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E-3-2

A Study on the Design and Properties of an SiON/SiO_2 Waveguide: The Effect of the Substrate on Propagation Loss

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Abstract: We designed and investigated the properties of an SiON/SiO_2 optical channel waveguide (WG) operating around a wavelength of 800 nm. We optimized the WG structure to minimize the loss of the WG by calculating the dispersion relation and the propagation loss for the WG on an Si substrate. The simulations showed that an insufficiently thick lower cladding layer on an Si substrate causes not only propagation loss but also intensifies the fluctuation of propagating field.

1. Introduction

Silicon nanophotonics has attracted significant interest because of the potential of integrating electric and photonic circuits and because of the availability of industrial facilities for Si semiconductor technology. Among various optical interconnections, an on-chip optical interconnection is ultimate in size, and it can potentially be used to achieve high-quality signal distribution and wide-band interconnection on a large-scale integration chip. We designed an optical waveguide (WG) with an SiON core and an SiO_2 cladding layers to achieve an on-chip optical interconnection operating around a wavelength of 800 nm. The WG devices optimized for this wavelength can be integrated with Si nano-photodiodes[1–4)] to guide the electromagnetic (EM) field emitted from an cost-effective light emitter like a vertical-cavity surface-emitting laser.

2. Numerical Results and Discussion

2.1 Dispersion Relation and Single Mode Condition

Figure 1(a) shows the schematic illustration of the WG structure, which consists of an SiON core with a rectangular cross-section and upper and lower SiO_2 cladding layers.[5)] We assume that only a linear, homogeneous, and lossless medium is in each region and that the refractive index distribution has mirror symmetry (σ_x and σ_y) for the horizontal and vertical directions, as shown in Fig. 1(b). The parity associated with these symmetry operations, which is defined by $\hat{O}_\sigma \mathbf{E}(\mathbf{r}) = \pm\mathbf{E}(\mathbf{r})$ and $\hat{O}_\sigma \mathbf{H}(\mathbf{r}) = \pm\mathbf{H}(\mathbf{r})$ (where $\hat{O}_\sigma$, $\mathbf{E}$, and $\mathbf{H}$ are operators for the symmetry (σ) and the EM field of the eigen mode), is useful for identifying and categorizing the obtained eigen modes.

Figure 2 shows the typical dispersion relation of the WG with a refractive index difference between the core and the clad, $\Delta n = 2.7$ % ($n = 1.491$ for the SiON core and $n = 1.45$ for the SiO_2 clad), for the TE-like (even parity under the mirror symmetry operation associated with the plane $y = 0$) and the TM-like (odd parity) modes. It is obtained by numerical calculations based on the plane-wave expansion (PWE) method under a periodic boundary condition.[6)] The effective refractive index, $n_{\rm eff}$, (defined by $k = \omega n_{\rm eff}(\omega)/c$, where k, ω, and c stand for wavenumber, angular frequency of the eigen mode, and the speed of light in vacuum) is normalized by using the maximum and minimum values of $n_{\rm eff}$. The polarization dependence is too small to distinguish between them, as shown in Fig. 2.

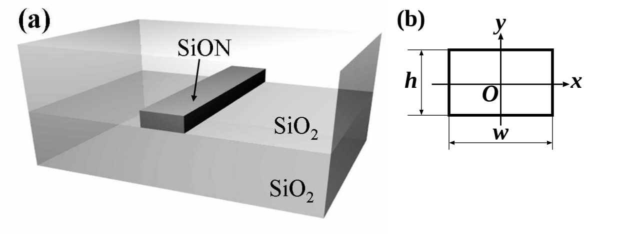

Fig. 1. (a) Schematic view of structure of SiON channel WG with rectangular cross-section embedded in SiO_2 cladding layer. (b) A cross-section of the optical waveguide with two mirror symmetry planes ($x = 0$ and $y = 0$). These symmetries prevent two different-parity modes under a symmetry operation from coupling in this WG.

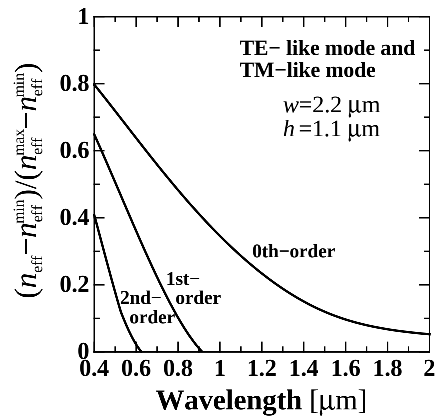

Fig. 2. Typical dispersion relation for TE-like and TM-like modes obtained by using PWE method, where only 0th-, 1st-, and 2nd-order modes are plotted. There is no visible difference between two polarization modes shown in this figure.

