Design and Characterization of Dispersion-Tailored Silicon Strip Waveguides toward Wideband Wavelength Conversion

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SUMMARY One of cost-effective ways to increase the transmission capacity of current standard wavelength division multiplexing (WDM) transmission systems is to use a wavelength band other than the C-band to transmit in multi-band. We proposed the concept of multi-band system using wavelength conversion, which can simultaneously process signals over a wide wavelength range. All-optical wavelength conversion could be used to convert C-band WDM signals into other bands in a highly nonlinear fiber (HNLF) by four-wave mixing and allow to simultaneously transmit multiple WDM signals including other than the C-band, with only C-band transceivers. Wavelength conversion has been reported for various nonlinear waveguide materials other than HNLF. In such nonlinear materials, we noticed the possibility of wideband transmission by dispersion-tailored silicon-on-insulator (SOI) waveguides. Based on the CMOS process has high accuracy, it is expected that the chromatic dispersion fluctuation could be reduced in mass production. As a first step in the investigation of the broadness of wavelength conversion using SOI-based waveguides, we designed and fabricated dispersion-tailored 12 strip waveguides provided with an edge coupler at both ends. Each of the 12 waveguides having different widths and lengths and is connected to fibers via lensed fibers or by lenses. In order to characterize each waveguide, the pump-probe experimental setup was constructed using a tunable light source as pump and an unmodulated 96-ch C-band WDM test signal. Using this setup, we evaluate insertion loss, input power dependence, conversion bandwidth and conversion efficiency. We confirmed C-band test signal was converted to the S-band and the L-band using the same silicon waveguide with 3 dB conversion bandwidth over 100 nm. Furthermore, an increased design tolerance of at least 90 nm was confirmed for C-to-S conversion by shortening the waveguide length. It is confirmed that the wavelength converters using the nonlinear waveguide has sufficiently wide conversion bandwidth to enhance the multi-band WDM transmission system.

key words: optical fiber communication, optical wavelength conversion, nonlinear optics

1. Introduction

With the advent of the full-fledged 5G era, communication traffic is expected to continue to increase [1]. In optical communications networks, the transmission capacity per optical fiber is expanding rapidly due to the increasing multiplexing, signal density and multi-leveling [2]. It is desirable to economically realize a further demand in capacity. One option where new fiber could not be added easily is the simultaneous use of today’s standard wavelength division multiplexing (WDM) transmission systems, centered on the C-band (1530-1565 nm), in multiple wavelength bands of short and long wavelengths called S-band (1460-1520 nm) and L-band (1570-1620 nm). However, transmitter and receiver equipment in the wavelength band other than the C-band is not as mature as the C-band. This may increase the investment burden on network operators. As a solution to this problem, we proposed the concept of using wavelength conversion, which is one of all-optical signal processing techniques that can process signals simultaneously over a wide wavelength range (see Fig. 1). All optical wavelength conversion can be used for both the conversion from the transmission signal generated in the C-band to the target band by specifying a specific target band and the conversion from the target band to the signal received in the C-band. Therefore, only the C-band transceiver can simultaneously transmit a plurality of WDM signals in a wavelength band other than the C-band. As a proof-of-concept, we previously reported transmission experiments of WDM signals in a triple-band configuration (S + C + L band) using C-band transceivers and wavelength converter based on highly nonlinear fiber (HNLF) [3]. By using such a system concept, it is expected that the transmission capacity of the existing system can be easily and inexpensively expanded. Wavelength conversion has been reported for waveguide materials other than HNLF, such as silicon-on-insulator (SOI) [4-7], silicon nitride [8,9], AlGaaS [10], and periodically poled lithium niobate (PPLN) [11,12]. In such nonlinear waveguides, we focused on the possibility of wideband transmission in dispersion-tailoring by SOI-based waveguides. Because of the large refractive index contrast, the light is tightly confined in a waveguide

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Fig. 1 Schematic diagram of proposed multi-band system using wavelength conversion.

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with a much smaller effective area than a single-mode fiber, resulting in a higher optical power density. Thus, a high nonlinear effect is realized within a shorter interaction length, and a device in which signal processing constituent blocks are densely integrated becomes possible. Moreover, since the waveguide manufacturing process using the SOI wafer based on the CMOS process has overwhelmingly high accuracy, it is expected that the chromatic dispersion fluctuation in-plane wafer and between wafers can be reduced in mass production.

