OPTOELECTRONICS AND ADVANCED MATERIALS – RAPID COMMUNICATIONS Vol. 4, No. 12, December 2010, p. 1968 – 1972

Gain and phase regeneration characteristics of Silicon-based symmetric-pump phase-sensitive parametric amplifier

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Based on the symmetric-pump phase-sensitive parametric amplifier (SP-PSA) model in silicon waveguide, the gain and phase generation characteristics of SP-PSA in the presence of two-photon absorption (TPA) are investigated. Different parameters of pumps and medium have been considered to illustrate their effect on SP-PSA. The results show that the net gain and low noise can be only achieved with appropriate pump power and free carrier lifetime while dispersion is not very important. In addition, the phase regeneration performance can also be influenced by pump and medium parameters.

(Received November 15, 2010; accepted November 29, 2010)

Keywords: (190.4410) Nonlinear optics, Parametric processes, (230.4320) Nonlinear optical devices, (250.3140) Integrated optoelectronic circuits, (250.4480) Optical amplifiers

1. Introduction

Silicon photonics has emerged as an exciting area of research in the last decade since it offers an opportunity for low cost solutions to optical communications and optoelectronics integration. The power density of a Si wire is higher by a factor of about 1000 than that of conventional single-mode fiber with a small core less than a micrometer. In the past few years, a variety of different applications have been investigated, such as wavelength conversion [1], laser [2, 3], amplifier [4-9] and modulator [10]. Until now research of amplifier in silicon concentrated mainly on phase insensitive amplifier such as Raman amplifier [4-6] and parametric amplifier[7-9] which is independent with signal phase, phase sensitive amplifier (PSA) has not gain enough attention though it has been proved to own phase regeneration performance.

PSA based on four wave mixing (FWM) effect is an important promising candidate as an amplifier to the future communication system with benefits including the reduction of pulse arrival-time and phase jitter, and the suppression of the modulation instability. That is to say, PSA can regenerate the phase of phase-modulation format signals while amplifying, which is very useful to improve degenerated signal performance before the receiver. FWM processes phase sensitive by providing input idlers that beat with the signals [11-15], or choosing the pump and signal frequencies in ways that allow the signals to beat with themselves [16-19]. The latter scheme in fiber involving one signal and two symmetrical pumps around signal, which can be referred to as a symmetric-pump PSA (SP-PSA), has been proved to regenerate the phase of DPSK perfectly, so this paper focuses on this SP-PSA.

Since the parametric frequencies span a wide range, multi-photon processes such as TPA could be efficient. Such a nonlinear process may strongly affect the optical parametric oscillation. In the past, almost all the works have concentrated on the situation in which the TPA is completely avoided and it is rational because of low pump intensity in fiber. However, TPA is omnipresent in silicon with large linear absorption, and the most importantly, large TPA coefficients in the telecom band. Therefore, nonlinear losses caused by TPA and FCA induced by TPA could dramatically affect the characteristics of the SP-PSA based on silicon.

In this paper, the gain and phase regeneration characteristics of Si-based SP-PSA in presence of nonlinear losses caused by TPA are demonstrated. The numerical investigations involve different parameters of pump and waveguide and initial relative phase particularly. Results show that initial relative phase play an important role in order to achieve high net gain. In addition, phase regeneration also been analyze with different pump power and free carrier lifetime. In order to realize phase regeneration well, the pump power and free carrier lifetime should be chosen appropriately.

2. Theory

SP-PSA is the process of degenerate FWM in which a signal is amplified by two pumps. The wavelengths of two pumps differ from the signal frequency by equal and opposite amounts [16-18].

