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Influence of the structure parameters on the gain and noise figure in silicon parametric amplifiers based on SOI Rib waveguides

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ABSTRACT

Gain and Noise figure (NF) characteristics in dual-pump parametric amplifier based on silicon on insulator (SOI) Rib waveguides are numerically investigated in the presence of nonlinear losses. The impact of structure parameters of the silicon optical parametric amplifiers (SOPAs) on the gain and the NF are also analyzed. The results show that both the height and the width of the silicon on insulator (SOI) can affect the gain and the NF of SOPAs. 354 nm bandwidth (3 dB) and 8.135 maximum gain can be achieved by tailoring the structure parameters of the SOI rib waveguides. Moreover, the dispersion and the effective mode area of SOI are also analyzed.

1. Introduction

Silicon photonics has attracted much attention recently because of its potential for low-cost solutions to optical communications and interconnects. Silicon-on-insulator (SOI) waveguides can provide highly optical nonlinearities because of the large index mismatch between the silicon and SiO_2. This distinguishing property of SOI has been used to realize functionalities such as optical modulation [1,2], Raman amplification and lasing [3–7], wavelength conversion [8–12], pulse compression [13,14], all optical switching [15–17], and optical signal regeneration [18,19] and so on. In despite of the SOPAs is deteriorated by two photon absorption (TPA) and TPA induced free carrier absorption (FCA), net gain and large bandwidth [20] are possible in silicon parametric amplifiers. The structure parameters of SOI can influence the dispersion and the nonlinearity parameter of the SOI [21]. However, the Influence of the structure parameters on the gain and noise figure in dual-pump SOPAs based on SOI rib waveguides is not considered in previous reports.

In this paper, influences of pump power, free-carrier lifetime, pump repetition rate and the structure parameters of the SOI rib waveguides on the gain and the NF characteristics in the dual-pump SOPAs are analyzed. 354 nm bandwidth (3 dB) and 8.13 maximum gains can be achieved by optimum the parameters of the dual-pump SOPAs. Moreover, the influences of other factors on stimulation are also discussed.

2. Nonlinear processes in SOI waveguides

In this section we focus on the non-degenerate four-wave-mixing (FWM) configuration in which dual-pump beams are employed. By combing two strong pump waves at the angular frequencies ω_{p1}, ω_{p2} and a weak signal wave at frequency ω_s into a silicon waveguide, FWM parametric process may occur and an idler wave at frequency ω_i is generated. The evolution process of the pumps A_{p1}, A_{p2}, signal A_s and idler A_i field amplitudes along the silicon waveguide can be described by the following coupled equations [22]:

$$\frac{dA_{p1}}{dz} = \frac{1}{2}\left[\alpha + \alpha_{p1}^{FCA}\right] A_{p1} + i\beta_{01}A_{p1} + i\gamma_e(\left|A_{p1}\right|^2 + 2\left|A_{p2}\right|^2)A_{p1} \quad (1)$$

$$\frac{dA_{p2}}{dz} = -\frac{1}{2}\left[\alpha + \alpha_{p2}^{FCA}\right] A_{p2} + i\beta_{02}A_{p2} + i\gamma_e(\left|A_{p2}\right|^2 + 2\left|A_{p1}\right|^2)A_{p2} \quad (2)$$

$$\frac{dA_s}{dz} = -\frac{1}{2}\left[\alpha + \alpha_s^{FCA}\right] A_s + i\beta_{0s}A_s + i2\gamma_e A_{p1}A_{p2}A_i^* \quad (3)$$

$$\frac{dA_i^*}{dz} = -\frac{1}{2}\left[\alpha + \alpha_i^{FCA}\right] A_i^* - i\beta_{0i}A_i^* - i2\gamma_e A_{p1}^* A_{p2}^* A_s \quad (4)$$

where A_{p1}, A_{p2}, A_s and A_i denote the amplitudes of pump at ω_{p1}, ω_{p2}, ω_s and ω_i. We use the linear loss coefficient $\alpha = 1$ dB/cm

