupling loss due to mode field mismatching between a Si wire waveguide and optical fiber. An inverted taper-based double-core fiber coupling structures has been proposed, and it has already provided highly efficient and low-polarization-dependent optical coupling [4,5]. The conventional coupling structure consists of an adiabatic Si inverted taper overlaid with a secondary waveguide made of low-refractive-index materials such as silicon-rich silica (SiOx) [4] and silicon oxynitride (SiON) [5]. Depending on the mode field diameter of the optical fiber, the optimum core dimensions of the secondary waveguide are formed to a level of several micrometers. However, fabricating a waveguide with such a large core requires thick-film processes, which are not supported in CMOS fabrication systems and reduce producibility. In the practical application of Si photonics technology, it is therefore very important to construct fiber coupling structures which are suitable for standard CMOS fabrication systems.

In this paper, we propose a novel fiber coupling structure for a Si wire waveguide, in which CMOS-compatible thin-film processes are applied for the fabrication of the secondary waveguide. In this fiber coupling structure, as an alternative to the SiOx/SiON waveguide, a silicon-nitride (SiN) waveguide with a very small core is used as the secondary waveguide.

2. Concept and Design

Figure 1 shows the structural model for device design. The structure consists of an SiN waveguide for fiber coupling and a Si wire waveguide. The Si wire waveguide is formed on SOI substrate with a 3-μm-thick buried oxide (BOX) layer. The width and height of the Si wire waveguide core are 420 and 220 nm. The refractive indices of the Si and BOX are 3.5 and 1.45, respectively. In addition, because of restrictions on fabrication techniques, the tip width of the Si inverted taper is defined as 80 nm, which is consistent with that of the conventional structure [6]. A planarized silicon dioxide (SiO_2) spacer layer with a thickness S_{spacer} is inserted between the Si waveguide and the SiN secondary waveguide. The refractive index of the spacer layer is 1.47, which is set a bit higher than that of the thermal oxide in the BOX. The SiN waveguide is straight and located parallel to the Si wire waveguide and it is covered by a SiO_2 upper cladding. The length of the SiN waveguide is typically several hundred micrometers. Although SiN has a relatively high refractive index of around 2.0, we can expand the optical field enough for efficient fiber coupling by reducing the core size. Such a large optical field in the SiN waveguide can be adiabatically converted to that in Si wire waveguide efficiently through a Si inverted-taper waveguide. The length of the Si inverted taper is denoted as L_{taper}.

The mode field profiles and light propagation performance were calculated by using the finite difference method and the eigen-mode expansion method, respectively. These calculations were performed by using commercially available software (Photon Design, FIMMWAVE) [7].

3. Performance Estimation

First, we designed the SiN secondary waveguide to provide efficient optical coupling with an external fiber. As an

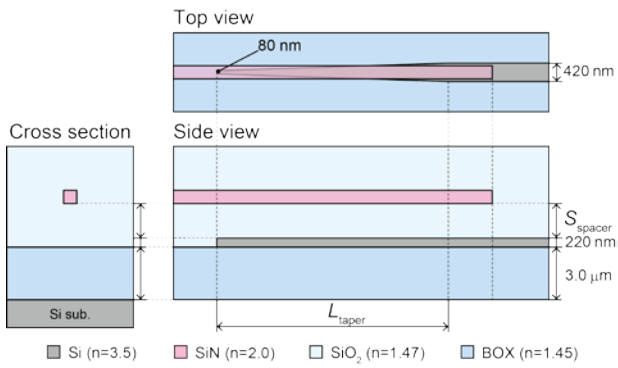

Fig. 1 Schematic of fiber coupling structure.