The frequency relationship for phase-sensitive interaction is $\omega_{p1}+\omega_{p2}=2\omega_s$, where ω_{p1}, ω_{p2}, ω_s are the frequencies of two pumps and signal respectively. This frequency condition allows the signal to interact with itself and this interaction becomes dependent on the input signal phase. If the intensities of signal are assumed much smaller than the pump intensity, the pump is not depleted and high-order nonlinear effects are neglected. Different from fiber, TPA in silicon is particularly strong and can not be ignored which results in pump depletion and generation of free carriers through the free carrier plasma effect. In this situation, we must consider TPA and FCA into coupling equation of FWM and coupled propagation of pumps and signal in the silicon waveguide can be described as the following set of coupled-mode according to [21] and [22],

$$
\begin{aligned}
\frac{dA_{p1}}{dz} &= -\frac{1}{2}\left[\alpha+\alpha_{p1}{}^{FCA}(z)\right]A_{p1}+i(\gamma_0+i\beta_T)\left(\left|A_{p1}\right|^2+2\left|A_{p2}\right|^2+2\left|A_s\right|^2\right)A_{p1}+i\gamma_0 A_s{}^2 A_{p2}{}^* \exp(i\kappa z)\\
\frac{dA_s}{dz} &= -\frac{1}{2}\left[\alpha+\alpha_s{}^{FCA}(z)\right]A_s+i2(\gamma_0+i\beta_T)\left(\left|A_s\right|^2+2\left|A_{p2}\right|^2+2\left|A_{p1}\right|^2\right)A_s+i2\gamma_0 A_{p1}A_{p2}A_s{}^* \exp(-i\kappa z)\\
\frac{dA_{p2}}{dz} &= -\frac{1}{2}\left[\alpha+\alpha_{p2}{}^{FCA}(z)\right]A_{p2}+i(\gamma_0+i\beta_T)\left(\left|A_{p2}\right|^2+2\left|A_{p1}\right|^2+2\left|A_s\right|^2\right)A_{p2}+i\gamma_0 A_s{}^2 A_{p1}{}^* \exp(i\kappa z)
\end{aligned}
\tag{1}
$$

where β_{p1}, β_{p2} and β_s is the propagation constant, $\beta_T=0.45cm/GW$ is the TPA coefficient. As described in [5], from these coupling equation, losses of SP-PSA included linear and nonlinear parts while latter is due to FCA, where linear loss coefficient $\alpha=0.4dB/cm$. Free carrier concentration determined the magnitude of TPA-induced FCA coefficient through the relation: $\alpha^{FCA}=1.45\times10^{-17}(\lambda/1550)^2 N$, N is the density of electron-hole pairs where λ is the wavelength in microns and it is related to the pump intensity where signal intensity is small enough comparable to pump by $N=\beta_T\cdot I_p^2\cdot\tau_{eff}/(2\cdot h\nu)$ for CW pumping or long pulse pumping, where $h\nu$ is the pump photon energy and τ_{eff} is the effective recombination lifetime for free carriers.

Phase mismatch $\kappa=\beta_{2c}(\omega_{sc}^2-\omega_d^2)+\beta_{4c}(\omega_{sc}^4-\omega_d^4)+\gamma_0 I_p$ is important factor and is preferred to be 0 for high performance SP-PSA which involve nonlinear coefficient, total pump power, second and fourth order dispersion and relative wavelength, where

$$\omega_{sc}=\omega_s-\omega_c \quad \omega_c=(\omega_{p1}+\omega_{p2})/2$$

and $\omega_d=(\omega_{p1}-\omega_{p2})/2$.

In SP-PSA, $\omega_{sc}=0$, so $\kappa=-\beta_{2c}\omega_d^2-\beta_{4c}\omega_d^4+\gamma_0 I_p$, small normal dispersion is more suitable to satisfy phase matching condition.

3. Results

For measuring the performances of SP-PSA in silicon waveguides, we numerically investigate the impact of waveguide and pump parameters based on related principles in Section 2. The silicon waveguides have been considered to be 1cm long with 0.1 μm^2 effective area. In SP-PSA based on silicon waveguide, the phase matching condition and losses are two important factors to determine the performance of amplifier as a whole. Phase matching condition is related to dispersion and nonlinear coefficient of medium and wavelength spacing of two pumps. Losses in silicon waveguide included three parts: linear loss, nonlinear losses caused by TPA and FCA. We will illustrate how these complicated parameters impact the performance of SP-PSA in the following content.