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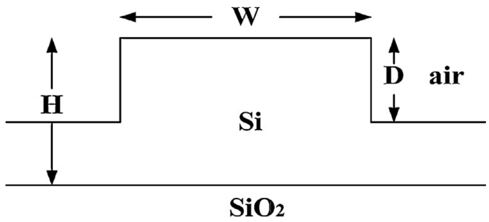

Fig. 1. The cross-section of the SOI rib waveguide.

and β represents the propagation constant. $\gamma_e = \gamma + i\beta_T$ represents the nonlinear parameter where $\beta_T = 0.7$ cm/GW is the TPA coefficient[23,24]. $\alpha_{p1}, \alpha_{p2}, \alpha_s$ and $\alpha_i = 1.45 \times 10^{-45}(\lambda/1550)^2 N_{eh}(z, t)$ accounts for TPA-induced FCA loss where N is the free carrier density which satisfy the rate equation:

$$\frac{\partial N_{eh}}{\partial t} = \frac{\beta_T I_p^2}{2h\upsilon} - \frac{N_{eh}}{\tau_o} \tag{5}$$

where τ_0 represents free carrier life time, and $I_p = \left|A_{p1}\right|^2 + \left|A_{p2}\right|^2$ is the total pump intensity. For CW pump, the steady state solution of Eq. (5) is $N_{eh} = (\tau_o I_p^2/2h\upsilon)$. For pulsed pump whose width $T \ll \tau_0$, the repetition rate R of pulsed pump is an important factor impacting N, the solution is $N_{eh} \approx (\beta_T T I_p^2/2h\upsilon(1 - e^{-1/R\tau_o}))$ [23].

The efficiency of FWM depends on the case of Δk:

$$\Delta k = \Delta\beta_0 + \gamma I_p \tag{6}$$

where $\Delta\beta_0 = \beta_{p1} + \beta_{p2} - \beta_s - \beta_i$ is the linear phase mismatch, related to the waveguide dispersion as [23]:

$$\Delta\beta_0 \approx \beta_{2c}(\omega_{sc}^2 - \omega_d^2) + \frac{1}{2}\beta_{4c}(\omega_{sc}^4 - \omega_d^4) \tag{7}$$

where $\omega_{sc} = \omega_s - \omega_c$, $\omega_c = 1/2(\omega_{p1} + \omega_{p2})$, $\omega_d = 1/2(\omega_{p1} - \omega_{p2})$, β_{2c} and β_{4c} are second and fourth order dispersion parameter at ω_c, respectively.

The noise figure (NF) induced in silicon waveguide can be expressed [24]:

$$NF_{silicon} = \frac{T + N_{loss} + N_{gain}}{T} + \frac{N_{gain}(T + N_{loss})}{|\alpha|^2 T} \tag{8}$$

where $T = \exp(\int_0^L (g(z) - l(z))dz)$ is the net gain, $N_{loss} = \int_0^L l(z)\exp(\int_0^L (g(x) - l(x))dx)\,dz$ and $N_{gain} = \int_0^L g(z)\exp(\int_0^L (g(x) - l(x))dx)dz$ are photon fluctuations due to gain and loss. $|\alpha|^2$ is the photon number at the input frequency. $g(z)$ is parametric gain and $l(z)$ is total loss coefficient. Assuming that the input signal power is large enough, the second term in Eq. (8) can negligible. The following simulations are based on the above theory.

3. Results and discussion

The cross section of the SOI rib waveguide is shown in Fig. 1, the W, D and H are the width of the rib, the height of the rib and the height of the Si, respectively.

The structure parameters are very important to the dispersion and the effective mode area of SOI. To investigate on the influence of the W and H on the dispersion and the effective mode area silicon rib waveguides with a 2 cm long are considered. The numerically results are shown in Fig. 2.

In Fig. 2, when the W and H are changing, the dispersion and effective mode area are changing. So we can choose the best dispersion and the effective mode area by tailing the W and H.

