All-optical Signal-conversion Efficiency with a Parameter-dependent
Four-wave-mixing Process in a Silicon Nanowaveguide

Heung-Sun Jeong, Dong Wook Kim and Kyong Hon Kim*
Department of Physics, Inha University, Incheon 402-751, Korea

Jong-Moo Lee
Electronics & Telecommunications Research Institute (ETRI), Daejeon 305-350, Korea

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We report on experimental measurements of the signal-wavelength conversion efficiency through the four-wave-mixing (FWM) process in a silicon strip nanowaveguide (SiNW) compared with theoretically-calculated results. The conversion efficiency has been investigated as a function of various parameters, such as the pump power and the pump and signal wavelengths. The measured and the calculated results indicate that a significant variation of the chromatic dispersion (CD) of our test SiNW device among the pump, signal and idler beam wavelengths and a high insertion loss in the device cause a very low FWM conversion efficiency. Our simulation tool can provide a direction for further improvement in the waveguide design by providing optimized CD values for the SiNW in desired ranges of the operation wavelengths.

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I. INTRODUCTION

Recently, nonlinear optic effects in silicon nanowaveguide (SiNW) devices have attracted much attention for their potential applications to high-speed all-optical signal processing [1,2]. Because of the relatively high refractive index value ($n = 3.45$) of the silicon material, the dimension of the silicon waveguides can be reduced significantly compared to those of other silica and polymer waveguides. Thus, very tight confinement of the optical beam in the silicon waveguides is possible; thus, efficient nonlinear optic devices can be achieved in a small device size. In addition, silicon waveguide devices are expected to be very useful for photonic integrated circuits (PICs) in future high-speed and high-capacity signal processing. Beside the high refractive index property, silicon also has high nonlinear optic properties. The four-wave-mixing (FWM) process, which is one of the nonlinear optic properties in the SiNW, has been investigated by many researchers for applications to all-optical signal wavelength conversion and high-speed optical switching [3,4].

The wavelength conversion efficiency in the SiNWs via the FWM processing is known to have a strong dependence on the phase-matching condition among the pump, the signal and the generated idler beams [5]. The phase-matching condition is also affected significantly by the chromatic dispersion (CD) profile of the SiNWs at the wavelengths of the beams. Thus, knowledge of the spectral CD profile of the SiNWs, as well as suitable selection of the pump and signal beam wavelengths, is very important for efficient FWM processes.

In this research, we have investigated the signal wavelength-conversion efficiency of a silicon nano-strip waveguide based on the FWM process for changes in various parameters, such as the pump power and the pump and signal wavelengths. The measured experimental results are compared to theoretically-calculated results with the coupled-wave equations for both the FWM process and the phase-matched conditions.

II. THEORETICAL BACKGROUND

1. Four-wave-mixing Process and Coupled Wave Equations

In a degenerated FWM process, the two photon process through an interaction of pump photons with a nonlinear optic material converts the pump-photon energies into signal and idler photons as illustrated in Fig. 1. For
the degenerated FWM processes with pump lightwaves at an angular frequency of \( \omega_p \), signal lightwaves at \( \omega_s \) and idler lightwaves at \( \omega_i \), the low power linear phase-matching condition and the resonant energy conservation condition are given by

\[
\Delta \beta = \beta(\omega_s) + \beta(\omega_i) - 2\beta(\omega_p) = 0, \tag{1}
\]

\[
2\omega_p = \omega_s + \omega_i, \tag{2}
\]

where \( \beta_{s,i,p} = \omega_{s,i,p} n(\omega_{s,i,p})/c \) is the propagation constant of each lightwave, \( c \) is the speed of light in free space and \( \Delta \beta \) is the linear phase mismatch. The coupled wave equations for the pump, signal and idler lightwave powers, \( P_p, P_s, \) and \( P_i \), can be expressed as follows [6–9]:

\[
\frac{dP_p}{dz} = -\alpha P_p - 4\gamma \sqrt{P_p^2 P_s P_i} \sin \theta, \tag{3}
\]

\[
\frac{dP_s}{dz} = -\alpha P_s + 2\gamma \sqrt{P_p^2 P_s P_i} \sin \theta, \tag{4}
\]

\[
\frac{dP_i}{dz} = -\alpha P_i + 2\gamma \sqrt{P_p^2 P_s P_i} \sin \theta, \tag{5}
\]

where \( \gamma = 2\pi n_2/\lambda A_{\text{eff}} \) is the nonlinearity coefficient, \( \lambda \) is the wavelength of light and the three light waves are similar such that the \( \gamma \) are equal. \( A_{\text{eff}} \) is the effective mode area, and \( \alpha \) is the absorption coefficient. \( n_2 \) is the nonlinear refractive index as a function of wavelength [10].

The relative phase difference between the three light waves \( \theta(z) \) is

\[
\theta(z) = \Delta \beta z - 2\phi_p(z) + \phi_s(z) + \phi_i(z), \tag{7}
\]

where \( \phi_p,s,i(z) \) represents the nonlinear phase shift during the propagation including the initial phase at \( z = 0 \). If we expand the propagation constant in a Taylor series about \( \omega_0 = 2\pi c/\lambda_0 \) up to the third-order in \( (\omega - \omega_0) \), it can be written as

\[
\beta(\omega) = \beta(\omega_0) + (\omega - \omega_0) \left[ \frac{d\beta(\omega)}{d\omega} \right]_{\omega=\omega_0} + \frac{1}{2} (\omega - \omega_0)^2 \left[ \frac{d^2 \beta(\omega)}{d\omega^2} \right]_{\omega=\omega_0} + \frac{1}{6} (\omega - \omega_0)^3 \left[ \frac{d^3 \beta(\omega)}{d\omega^3} \right]_{\omega=\omega_0}
\]

\[
= \frac{\omega_0}{v_p(\lambda_0)} + \frac{\omega - \omega_0}{v_s(\lambda_0)} = \frac{\lambda_0^2}{4\pi c} (\omega - \omega_0)^2 D_c(\lambda_0)
\]

\[
+ \frac{\lambda_0^2}{24\pi^2 c^2} (\omega - \omega_0)^3 \left[ 2 \lambda_0 D_c(\lambda_0) + \lambda_0^2 \left[ \frac{dD_c(\lambda)}{d\lambda} \right]_{\lambda=\lambda_0} \right] + \frac{2\pi f_0}{v_p(\lambda_0)} + \frac{2\pi (f - f_0)}{v_s(\lambda_0)} + \frac{\pi \lambda_0^2}{3c^2} (f - f_0)^2 D_c(\lambda_0)
\]

\[
+ \frac{\pi \lambda_0^2}{3c^2} (f - f_0)^3 \left[ \frac{dD_c(\lambda)}{d\lambda} \right]_{\lambda=\lambda_0}, \tag{8}
\]

where \( v_p(\lambda_0) = c/n(\lambda_0) \) and \( v_s(\lambda_0) = c/n(\lambda_0) \) are the phase and the group velocities of the lightwave at the wavelength \( \lambda_0 \) in the waveguide, respectively. \( D_c(\lambda_0) \) is the chromatic dispersion of the waveguide at the wavelength \( \lambda_0 \).

\[
D_c(\lambda_0) = -\frac{2\pi c}{\lambda_0^3} \left[ \frac{d^2 \beta}{d\omega^2} \right]_{\omega=\omega_0}, \tag{9}
\]

and \( dD_c(\lambda)/d\lambda \) is the dispersion slope. From Eqs. (1) and (8), the linear phase mismatch \( \Delta \beta \) can be rewritten as