In this paper, we design and fabricate SOI-based strip waveguides which converts the whole C-band signals to an other band, and we evaluate the wideband characteristics of the wavelength conversion. In section 2, the design of waveguides and the layout of chips are summarized with consideration of chromatic dispersion affecting the conversion bandwidth, with the S-band as the first target of the wavelength conversion destination. Section 3 describes the setup of the experimental system and discusses the experimental results of linear and nonlinear characteristics evaluation and wavelength conversion characteristics in the fabricated waveguide. In addition, we confirmed that a single dispersion-tailored waveguide can convert the WDM signal across the C-band into both S-band and L-band by changing the pump wavelength. The conclusions are drawn in section 4. Our fabricated chip has multiple waveguides with different lengths and widths. The results of evaluating the wideband characteristics of a specific waveguide have been reported in reference [13], but all fabricated waveguides are evaluated in this paper.

2. Design of Silicon-based Waveguides for Wideband Wavelength Conversion

In this paper, we use four-wave mixing (FWM) with a degenerate pump wave in the spectral gap between the original and converted bands. Efficient FWM process requires minimal phase-mismatch of the four interacting waves. Phase-mismatch \( \Delta k \) is given by [6],

\[
\Delta k = 2\gamma P_p - \Delta k_L
\]  

(1)

where \( \gamma \) is the nonlinear coefficient, \( P_p \) the pump power, \( \Delta k_L = 2k_p - k_s - k_i \) is the linear phase-mismatch, and \( k_p, k_s, \) and \( k_i \) are the pump, signal, and idler propagation constants. Including the effects of dispersion up to fourth-order, \( \Delta k_L \) is approximately given by,

\[
\Delta k_L = \beta_2 (\Delta \omega)^2 - \frac{1}{12} \beta_4 (\Delta \omega)^4
\]  

(2)

where \( \beta_2 \) is the GVD parameter at the pump wavelength, \( \beta_i \) is the fourth-order dispersion parameter at the pump wavelength, and \( \Delta \omega \) is the frequency difference between the pump and signal. Only the even-order dispersion terms play a role in the phase-mismatch due to the symmetry of the FWM process. A commonly used GVD parameter \( D \) is related to \( \beta_2 \) by \( D = -2\pi c \beta_2 / 2 \). As presented in [14], neglecting two photon absorption (TPA), free carrier absorption and linear loss, the formula for the external conversion efficiency \( \eta_1 \) is given by,

\[
\eta_1 = \frac{P_{\text{out}}^{\text{idler}}}{P_{\text{in}}^{\text{signal}}} = \left[ \gamma P_p \sinh(gL) \right]^2
\]  

(3)

where

\[
g = \left[ \gamma P_p \Delta k_L - \left( \frac{\Delta k_L}{2} \right)^2 \right]^{1/2}
\]  

(4)

is the parametric gain parameter, \( P_p \) is the pump power, \( P_{\text{out}}^{\text{idler}} \) is the output power in the idler wave, \( P_{\text{in}}^{\text{signal}} \) is the input power of the signal wave, and \( L \) is the interaction length. The conversion bandwidth (BW) can be estimated as the bandwidth for which \( |\Delta k_i| < \pi \). In the small-gain limit, \( 2\gamma P_p L \ll \pi \), this bandwidth is independent of the pump power, and including solely the effects of GVD, BW is approximately given by [6],

\[
\text{BW} \approx \frac{4\pi}{\beta_2 L}
\]  

(5)

In practice, since the propagation loss of the Si waveguide is not as small as about 1 to 2 dB/cm [15], the output power and conversion efficiency do not completely agree with the equation, but the wavelength dependence can be described from Eqs. (2) - (5). BW is inversely proportional to the square root of the product of \( \beta_2 \) and \( L \). Figure 2 (a) shows a result of calculating the wavelength dependence of \( \eta_1 \) derived from the equation (3) using values of a plurality of chromatic dispersions. For the parameters used in the calculation, pump wavelength was 1525 nm, \( P_p \) was 15 dBm, \( \gamma \) was 200/W/m, and \( L \) was 4 cm. It is assumed that there is no loss in the calculation. It was confirmed that the conversion bandwidth became wider as the absolute value of the chromatic dispersion approached 0. In our already proposed multi-band system, in order to convert the entire C-band to other bands, it is required that a bandwidth of over
80 nm on both sides including the pump, signal, and idler. Therefore, in order to satisfy this requirement, it is desirable to be within a range of ± 0.1 ps/nm/m from Fig. 2 (a).

