Four-wave mixing in silicon wire waveguides

Hiroshi Fukuda, Koji Yamada, Tetsufumi Shoji, Mitsutoshi Takahashi, Tai Tsuchizawa, Toshifumi Watanabe, Jun-ichi Takahashi, and Sei-ichi Itabashi

NTT Microsystem Integration Laboratories, 3-1, Morinosato-Wakamiya, Atsugi-Shi, Kanagawa, Japan
hfukuda@aecl.ntt.co.jp

Abstract: We report the observation of four-wave mixing phenomenon in a simple silicon wire waveguide at the optical powers normally employed in communications systems. The maximum conversion efficiency is about -35 dB in the case of a 1.58-cm-long silicon wire waveguide. The nonlinear refractive index coefficient is found to be $9 \times 10^{-18}$ m$^2$/W. This value is not negligible for dense wavelength division multiplexing components, because it predicts the possibility of large crosstalk. On the other hand, with longer waveguide lengths with smaller propagation loss, it would be possible to utilize just a simple silicon wire for practical wavelength conversion. We demonstrate the wavelength conversion for data rate of 10-Gbps using a 5.8-cm-long silicon wire. These characteristics are attributed to the extremely small core of silicon wire waveguides.

References and links

1. Introduction

Silicon wire waveguides (WGs) based on the silicon-on-insulator (SOI) structure are promising for high-density integration of optical circuits [1]–[7]. A Si wire WG can achieve strong light confinement due to its high refractive-index contrast. The core size of a Si wire WGs for single-mode propagation is less than a micrometer. Because of such a small core, the power density of a Si wire is higher by a factor of about 1,000 than that of conventional single-mode fiber. Consequently, it is expected that nonlinear optical effects will occur when using a low input power equivalent to that in optical communications. Light propagation with such a high power density can produce a wide variety of nonlinear phenomena [8], including stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), self-phase modulation (SPM), cross-phase modulation (XPM), two-photon absorption (TPA), and four-wave mixing (FWM). In the past few years, all-Si active optical devices have been extensively studied in connection with these nonlinear effects. A variety of different applications have been investigated, such as laser [9]–[12], amplifier [13], [14], modulator [15], [16] and wavelength converter [17].

FWM is potentially detrimental to dense wavelength division multiplexing (DWDM) applications because it can produce crosstalk between different wavelength channels. Therefore, it is important to estimate how large the crosstalk will be when Si wire WGs are applied to DWDM components. From the view point of wavelength conversion, the FWM phenomenon is very important in DWDM networks. The third order nonlinear coefficient of Si crystal is much smaller than that of III-V semiconductor or that of nonlinear optical crystal. However, in the Si wire WG structure, since even a 10-dBm laser can yield a power density of 100 MW/cm², the nonlinear phenomenon is remarkably enhanced, and efficient wavelength conversion may be possible in Si wire WGs.

In this paper, we demonstrate FWM in simple Si wire WGs. We estimate the crosstalk when they are applied to a DWDM component. In addition, we discuss the potential of Si wire WGs for use in nonlinear optical devices.
2. Experiments

2.1. Sample preparation

The cross-sectional structure of the Si wire WG is shown in Fig. 1. The Si wire WGs were fabricated on SOI wafer with a Si top layer on a 3-μm SiO$_2$ layer. The fabricated Si wire WGs were 400-nm wide, 200-nm thick, and 0.35–5.18-cm long. The details of the fabrication are described elsewhere [7]. For efficient coupling between the Si wires and external fiber, we made spot-size converters (SSCs) at the ends of the Si wires [4]. The SSC has a Si reverse taper with an 80-nm wide tip, a 2nd 3-μm-square SiO$_x$N$_y$ core, and a 7-μm-thick SiO$_2$ overcladding.

The propagation loss was measured using the cutback method and found to be 2.4 dB/cm for TE polarization. Coupling losses were 0.5 dB/point for a small-core fiber with a mode-field diameter of 4.3 μm and 3.0 dB/point for a normal single-mode fiber. These low propagation and coupling losses of Si wire WGs enable us to measure small signals ascribed to nonlinear effects.

