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Low Birefringence Silicon-on-insulator Waveguide and Its Optical Interconnection using High Numerical Aperture Fiber

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Abstract: 5 μm thick silicon-on-insulator waveguide was demonstrated to low birefringence of 4.6×10^{-5}. Instead of complex processing from 3D mode-size-converter, the high numerical aperture fiber was utilized to get competitively coupling loss of 0.4 dB.

Introduction

Silicon-on-insulator (SOI) is a critical platform for integrated optoelectronic circuits since it offers the potential of monolithic integration for photonic and electronic functions on a single substrate [1]. Integrating photonics functions on a silicon platform will be a low cost solution if integrated optoelectronics circuits are feasible. Birefringence is a serious problem faced by many photonics devices, which results in polarization dependent wavelength (PDW) shift and polarization dependent loss (PDL). However the beam propagation method (BPM) with semi-vectorial capability to simulate SOI waveguides shows that the waveguide height of a few microns has lower birefringence than one micron or less height waveguide, which is approximately 10^{-2}, two orders of magnitude larger. Therefore a bigger core size for SOI waveguide is preferred due to higher birefringence effect on a smaller core. On the other hand, thicker SOI waveguides will cause significantly large bend radius. A suitable core size for SOI waveguides should compromise between low birefringence and competitively compact device size.

The mode field diameter (MFD) from thinner SOI waveguides will have significant coupling loss associated with a SMF-28 fiber. A complex mode-size-converter taper was then utilized on this kind of SOI waveguides to make optical modes extended to match fiber modes via three dimensional expansion [2]. A simple SOI waveguide process is necessary for further multiple layers integration and cost reduction. Therefore, a high numerical aperture (HNA) fiber with small MFD was used as the bridge between a standard telecommunication fiber, SMF-28, and higher refractive-index-contrast SOI waveguides [3]. To optimize the coupling loss, the SOI waveguide mode can be chosen as similar as the HNA fiber. In this paper, the birefringence and PDW shift of SOI waveguide with suitable thickness will be discussed and demonstrated based on the waveguide geometric width and etch depth. A low coupling loss between HNA fiber and SOI waveguides will also be presented.

Birefringence Study for SOI Waveguides

The mechanical stress to an optical substrate modifies the optical properties of a material by the dielectric impermeability. Thus, a homogeneous and isotropic material subject to mechanical stress will become optically anisotropic. The phenomenon is known as the stress birefringence or photo-elastic effect. The changes in the indices of refraction are due to the effects of stress imparting changes in the dielectric impermeability that alter the size, shape, and orientation of the index ellipsoid.

The correlation between PDW shift and PDL can be illustrated by the array waveguide grating (AWG) demultiplexer. The modal birefringence can be observed as PDW shift on the central wavelengths, which can be given by

$$PDW=\lambda_{TE}-\lambda_{TM}=(n_{TE}-n_{TM})\Delta L/m$$

Here λ and n are the wavelength and effective index of the waveguide, respectively, for transverse electric (TE) and transverse magnetic (TM) polarization states; ΔL is the difference of two adjacent grating lengths; and m is the grating order in an AWG. Once the PDW shift is verified, the difference between highest and lowest optical power on the central wavelength is called PDL. The lowest birefringence and PDL are required for telecommunication system design.

A BPM simulation shows that if the waveguide dimensions shrink to around 1 μm or less in high refractive-index-contrast SOI waveguide layer structures [4], it is not only that the birefringence effect is large, but also the PDL becomes significant. The overlap integral simulation suggested that the most efficient coupling with a SMF-28 fiber is 12 μm thick SOI waveguides. The large core thickness is then preferred for decent optical performance. Nevertheless, the large core needs a very big bend radius to maintain the single mode operation and the device layout can not be maintained as compact as expected. For example, 12 μm thick core of SOI waveguides satisfies the single mode conditions only when 20 mm minimum bend radius is applied. For the points of view with regard to low birefringence, low PDL, compactness, and efficient interconnection, another compromise thickness for SOI waveguides is needed.

The recent progress on fusion splicing can joint two different cores of fibers within 0.1 dB coupling loss. The HNA fiber is a good selection to play an intermediate role to connect SOI waveguides and SMF-28 fibers. The MFD of HNA fiber is typically around 5 μm, which corresponding bend radius is around 7 mm for single mode operation. Therefore, the BPM simulation tool, BeamPROP, was implemented onto 5 μm thick SOI waveguide to understand the birefringence performance. In Fig. 1 (a), a reasonable etch depth, 2.65 μm, to get a compact bend radius, 7 mm, was utilized to study the width effect on birefringence variation for 5 μm thick SOI waveguide. The birefringence and PDW will have a minimum value on 3.8 um width. And then 3.8 μm width is fixed, the etch depth is varied before reaching the multimode region, 2.8 μm etch depth. The lowest birefringence and PDW are 5×10^{-5} and 3 GHz, respecttively, on 2.76 μm etch depth and 3.8 μm width on 5 μm thick SOI waveguide.

