High-Repetition-Rate Pulsed-Pump Optical Parametric Amplification in Silicon Waveguides

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Abstract: The net parametric gain evolution inside the silicon waveguides for high speed optical communications is investigated. Pulsed-pump parametric amplification can be a chip-scale solution for high bit rate DWDM systems with pulse width <1 ps.

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1. Introduction

Silicon photonics becomes a rapidly growing field because of its possible dense on-chip integration with microelectronics and significant advances in nonlinear effects. Due to the high-index contrast between the silicon core and silica cladding, the silicon waveguide allows strong optical confinement and large effective nonlinearity, which facilitates chip scale demonstration of all-optical nonlinear functional devices at low power. Nonlinear silicon photonic functional devices, such as Raman amplification and lasing [1-2], optical modulation [3], wavelength conversion[4-5] etc, have been already demonstrated. In modern optical fiber communication systems, the dense wavelength division multiplexing (DWDM) is adopted to provide high capacity in a single fiber. However, the relatively narrow Raman gain in silicon can only amplify one wavelength channel with one pump.

Optical parametric amplifiers (OPAs) through four-wave-mixing (FWM) are promising amplifiers with multifunctional capabilities because of their large and flexible gain bandwidth. FWM in silicon waveguides has been observed and used for wavelength conversion, but it is not suitable for parametric amplification due to low FWM efficiency operating in normal dispersion regime[4-5]. By tailoring the cross-sectional size and shape of the silicon waveguide, the waveguide geometries that allow anomalous GVD were investigated recently [6], and parametric amplification over 28 nm using pulsed pump with a 75-MHz repetition rate was demonstrated in suitably designed silicon waveguides[7]. To gain further understanding of the OPA in silicon waveguides and especially for its applications in high-speed DWDM optical communications, it is necessary to investigate the amplifier more thoroughly. Here we show that how the net gain evolves inside the silicon waveguides with high-repetition-rate pulsed pump, and conditions for net gain amplifiers considering two-photon absorption(TPA), TPA-induced free-carrier absorption(FCA), free-carrier-induced dispersion and linear loss.

2. Parametric amplification principle

The transmission of the pump A_p, signal A_s and idler A_i field along the silicon waveguide can be presented by the following coupled equations[5]

$$\frac{dA_p}{dz} = -\frac{1}{2}\left[\alpha + \alpha_p^{FCA}(z)\right]A_p + i\left(\gamma_p + i\frac{\beta}{2}\right)\left|A_p\right|^2 A_p, \quad (1)$$

$$\frac{dA_s}{dz} = -\frac{1}{2}\left[\alpha + \alpha_s^{FCA}(z)\right]A_s + 2i\left(\gamma_s + i\frac{\beta}{2}\right)\left|A_p\right|^2 A_s + i\gamma_s A_p^2 A_i^* \exp(-i\Delta k \cdot z), \quad (2)$$

$$\frac{dA_i^*}{dz} = -\frac{1}{2}\left[\alpha + \alpha_i^{FCA}(z)\right]A_i^* - 2i\left(\gamma_i - i\frac{\beta}{2}\right)\left|A_p\right|^2 A_i^* - i\gamma_s A_p^{*2} A_s \exp(i\Delta k \cdot z), \quad (3)$$

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where α is the linear loss, β is the TPA coefficient, $\gamma_j = n_2\omega_p/c$ with nonlinear refractive index $n_2 = 4.5\times10^4$ cm^2/W is the nonlinear coefficient(j=p,s,i). The TPA-induced FCA loss $\alpha_i^{FCA}(z) = 1.45\times10(\lambda_j/1550)^2 N$, where λ_j is the wavelength (nm), N is carrier density generated by TPA. For pulsed pump $I(t,0)=I_0\exp(-4\ln2 t^2/T_0^2)$, N is given by

$$\frac{dN(t,z)}{dt} = \frac{\beta}{2h\nu} I^2(t,z) - \frac{N(t,z)}{\tau} \tag{4}$$

where I_0 is peak intensity , T_0 is the pulse width, $h\nu$ is the one-photon energy and τ is the carrier lifetime. The FWM efficiency depend on how well the phase mismatch Δk meets the phase-matching condition:

$$\Delta k = k_s + k_i - 2k_p + 2\gamma P_p = (n_s\omega_s + n_i\omega_i - 2n_i\omega_i)/c + 2\gamma P_p = 0 \tag{5}$$

where P_p is pump power. The TPA-induced free carrier dispersion may influence the phase-matching condition by refractive index $\Delta n = -8.2\times10^{-16}\lambda_j^2 N$. From Eq.(5), the phase matching is most easily met when the pump wavelength has anomalous GVD and close the zero dispersion wavelength. When the repetition rate of the pulsed pump is low and the pulse width is short, the TPA-induced free carrier dispersion can be neglected. However, with increasing the repetition rate and the pulse width, it should be considered.

Based on the above theoretical model, we calculate the parametric gain with the experimental parameters in references[6-7], and compare the theoretical results with experimental results as given in Fig.1. We can see that they agree well.