As mentioned in section 2, the pump power plays a key role in phase matching condition and nonlinear loss coefficient caused by FCA in the same time. Fig.1 shows the influence imposed on net gain by pump power with different input signal phase: 0, 0.25 π, 0.5 π, 0.75 π and π. As the power increases, net gain rises very quickly at first and reaches its peak value when the pump power is smaller than 2.5W. If pump power continues to increase, quantity of electron-hole pairs exist and the density enhanced, α^{FCA} is too large to ignore which is proportional to pump power. At this situation, net gain begins to deplete and decrease to lower than 0dB gradually. In Fig. 1, curves with different types denote the net gain with different signal initial phase, coincidence of curves with signal phase equals to 0 and π indicates gain changing with π period. Fig. 1 shows that the power flow depends on the value of the relationship in the nonlinear media. In PSA, when the phase-matching condition is perfect, the optical power can be transferred maximally either from the pump to the signal and idler or from the signal and idler to the pump. This illustrates that the signal and idler could either be amplified (pump transfers energy to them) or de-amplified (they transfer energy to the pump), depending on the available value of the phase relationship at the location of the nonlinear medium which include linear and nonlinear phase as a whole. In Fig. 1, difference of net gain with different input phase verifies that this amplifier is phase-sensitive firstly. Secondly, when input phase equals to 0.5 π, signal is de-amplified first then amplified because power transfer from signal to pump and then backwards.

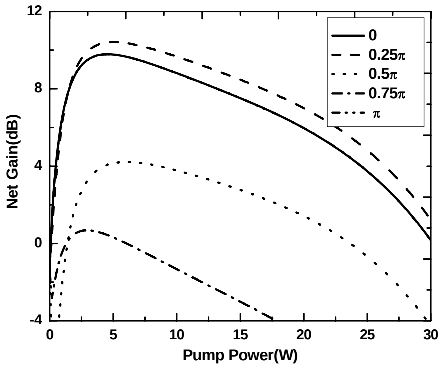


Fig. 1. Net gain versus pump power for different initial relative phase.

As mentioned in section 2, the phase mismatch is crucial to realize high efficient PSA influenced primarily by dispersion and wavelength spacing of pump. Silicon exhibits very large normal GVD generally induced by the proximity of the absorption band edge at 1.1 μm at wavelengths at telecom band until waveguide confinement was introduced to create net anomalous-GVD regions several octaves from any material resonance. It is experimentally verified that through proper design of waveguide shape and size, anomalous GVD in the range of 200-1200 $ps/\left(nm\cdot km\right)$ can be obtained at 1550 nm. In [4], anomalous GVD is adopted and evaluated as a breakpoint to realize broad-band optical parametric amplifier. However, in SP-PSA based on silicon, small normal dispersion is more suitable to satisfy phase matching condition and keep stable according to equation mentioned in section 2. Fig. 2 shows evolution of net gain versus pump power with different dispersion. When wavelength spacing is 10nm, coincidence of net gain curves with D=-200, 200 or 600 $ps/\left(nm\cdot km\right)$ illustrates that if two pump wavelength is close enough, net gain is not sensitive to pump power. However, if wavelength spacing is large enough, for example 90nm, net gain changes dramatically in different D which enhances the requirement to dispersion of nonlinear medium.

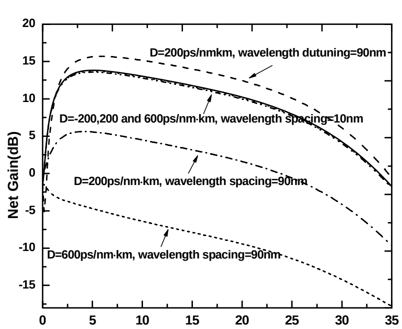


Fig. 2. Net gain versus pump power for different values of D and wavelength spacing of pumps.