Next, we describe the design of the waveguide. The chromatic dispersion is determined by the material dispersion and the structural dispersion of the waveguide. Since the material dispersion has a specific value, the control of the structural dispersion was examined first. There are two candidate waveguide structures, a rib waveguide and a strip waveguide. In many fabs, the thickness of the Si layer of SOI is nominally 220 nm and the thickness, including slab height, is typically not a free parameter. Therefore, this study was conducted on the assumption that the waveguide thickness was 220 ± 10 nm and waveguide width can be changed as a free parameter. On the other hand, in a silicon waveguide, it is known that free carrier absorption occurs by two-photon absorption [7, 16]. In above two candidates, this effect can be minimized by supplying a reverse bias voltage to the p-i-n junction formed only in the rib waveguide to extract carriers. However, in a 220 nm-thick rib waveguide, it has been reported that the chromatic dispersion does not exceed 0 near both ends of the C-band [7]. Therefore, by limiting the candidate to the strip waveguide, the relationship between wavelength dependence of the chromatic dispersion and width of the waveguide was investigated by the calculation. The calculation is performed using the Lumerical MODE, and detailed conditions are described in ref. [17]. The calculation result is shown in Fig. 2(b). The conversion from the C-band to the S-band, with a pump wavelength in the range of 1515 nm to 1527 nm, was envisaged as a first target. Therefore, from Fig. 2(b), it was found that the optimum width in the C-to-S conversion was around 570 nm.

Figures 3 (a) and 3 (b) show a prototype chip layout and waveguide design. There are two types of fiber-to-chip interfaces, grating coupler and edge coupler, but it is preferable to have a wider coupling bandwidth for our proposed multi-band system. Since the coupling bandwidth of the edge coupler exceeds 100-nm and is wider than that of a grating coupler [18], we used an edge coupler as a fiber-to-chip interface. The edge coupler is an adiabatic spot size converter as standard block of fab and is connected nonlinear waveguide with an inner taper (see Fig. 3 (c)). As a first step of verification from the viewpoint of wavelength dispersion and bandwidth, it was decided to design a plurality of types of waveguides including a strip waveguide with a width of 570 nm, assuming a dispersion shift due to fluctuation of the waveguide cross-sectional structure in the manufacturing process. Table 1 shows the design parameters of our fabricated 12 waveguides. The cross-sectional view of the waveguide WG # 3 is shown in Fig. 3 (d) as an inset in Fig. 3 (b). The waveguide width $W$ is set in 10 types between 390 nm and 595 nm. As described above the waveguide thickness $H$ are not a design parameter. The bend radius of the waveguide was 40 μm, and the length was made to be 2 types of 42 mm and 9 mm, and the waveguide of 42 mm length constituted the spiral structure in the chip.

3. Insertion Loss and Wideband Characteristics of Wavelength Conversion from C-Band to Other Bands

In Section 2, the chip with multiple waveguide widths was designed from the viewpoint of the wideband property of the wavelength conversion. On the other hand, in the multi-band system using our already proposed, the optical power of the converted idler is also an important index. In order to clarify the characteristics of the fabricated waveguide from the above two viewpoints, the insertion loss characteristics and the wavelength conversion characteristics were evaluated.

![Fig. 3 Schematic diagram of (a) chip layout, (b) waveguide design, (c) edge coupler, and (d) cross-section view](image-url)
Our experimental setup is shown in Fig. 4, comprising two types of wavelength converters by FWM (C-to-S and C-to-L conversion) using the fabricated waveguide. For the WDM test signal, a C-band amplified spontaneous emission (ASE) light source and a C-band wavelength selective switch (WSS) are used to generate an unmodulated 96-ch WDM test signal at 50 GHz intervals in the frequency range from 191.35 to 196.10 THz (wavelength range from 1528.77 to 1566.72 nm). An integrable tunable laser assembly (ITLA) in the wavelength range from 1515 nm to 1575 nm was used as the pump light. The wavelength conversion in both directions is confirmed by setting the pump wavelength outside the signal wavelength range. Since there is no optical amplifier that covers the entire operating wavelength range of ITLA, it was decided to switch Erbium-doped or Thulium-doped fiber amplifier (EDFA/T DFA) according to the wavelength range and to ITLA. The 96-ch WDM test signal amplified by an EDFA is combined with the pump light using a 10 dB coupler. The combined signal and pump light are tapped by a 20 dB coupler in front of the waveguide. The optical output from the waveguide is split by a 10 dB coupler, with 90% of the light connected to a power meter (PM) to check for the insertion loss. The other 10% of light split by a 10 dB coupler is connected to an Optical Spectrum Analyzer (OSA) to check the spectrum. Since the dynamic range of the OSA is limited by the high pump power and the noise near the idler cannot be accurately measured, a bandpass filter (BPF) is placed in front of the OSA to remove pump light.