2.2. Experimental setup and results

First we tried to measure FWM in the Si wire WGs. The experimental setup is shown in Fig. 2. Pump light with frequency $\nu_1$ was amplified by an Erbium-doped fiber amplifier (EDFA), combined with idler light with frequency $\nu_2$, and coupled into the Si wire WG through the SSC. Both lights were adjusted to TE polarization by polarization controllers. The wavelengths of the pump and idler light were 1546.9 nm (193.8 THz) and 1547.7 nm (193.7 THz), respectively, and the pump power was +7 dBm at the entrance of the Si wire.

The input and output spectra for a 1.58-cm-long Si wire WG are shown in Fig. 3. In the output spectrum, two additional peaks appear outside of the input peaks. Since the frequencies of these peaks correspond to $2\nu_1 - \nu_2$ and $2\nu_2 - \nu_1$, we speculate that they are phase-conjugated waves caused by FWM in the Si wire. Conversion efficiency as a function of pump power is shown in Fig. 4. Conversion efficiency is defined as the peak level ratio between $\nu_2$ and $2\nu_1 - \nu_2$ for several pump powers. The fact that the slope of fitted line is nearly 2 in the Log-Log plot...
provides undisputed evidence that the peak of $2\nu_1 - \nu_2$ is caused by FWM. The important point is that this nonlinear effect was produced with just a simple Si wire WG at the optical powers normally employed in communications systems.

![Fig. 3. Input and output spectra for a 1.58-cm-long Si wire WG.](image)

![Fig. 4. Conversion efficiency as a function of pump power. The dots are the measured points and the solid line is a fit.](image)

2.3. Detuning characteristics

Figure 5 shows the detuning characteristics of FWM for Si wire WGs of various lengths. The detuning is defined as the wavelength difference between pump and idler lights. For a short waveguide, the conversion efficiency is low, but the wavelength characteristics are flat over a wide detuning range. In contrast, for a long waveguide, the efficiency is high, but the efficient range is narrow. These characteristics are reflected in the phase mismatch and interaction length. A long waveguide has a long interaction length, but propagation through the waveguide produces a phase mismatch between the pump and idler lights. As a result, the efficient range becomes narrow. When the length of the Si wire is 1.58 cm, the conversion efficiency reaches -34 dB, and when it’s 0.35 cm, the 3-dB-down bandwidth is over 50 nm.

Spectral dips appear near ±17 nm detuning for the 1.58-cm-long sample. These are explained by the coherent length in phase matching [8]. The coherent length $L_{coh}$ is given by

$$L_{coh} = \frac{2\pi}{|\Delta k|}$$

(1)

$$\Delta k = \frac{dn_e (\Delta \omega)^2}{c},$$

(2)
where $\Delta k$ is the maximum wave-vector mismatch that can be tolerated, $n_g$ the group index of WG, $\Delta \omega$ the angular frequency difference between pump and idler light, and $c$ light velocity. For our Si wire WGs, $dn_g/d\omega$ is calculated to be $6.5 \times 10^{-16}$ from numerical simulations performed using the mode-solver. Therefore, $L_{coh}$ is $\sim 1.5$ cm in the case of 17-nm detuning.

Fig. 5. Detuning characteristics of FWM for Si wire WGs.

2.4. Nonlinear refractive index $n_2$

The nonlinear refractive index $n_2$ can be expressed using the CW method [18][19] as

$$n_2 = \frac{A_{eff} c}{2\omega_0 L_{eff} P} \phi,$$

(3)

$$\frac{I_0}{I_1} = \frac{J_0^2(\phi/2) + J_2^2(\phi/2)}{J_1^2(\phi/2) + J_2^2(\phi/2)},$$

(4)

where $A_{eff}$ is the effective area of Si wire WG, $\omega_0$ the angular frequency of light, $L_{eff}$ the effective WG length, $P$ the average power of the idler, $\phi$ the nonlinear phase shift, $J_n(x)$ a $n$th order Bessel function, and $I_0$ and $I_1$ are the intensities of the input and output light. The nonlinear phase shift is a function of $I_1/I_0$ only, which can be readily measured with an optical spectrum analyzer. The effective area $A_{eff}$ is defined [8] by

$$A_{eff} = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |E(x,y)|^2 dx dy)^2}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |E(x,y)|^4 dx dy},$$

(5)

where $E(x,y)$ is the electrical field of the propagation mode. In the Si wire, we have to consider the contribution from only the Si core because the nonlinear effect of Si is much larger than that of the clad materials. We calculated the mode field profile by the mode-solver and calculated $A_{eff}$ to be 0.033 $\mu m^2$.