Zhang yi et al. in [9] has demonstrated that in dual-pump PA several combinations of pump wavelengths can be used for similar gain spectra different from single-pump amplifiers and this pump wavelength flexibility is beneficial to SP-PSA based on silicon. We also analyze impact of wavelength spacing imposed on the net gain. As shown in Fig.3, net gain is not sensitive to wavelength spacing when D=-200 $ps/\left(nm\cdot km\right)$, however, if silicon owns abnormal dispersion, wavelength spacing is not negligible and degrades the performance of net gain of SP-PSA, as predicted in section 2 theoretically, small normal dispersion is more suitable to SP-PSA. Another conclusion is when wavelength detuning (ω_d) is smaller than 10 nm, D and ω_d have little influence on net gain which declines the requirement of SP-PSA to the medium and pump as well.

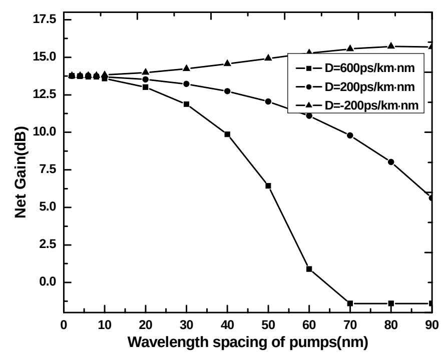


Fig. 3. Net gain versus wavelength spacing of pumps for different D.

The dependence of signal gain and output phase on the relative input phase is estimated and depicted in Fig. 4. In order to simplify the analysis, the two pumps are considered to have opposite initial phase values. It is observed that the gain peaks occur periodically at multiples of π, signifying that field components either in phase or out of phase by π with the pumps is amplified strongly, while those that are out of phase by $\pi/2$ are not amplified. The theoretical approach is valid as long as the input signal does not deplete the pumps. Fig. 4 also shows the output signal phase versus input phase for the undepleted-pump PSA. As seen in the Fig. 4, the output phase varies as a step-like function of the input phase exhibiting two phase states with difference equal to π exactly, indicating that all regenerated signal pulses have a differential phase shift of 0 or π. As a result, the region of interest for the PSA application is close to gain maximum value and variance of regenerated phase is faint. On the contrary, when net gain is lowest, output phase changes significantly including the beating among signal and pumps.

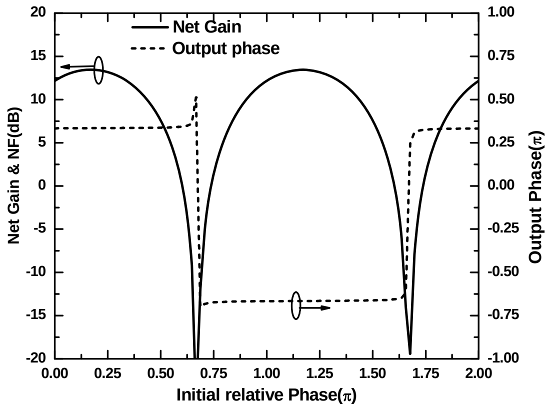


Fig. 4. Signal gain, NF and output phase versus the initial relative phase.

To further analyze the performance of phase regeneration, we change dispersion in the region -200~600 $ps/(nm \cdot km)$ as shown in Fig.5. As dispersion changing from positive to negative, the variance of regenerated phase becomes large and the effect of regeneration degrades. When D=600 $ps/(nm \cdot km)$, the output phase totally becomes garbled and can not regenerate phase at all. This phenomenon illustrates that parametric efficiency is low with unsuitable dispersion value because dispersion is one of important factors to phase matching condition.