The single-mode condition (SMC) can be obtained from the maximum wavelength of the 1st-order mode or the wavelength with $n_{\rm eff} = n_{\rm eff}^{\rm min}$ of it, where Nth-order mode means that the main field components (E_x and H_y for the TE-like mode and E_y and H_x for the TM-like

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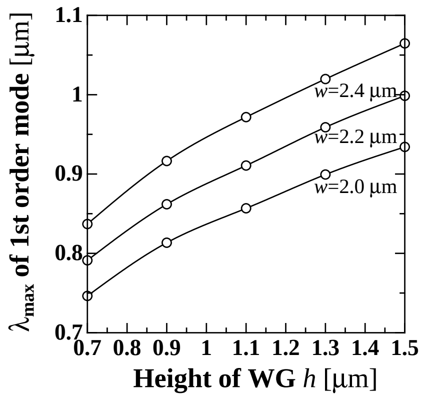

Fig. 3. Core-shape dependence of SMC on height and width of WG. The wavelength, $\lambda_{\max}$, (in the SMC $\lambda > \lambda_{\max}$), can be derived from the dispersion relations in Fig. 2 and by examining the EM field distribution of the eigen modes.

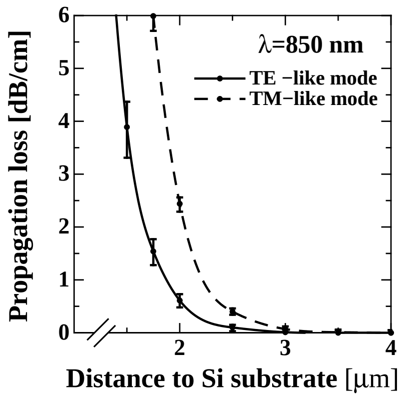

Fig. 4. Propagation loss as function of distance between Si substrate and base of WG core.

mode) have N nodes along the x-direction. Therefore, the SMCs, as a function of the height (h) and the width (w) of the WG core, are identified from the dispersion relation and the spatial distribution of the EM field of the modes, which is plotted in Fig. 3. Accordingly, we can identify the suitable form (the width and the height) of the channel WG for the desired operation wavelength.

2.2 Effect of Substrate on Propagation Loss

It is necessary to determine the sufficient thickness of the cladding layer to prevent the propagation loss due to the substrate upon which the WG (shown in Fig. 1(a)) is usually fabricated. The propagation loss of the fundamental propagation modes was calculated by using the three-dimensional finite difference time domain (FDTD) method, which is especially useful for determining what effect a substrate has on propagation loss.

Figure 4 shows propagation loss as a function of the distance between the base of the WG and the substrate. We assume that a wavelength of the EM field is 850 nm and that the refractive index of the Si substrate is $n = 3.4{+}i0.005$, so the Si substrate works as a high-index attractor, a reflector, and an absorber for the propagating EM field. The other structural parameters of the WG is the same as the dispersion relation calculation shown in Fig. 2.

The numerically calculated results show that a distance of more than 3.5 μm is needed to achieve a propagation loss less than 0.1 dB/cm (taking into account the error-bar) for both the TM- and TE-like modes. The error-bar comes from the time-dependent fluctuation of the cyclic averaged EM energy flow around the WG core.

The amount of error decreases with larger calculation volumes, but the error-bar of the TE-like mode is larger than that for the TM-like mode because of the interference between the propagation field and the polarization-dependent reflected field from the surface of the substrate. Therefore, in practical experiments, an insufficiently thick lower cladding layer causes fluctuation of the propagating EM field in addition to propagation loss. Moreover, the propagation loss for the TE-like mode is less than that for the TM-like mode. This can be explained by the Fresnel formula, *i.e.*, the reflectance of the TM (p-polarized) mode at an interface between two semi-infinite media is lower than that of the TE (s-polarized) mode under an inclined incidence angle.

All the results show that the designed WG is suitable as a low-loss optical WG operating around a wavelength of 800 nm.

3. Conclusion

We designed and investigated the properties of the SiON/SiO_2 optical WG, based on the theoretical analysis of the channel WG by using the PWE and FDTD methods, for an on-chip optical interconnection operating around a wavelength of 800 nm. The numerical simulations of the dispersion relations and the propagation loss calculations of the WG show that the designed WG can be used as a practical WG on an Si substrate[7] to achieve a low-loss interconnection on a chip. A sufficiently thick lower cladding layer on a substrate is needed to obtain lower propagation loss and lower fluctuation of the WG mode.

Acknowledgments

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