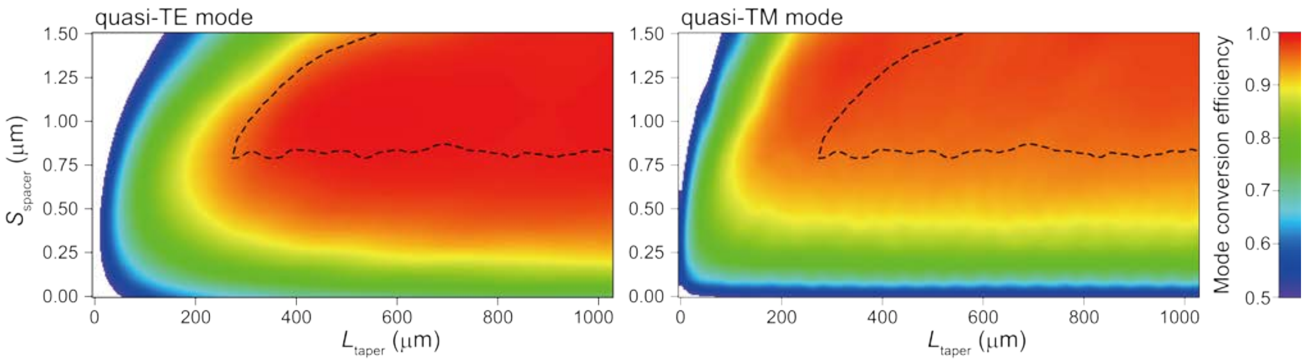

Fig. 2 Color-plotted mode-conversion efficiency as a function of the S_{spacer} and L_{taper} for each mode. The dashed lines denote mode conversion efficiency above 95%.

optical simulation model, we assumed that the SiN waveguide with a square core is surrounded by a sufficient thick SiO_2 cladding and BOX layer. An ultra-high NA single-mode fiber with a mode-field diameter of 4.0 μm is assumed for external guiding devices. The wavelength of the guided light is 1.55 μm. The SiN waveguide with a 310-nm-square core provides the highest coupling efficiency between the fiber and SiN waveguide for the quasi-TE and TM modes.

Next, we took into account the optical leakage to the Si substrate under the BOX layer. The optical field in the optimized SiN waveguide is expanded to about a few micrometers. The distance between the SiN waveguide and Si substrate is the sum of S_{spacer}, the 220-nm-high Si waveguide and the 3-μm-thick BOX layer. Therefore, the tail of the field might touch the Si substrate under the BOX layer and the optical power would leak into the substrate. The substrate-leakage loss becomes lower with increasing S_{spacer} for both modes. Through a detail calculation of the substrate-leakage loss, we have found that the loss is negligible for the SiN waveguide with a 1.0-μm spacer. Hence, the coupling efficiency of more than ~94 % is guaranteed.

Then, we examined mode conversion efficiency between the optimized SiN waveguide and Si wire waveguide. Figure 2 shows calculated mode conversion efficiency as functions of S_{spacer} and L_{taper}. In our proposed structure, to provide high mode-conversion efficiency, S_{spacer} and L_{taper} should be thicker and longer, respectively. In Fig. 2, regions providing conversion efficiency of over 95% for both polarizations are indicated by dashed lines. This mode-conversion structure can provide high conversion efficiency in a wide area of S_{spacer} and L_{taper}. Thus, the design and fabrication margins are very large.

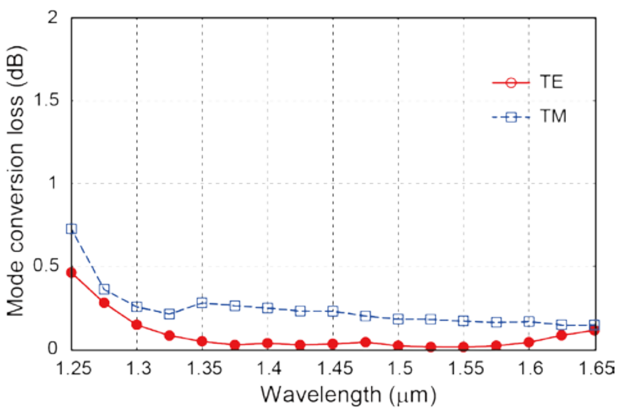

Fig. 2 Dependence of mode-conversion loss calculated wavelength ranging from 1.25 μm to 1.65 μm.

Figure 3 shows the wavelength dependence of mode-conversion loss between the SiN waveguide and Si wire waveguide. The wavelength of the guided light was set in the range of 1.25 μm to 1.65 μm. We used S_{spacer} = 1.0 μm and L_{taper} = 500 μm as representative design parameters. The mode-conversion loss of less than 0.5 dB was achieved in almost the entire range for both modes. Therefore, our proposed structure provides a low-loss and low-polarization-dependent mode conversion and can operate in a wide wavelength bandwidth.

4. Conclusions

We proposed and designed a CMOS-compatible, highly efficient fiber coupling structure for Si wire waveguides. The coupling structure consists of a Si inverted taper waveguide and a small SiN secondary waveguide. A SiN waveguide with a 310-nm-square core can provide low-loss and polarization-independent fiber coupling with a coupling efficiency of over 94 % for a fiber with a 4.0-μm mode-field diameter. An optimized SiN-Si double-core structure can provide low-loss and low-polarization-dependent mode conversion with a conversion efficiency of over 95 %.

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