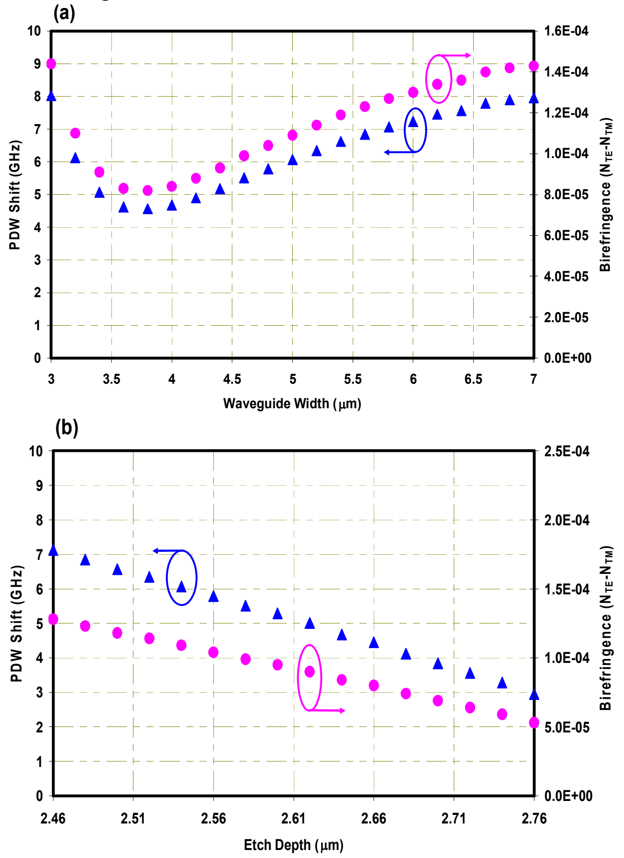

Fig. 1 (a) PDW vs. waveguide width for 5 μm thick waveguide and 2.65 μm etch depth (b) PDW shift vs. etch depth for a waveguide with 5 μm thickness and 3.8 μm width (Wavelength is assumed as 1550 nm)

5 μm Thick SOI Waveguide with 3.8 μm Width	Etch Depth (μm)	PDW Shift (λ_{TE}-λ_{TM}) (GHz)	Birefringence
SOI AWG1 Central Channel	2.45	4.375	8.1E-05
SOI AWG1 Central Channel	2.65	3.125	5.8E-05
SOI AWG2 Central Channel	2.45	5	9.2E-05
SOI AWG2 Central Channel	2.65	2.5	4.6E-05

Table 1 Birefringence comparison on various etch depths

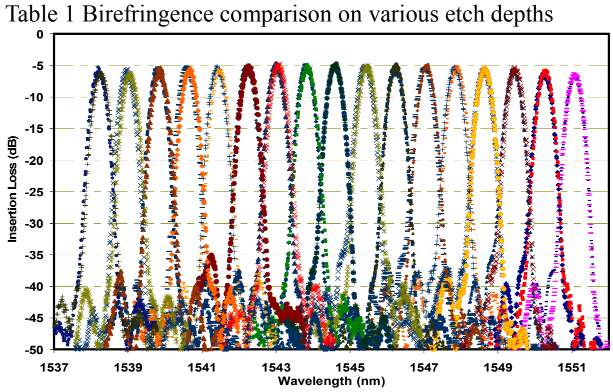

Fig. 2 Birefringence study from a 17-channel AWG

Experiment Results and Discussions

To avoid the multimode region for SOI waveguides and the processing variation, the reasonable etch depth for 5 μm thick SOI waveguide was only applied up to 2.65 μm and its bend radius can be controlled within 7 mm. The birefringence of the central channels from two AWGs, located in the same SOI wafer, are listed in Table 1, which indicates that the PDW shift gets improved when the etch depth is deeper. Due to the warpage of SOI wafer, the experimental data for PDW shift of Table 1 demonstrate 2 GHz higher than theoretic simulation of Fig. 1 (b). Finally a 17-channel AWG was employed to check the birefringence distribution across the whole 4" SOI wafer, shown in Fig. 2, which insertion loss is, excluding Fresnel effect in the power budget, around 5 dB. The residual birefringence induced by the stress via the photoelastic effect shows 6 GHz PDW shift variation on the 4" SOI wafer. A more uniform SOI wafer with less warpage is necessary for better birefringence control. The HNA fiber was then implemented to couple to the horizontal tapered SOI waveguides in the input/output areas of 17-channel AWG with a thickness of 5 μm, width of 5.5 μm, and etch depth of 2.65 μm. Another additional coupling loss of 0.4 dB needs to be considered for each interface. The splicing between HNA and SMF-28 fibers can be optimized to get the coupling loss as low as 0.1 dB per splicing.

The three-dimensional taper is a gradual transition from a large cross-sectional waveguide area to a smaller one. A vertical taper requires a differential etch rate along the length of the taper [4]. Recently a simpler two-step etch and regrowth can be applied together to remove the difficulties for a smooth vertical taper transition and achieve the coupling loss of less than 0.5 dB/facet on the interface [2]. Compared with two approaches for tapering, the two-dimensional tapers are relatively straight-forward to fabricate because this lateral taper is essentially just an etching process from the top of the silicon wafer. The suitable HNA fiber is then applied for efficient coupling. Due to the MFD from HNA fiber is a little bit bigger than 5 μm, our new design with 5.5 μm thick core of SOI waveguide can achieve a better coupling loss, within 0.2 dB, with the HNA fiber.

Summary

We demonstrated the low birefringence of 4.6×10^{-5} for a SOI waveguide with 5 μm thickness, 3.8 μm width, and 2.65 μm etch depth. The effect on birefringence from the wafer warpage still needs to be considered for better performance control. An AWG demultiplexer is a good indicator to demonstrate the birefringence distribution across the whole wafer. The HNA fiber was successfully utilized to connect 5 μm thick SOI waveguides and SMF-28 fibers, respectively, with 0.4 dB per interface and 0.1 dB per splicing for joint junction loss to achieve excellent coupling efficiencies as well as low birefringence.

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