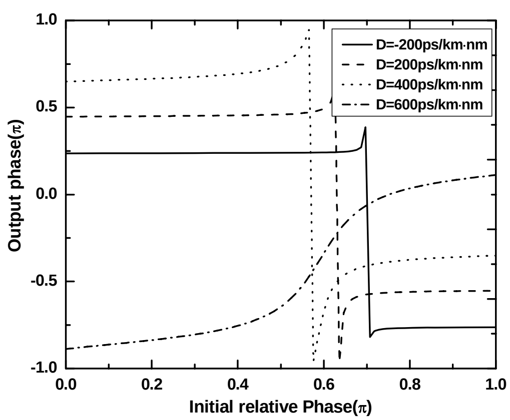
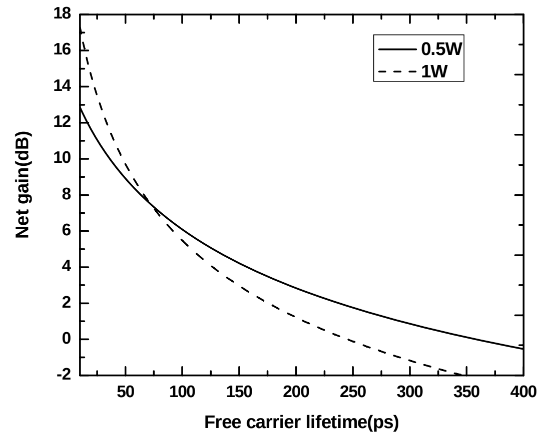
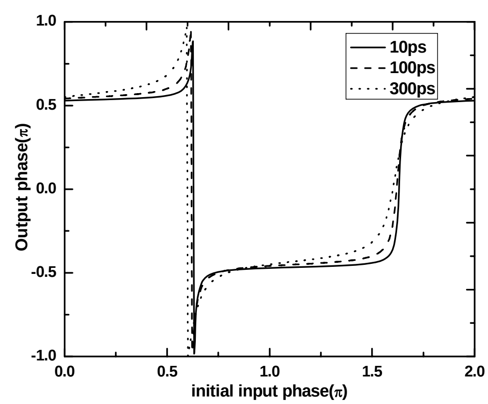


Fig. 5. Output phase on the initial relative phase.

The final part of this literature is to numerically estimate the performance of phase regeneration influenced by intrinsic TPA and FCA in silicon. According to equation (1) nonlinear losses caused by FCA in silicon as well as linear losses is another important factor to influence the light coupling and it is proportional to free carrier lifetime in silicon. Recently, free carrier lifetime has been reduced to values close to 10ps at low intensity excitation by removing active carrier [2, 3, 10] and 50ps by ion implantation [23]. We assume length of 2cm, ω_d of 10nm, $\beta_T = 0.45cm/GW$ and D of -200 $ps/(nm \cdot km)$ with fixed initial signal phase. Fig.6 shows net gain and output phase versus free carrier lifetime varying from 10ps to 400ps with different pump powers. To achieve net gain by a CW pump, the free carrier lifetime should smaller than 350ps. Phase generation is also influenced by free carrier lifetime as depicted in Fig.6(b), as long as the lifetime increases, variance of output phase becomes more obviously.



(a)



(b)

Fig. 6. (a) Net gain versus free carrier lifetime (b) output phase versus initial input phase with different free carrier lifetime.

4. Conclusion

We investigate the net gain and phase generation performance of SP-PSA in silicon waveguide. In order to achieve net gain the dual-pumps should operate with power lower than 4W, the wavelength spacing should be closer to avoid interacting between pumps, the input phase should be locked to a fixed value and the free carrier lifetime should be not higher than 350ps for CW pumps. SP-PSA can also regenerate phase of DPSK signal and its performance is related to parameters of pumps and medium which can degrade obviously by high pump power, large wavelength spacing and high free carrier lifetime. Thus, by choosing apposite duel-pumps and suitably designed silicon waveguide, SP-PSA may be a chip scale solution to realize not only amplifying but also phase regeneration.

Acknowledgements

This work is partly supported by the National Key Basic Research Special Foundation (2010CB328304), National Science Foundation of China (60807022), the key grant of Chinese Ministry of Education (No.109015) and the discipline Co-construction Project of Beijing Municipal Commission of Education (YB20081001301).

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