The measured phase shift for a 0.74-cm-long Si wire WG as a function of pump power is shown in Fig. 6. The detuning was set 100 GHz (0.8 nm), of which the conversion efficiency is flat around the range. One can see that the phase shift varies linearly with pump power. The slope gives a nonlinear refractive index $n_2$ of $9 \times 10^{-18} m^2/W$, which is close to the value of $6 \times 10^{-18} m^2/W$ reported for a Si-rib WG [20].

2.5. Enhancement by a ring resonator

Ring resonators enlarge conversion efficiencies. The effect of a ring resonator is shown in Fig. 7. Here, the ring resonator has a ring with 5-$\mu m$ radius, which provides a free-spectral range
Fig. 6. Nonlinear phase shift for Si wire WGs. The dots are the measured points and the solid line is a fit.

(FSR) of 2.2 THz and a quality factor $Q$ of $\sim 10000$. Because of such high confinement, the intensity in the ring resonator is much larger than that of straight WGs. Pump and idler wavelengths were set to two neighboring resonant wavelengths (1551.60 and 1569.85 nm), and conjugated lights appeared just at the other resonant wavelengths (1533.77 and 1588.53 nm). The filled circles show the conversion efficiency of 1533.77-nm conjugated light for the ring resonator at various idler powers, and the open circle shows that for a simple Si wire with the same path length as the ring resonator. In this experiment, we used an old sample which was made by the conventional fabrication process, and the propagation loss therefore is much larger than the later samples, which was used in the other experiments. Since the propagation loss of the Si wire was large, 18 dB/cm, the conversion efficiency is low. However, we can see an apparent gain in the ring resonator. The efficiency of FWM in the ring resonator is about 8 dB larger than that in the simple Si wire WG. This enhancement occurs because the power density is remarkably enhanced at the resonant frequencies.

Fig. 7. Enhancement by ring resonator.

2.6. Wavelength converter

We demonstrated wavelength conversion for a 10-Gbps data stream using a 5.18-cm-long Si wire. In this experiment, the wavelengths of the pump and idler lights were set to 1552.52 nm (193.1 THz) and 1550.92 nm (193.3 THz), respectively. Therefore, the phase-conjugated light appeared at 1554.12 nm (192.9 THz). The pump light was modulated into 100-ps pulses and amplified to a peak power of $\sim 200$ mW. The transmitted light was filtered to extract the wavelength of the phase-conjugated light. The output spectrum after the filter is shown in Fig.
8, where the right side is an enlarged view of the phase-conjugated spectrum. There are side bands corresponding to the 10-Gbps modulation of signal. The time-domain waveform was measured with an O-E converter and a sampling oscilloscope. The input and output waveforms are shown in Fig. 9. The output waveform contains two components: 100-ps pulse trains converted from the pump signal and an unwanted component that decreases slowly. This slow component reflects the free-carrier absorption generated during TPA.

![Fig. 8. Output spectrum for a 5.8-cm-long Si wire WG. Right: enlarged view of the phase conjugated light.](image1)

![Fig. 9. Waveforms for 100-ps pulse trains. Left: input pump light. Right: converted signal.](image2)