First, the insertion loss of each waveguide of five chips was measured by ITLA at 1530 nm wavelength, and the results were summarized in Figure 5. Figure 5 (a) shows the waveguide saturation of WG #4 (570 nm width). In the low-power regime, the linear slope corresponds to an insertion loss of about 13 dB. At higher powers, a clear saturation of the output at about 1 dBm is visible, which corresponds to input powers of around +15 dBm. Figure 5 (b) shows the insertion loss measured at about +10 dBm input power with respect to the width for 10 waveguides of #3 to #12 having a length of 42 mm. In Fig. 5 (b), the plot shows the average of five chips, and the error bar on the vertical axis shows the standard error. From Fig. 5(b), the insertion loss increases as the width becomes narrower than 450 nm and the insertion loss stays between 12 dB and 13 dB when the width is over 450 nm. The variation in insertion loss is also large with under 450 nm width, but is stable with over 450 nm width. Although not shown, in a 9 mm long waveguide, the insertion loss of WG #1 (540 nm width) was 6.2 dB to 6.4 dB for 5 chips and the insertion loss of WG #2 (450 nm width) was 5.6 dB to 6.5 dB. Based on these results, the propagation loss per unit length was calculated from the difference between the insertion losses at two different lengths, and they are 1.8 dB/cm for 540 nm width and 2.2 dB/cm for 450 nm width. Using the propagation loss per unit length, the coupling loss excluding the propagation loss of the waveguide from the insertion loss was calculated to be 2.6 dB/coupler at 540 nm width and 2.4 dB/coupler at 450 nm width. The 450 nm width waveguides are the technology defaults and act as a reference. It was confirmed that the coupling loss was almost equivalent, and the propagation loss was large in comparison to the reference specification. In the case of a length of 9 mm, since there was no difference in insertion loss depending on the waveguide width, it is considered that the excessive loss such as the influence of waveguide sidewalls caused by increasing the waveguide length is a factor.
Next, the wavelength conversion characteristics of the waveguide in the chip were evaluated in the experimental system of Fig. 4. In this experiment, the wavelength of the pump light was set to 1527.00 nm for the C-to-S conversion and 1570.00 nm for the C-to-L conversion, respectively. The intensity of the pump light was kept at +15 dBm and that of the total signal light was kept at +6 dBm. In the WG # 12 waveguide, no converted signal was observed in the S-band under this condition. Figures 6 (a) and 6 (b) show the output spectra in the 9 waveguides from WG # 3 to WG # 11 in which the unmodulated 96-ch C-band WDM signal was converted into both S-band and L-band. Further, in order to easily compare the bandwidth of the converted signals in each waveguide, the intensity of the converted light was offset, and 10 dB/div was set as a standard of the vertical axis. In the C-to-S conversion shown in Fig.6 (a), a nearly flat converted S-band spectrum was obtained at WG #3 (595 nm width) and WG #4 (570 nm width). Here, “flat” means that the difference between the output of the longer wavelength side and the shorter wavelength side of the converted signal into the S-band is within about 3 dB. The conversion bandwidth narrowed from WG # 5 (555 nm width) to WG # 9 (525 nm width), and it widened again at WG # 10 (450 nm width). In WG # 11 (410 nm width), only a part of 96-ch signal could be confirmed to be converted. From the results of the conversion bandwidth of WG # 3 and WG # 4, the zero-dispersion wavelength at 1527 nm is expected to be in the width range of around 570 to 595 nm. According to the result of the C-to-L conversion shown in Fig. 6 (b), the output power converted to the L-band greatly decreased toward the longer wavelength side. In addition, the conversion bandwidth tends to become narrower as the waveguide width becomes narrower than that of WG # 3. From the result of Fig. 6(a), some ripples of about 3 dB at maximum were observed in the converted idler of the S-band from WG # 3 to WG # 7 (540 nm width) and the wavelength dependence of the ripple was not observed. On the other hand, no ripple was observed in the L-band from Fig. 6 (b). The ripple is considered due to the excitation of higher order modes caused at the bending points.