To investigate on the influence of the W and H on the gain and the NF, silicon rib waveguides with a 2 cm long are considered. The free carrier lifetime is 1 ns. The pump wavelengths are located at 1512 nm and 1592 nm, the power, the pulse width and the pulses

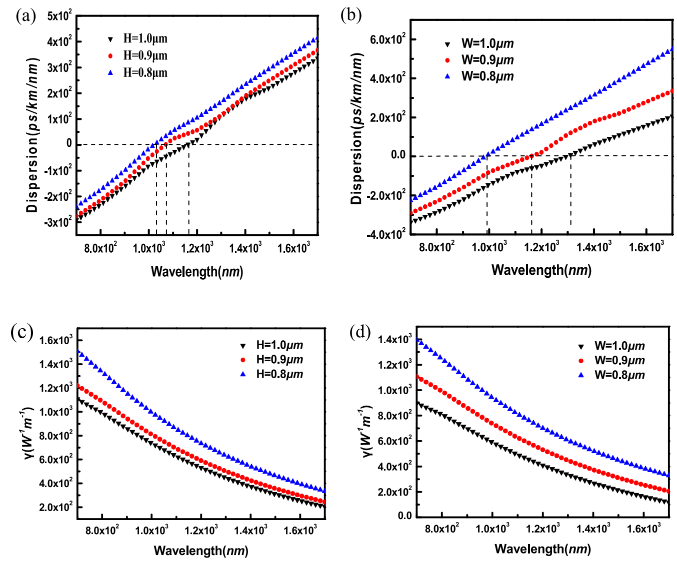

Fig. 2. The dispersion and effective mode areas versus signal wavelength with different structure parameters in (a) $D = 0.6$ μm, $W = 0.9$ μm, (b) $D = 0.6$ μm, $H = 1.0$ μm, (c) $D = 0.6$ μm, $W = 0.9$, (d) $D = 0.6$ μm, $H = 1.0$ μm.

repetition rate of the pumps waves are 0.6 W, 1 ps and 10 GHz, respectively. The numerically results are shown in Fig. 3.

In Fig. 3, when the H, D and W are different, the gain, bandwidth and NF are changing. Because the W and H can impact on the dispersion and the effective mode areas of the SOI, and dispersion and effective mode areas can influence the phase-matching condition. So we can change the W and H to make the pump central wavelength in the anomalous dispersion region closing to the zero dispersion wavelengths (ZDW) of SOI. This is good for achieving the phase mismatch of FWM [22].

The influence of the W, H and the free carrier lifetime on the gain and the NF are plotted with the free carrier lifetime from 0.1 to 2 ns, other parameters are the same as Fig. 3. The numerically results are shown in Fig. 4.

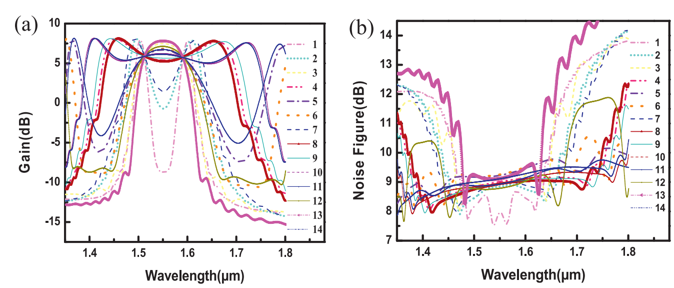

Fig. 3. Noise figure (NF) and corresponding gain versus signal wavelength with different structure parameters. The structure parameters of 1–14 are following Table 1.

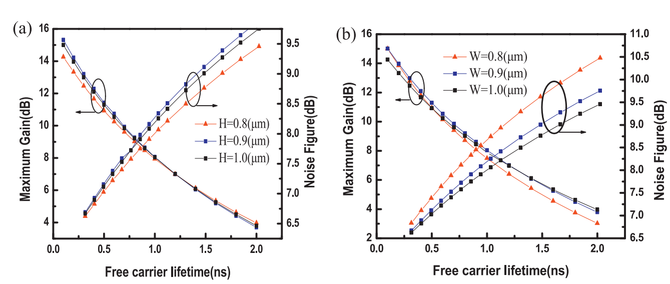

Fig. 4. Maximum gain and the NF versus the free-carrier lifetime with structure parameters in (a) $H = 0.8$–1.0 μm, $D = 0.6$ μm, $W = 0.9$ μm, (b) $W = 0.8$–1.0 μm, $D = 0.6$ μm, $H = 1.0$ μm