3. Discussion

3.1. Crosstalk in passive components

The extremely small core of Si wires produces the nonlinear optical effect even under low optical power, which should ensure that FWM contributes to crosstalk in passive components including waveguide, coupler and filter. Calculated conversion efficiencies as a function of waveguide length $L$, linear loss $\alpha$, and input power $P_{in}$ are summarized in Fig. 10. The value of $n_2$ is assumed to be $9 \times 10^{-18} \text{m}^2/\text{W}$. According to Eq. (1), $L_{coh}$ is 6.7 cm when $\Delta \nu=1$ THz. If a passive device based on a Si wire has length $L$ of 2 cm ($< L_{coh}$), propagation loss $\alpha$ of 1.0 dB/cm and optical input power $P_{in}$ is 10 mW, the crosstalk reaches -26 dB, which is too large for practical communication devices. Moreover, the crosstalk would increase in the device with a resonator-based add/drop filter because of its high $Q$ factor. Therefore, special care should be taken in designing devices with resonator-based passive components.
3.2. **Potential for wavelength converter**

On the other hand, with longer waveguide lengths with smaller propagation loss, it would be possible to utilize Si wire WGs for wavelength converters. In the case of a simple 5-cm-long Si wire WG, $\alpha = 0.5 \text{ dB/cm}$ and $P_{in}=50 \text{ mW}$, conversion efficiency is calculated to be -4.8 dB for $\Delta \nu = 1 \text{ THz}$. The increase in $P_{in}$ enlarges the conversion efficiency in the calculation.

Here, we consider the influence of SPM and XPM. Nonlinear phase shift $\varphi$ caused by SPM is assisted the phase matching. In the case of $L = 1 \text{ cm}$, $P = 10 \text{ mW}$ and $\alpha = 3 \text{ dB/cm}$, $\varphi$ is calculated to be smaller than 0.1 (rad), and hence the influence to FWM would be very small. However, in the case of $L = 5 \text{ cm}$, $P = 50 \text{ mW}$, and $\alpha = 0.5 \text{ dB/cm}$, $\varphi$ exceeds 2 (rad), so that the value of $L_{coh}$ and the shape of the detuning characteristics (Fig. 5) may change substantially.

Nevertheless an excessively high optical power results in other nonlinear optical phenomena, including SRS, SBS, and TPA. These effects reduce the effective optical power in the waveguides and degrade the waveform. As shown in Fig. 9, the heights of the pulse trains are reduced with time. We consider that this deformation is reflected in the free-carrier-absorption generated during TPA. Pulses with peak power higher than 100 mW increase this effect. The Raman process can also interfere with the FWM process since the generated Stokes line falls near the Raman-gain peak and can be amplified by SRS. Espinola et al. [14] observed stimulated Raman gain of 0.7 dB in Si wire WGs with optical power of 30 mW. FWM would not be affected by this small value. SBS presents a serious problem for fiber. However, the Brillouin scattering coefficient for silicon is much smaller than the Raman coefficient [21]. Therefore, the contribution of SBS would not influence FWM process.

As has been discussed above, several nonlinear effects decrease the optical power in the Si wire, even when high power is launched. Thus, the conversion efficiency would be limited to around -5 dB in practice. This limitation does not depend on the device structure, including the ring resonator. However, the conversion efficiency of -5 dB is as large as that of wavelength converters based on a semiconductor optical amplifier [22]. The Si wire system has great potential for use in nonlinear optical devices. In our experiment for a 10-Gbps data transmission, the modulation was applied to the pump light. However, if the idler light is modulated, the conversion efficiency can be enlarged with CW pump power and would be reached around the limited value, -5 dB.

![Fig. 10. Estimated crosstalk/conversion efficiency caused by FWM in Si wire WGs](image)

4. **Conclusion**

We observed FWM phenomenon in just a simple Si wire WG at the optical powers normally employed in communications systems. The nonlinear refractive index coefficient was found to be $9 \times 10^{-18} \text{ m}^2/\text{W}$. This value is not negligible for DWDM components, because it predicts...
the possibilities of large crosstalk. Attention should be given to this point in designing DWDM devices based on Si wires. On the other hand, with longer waveguide lengths with smaller propagation loss, it would be possible to utilize Si wire WGs for wavelength converters. We demonstrate the wavelength conversion for data rate of 10-Gbps using a 5.8-cm-long silicon wire. These characteristics are attributed to the extremely small core of Si wire WGs.