Figure 6 (c) shows the internal conversion efficiency $\eta_2$ of each channel of the WDM signals in C-to-S conversion and C-to-L conversion based on the converted wavelength pumped wavelength is set at 1523.00 nm for C-to-S conversion and 1570.80 nm for C-to-L conversion. We define $\eta_2$ as the ratio of the idler power to the signal power at the output of the waveguide. As shown in Fig. 6 (c), the maximum $\eta_2$ in S-band was -22.8 dB, and $\eta_2$ of most channels were in the range within 3 dB. In addition, the maximum $\eta_2$ in L-band was -25.5 dB, and the 3 dB conversion bandwidth is in the range of 15 nm from 1575 to 1590 nm. It is considered that the phase match in FWM process in L-band is not as optimal as in S-band. It was confirmed that wavelength conversion was possible in the wide range of 3 dB conversion bandwidth of 1480 to 1590 nm in the fabricated waveguide this time.

Finally, from the viewpoint of the optical power of converted signal in the C-to-S conversion, two types of comparison studies with different waveguide lengths were performed. Figures 7 (a), 7 (b), and 7 (c) show output spectra of converted signal and $\eta_2$ of WG # 1, WG # 2, and WG # 4, respectively. In this experiment, the pump wavelength was set to be 1519 nm for the comparative examination in the wider bandwidth. The left vertical axis of each graph indicates the optical power of the converted light, and the right vertical axis indicates the internal conversion efficiency $\eta_2$. Comparing Fig. 7 (b) and 7 (c), it was confirmed that the optical output of the converted signal was 5 dB higher in WG # 2 with a shorter waveguide length than in WG # 4. $\eta_2$ of WG # 2 is 4 dB to 5 dB lower than that of WG # 4, but the insertion loss of WG # 2 is about 7 dB lower than that of WG # 4 from Fig. 5 (b). Comparing Fig. 7 (a) and Fig. 6 (a), it was confirmed that the conversion bandwidth of WG # 1 was wider than that of WG # 7 having the same waveguide width of 540 nm. This is considered to be an effect of decreasing the accumulated dispersion and
the amount of phase mismatch by shortening the waveguide length. In addition, comparing Fig. 7 (a) and 7 (b), it was confirmed that WG # 1 and WG # 2 showed similar conversion bandwidth. Although it was necessary to confirm between 450 nm width and 540 nm width and waveguide width over 540 nm width, it was suggested that the design tolerance could be improved. On the other hand, the ripple observed in the S-band of Fig. 6 (a) was not observed in the WG # 1 shown in Fig. 7 (a) and WG # 2 shown in Fig. 7 (b) except for one point. It was confirmed that the ripple of about 2 dB observed in WG # 7 of 42 mm length shown in Fig. 6 (a) was suppressed to about 1 dB in WG # 1 shown in Fig. 7 (a) of the same waveguide width. From the layout of the present waveguide shown in Fig. 3 (b), it is considered that the ripple is suppressed by reducing the number of bends and shortening the length. Ripples around 1475 nm were observed in all WG # 1, WG # 2 and WG # 4. It is presumed that this ripple is not inherent to the waveguide and is caused by the influence of common components attached to the waveguide such as edge couplers.

In the future, it will be necessary to improve the conversion efficiency while securing this conversion bandwidth by optimizing the waveguide length. The transmission experiments by one C-to-S wavelength conversion using our fabricated chip have been reported in [17,19], but at least two wavelength converters are required for transmission experiments our proposed multi-band system shown in Fig. 1. We plan to verify the transmission performance once the wavelength converters are completed.

4. Conclusion

As a first step in investigating the feasibility of silicon waveguides for our proposed multi-band WDM transmission system using all-optical wavelength conversion, we designed and fabricated dispersion-tailored silicon-on-insulator based strip waveguides which converts the whole C-band signals to an other band and we evaluated the wideband characteristics of wavelength conversion in this paper. An unmodulated 96-ch C-band WDM test signal was converted to the S-band and the L-band using the same silicon waveguide in 570 nm width and 42 mm length with 3 dB conversion bandwidth over 100 nm. As one of the requirements for our system, the conversion bandwidth of at least 80 nm including the whole C-band is necessary, and it was clarified that this conversion bandwidth can be realized by controlling waveguide width. Furthermore, from the comparison result of the conversion bandwidth for two kinds of waveguide lengths in the same 540 nm width, it was clarified that the conversion bandwidth was expanded by shortening the waveguide length. This suggests that the design tolerance of the waveguide width can be improved by optimizing the waveguide length. It was also confirmed that the ripple of the converted signal in S-band was suppressed by reducing the number of bends and shortening the waveguide length. It is confirmed that the wavelength converters using the nonlinear waveguide has sufficiently wide conversion bandwidth to enhance the multi-band WDM transmission system.

References

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