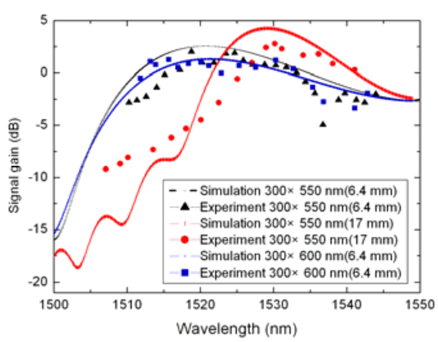

Fig.1 Parametric gain as a function of signal wavelength

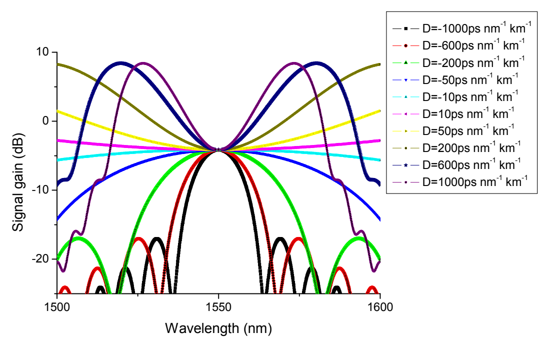

Fig.2 Parametric gain profiles at different dispersion value

3.Analysis and Discussion

To achieve large gain in parametric amplification, the pump wavelength should be operating in anomalous GVD regime. To demonstrated this, the 1.5 ps wide pump pulses centered at 1550 nm with a10 GHz repetition rate and 2.5 W peak power are used to investigated parametric gain at different dispersion value in a 1 cm silicon waveguide with effective area of 0.11 μm^2, and the results are given in Fig2. We can see that net gain can only be achieved within limited bandwidth in the anomalous GVD regimes.

Pump power is an important factor for parametric amplification because TPA and FCA are both intensity-dependent. The parametric gain profiles of 10 Gb/s at different peak pump power in a 1 cm silicon waveguide with dispersion of 600 ps/km/nm are shown in Fig.3. The results clearly indicate that high peak power doesn't mean large gain due to presence of TPA and FCA losses.

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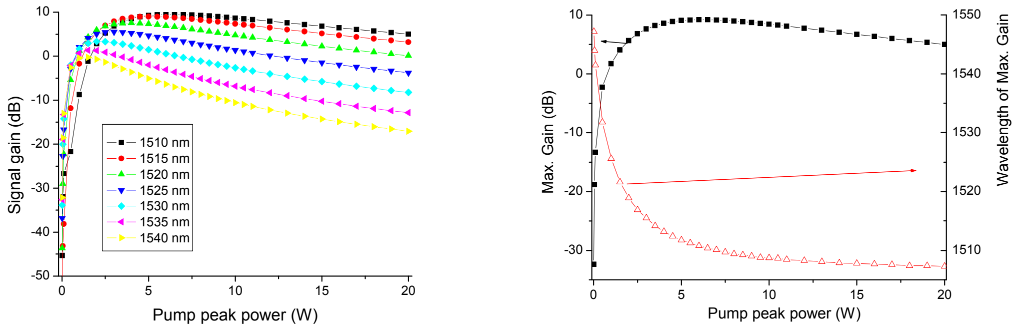

Fig.3(a) Parametric gain at different wavelength vs. peak pump power. Fig.3(b) Max. gain and corresponding wavelength vs. peak pump power.

The repetition rate and more important pump pulse width have significant impact on parametric gain by influencing free carrier density. Using pump pulses with peak power of 2.5 W in the same waveguide as the above, parametric gain profiles at different pulse width and repetition rate are shown in Fig.4. Fig.4(a) shows the gain profiles with pulse repetition rate of 10GHz. Fig.4(b) shows that we can achieve net gain even the pump pulse repetition rate reaches 80 GHz with 0.5 ps pump pulses.

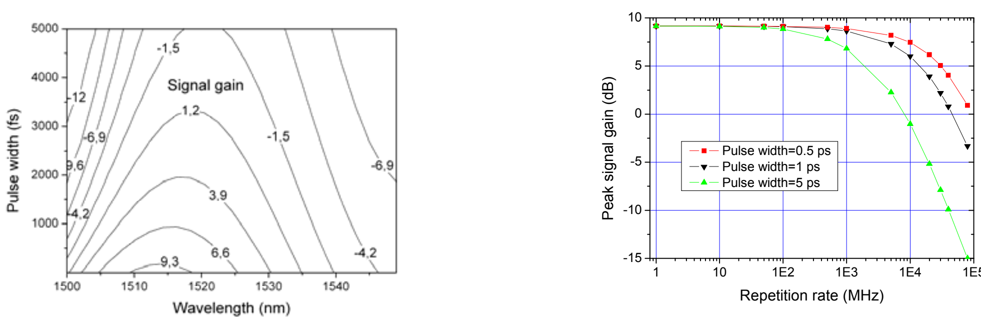

Fig.4(a) Parametric gain contour vs. pulse width and wavelength   Fig.4(b) Peak parametric gain vs. pump pulse repetition rate

4.Conclusion

The parameters of pulsed pump are important factors to generate broadband and large gain in silicon waveguide operating in anomalous GVD regime by four-wave mixing. Our investigation shows that net gain amplification can be only achievable with short pulse pump scheme operating in anomalous GVD regime due to phase matching condition, TPA and FCA losses. Parametric amplification can be a chip-scale solution in the high speed DWDM optical communication and optical signal processing systems.

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