Noise Figure of High-Repetition-Rate Optical Parametric Amplifiers in Silicon

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Abstract: A numerical investigation on noise figure (NF) inside the silicon waveguides pumped with high-repetition-rate pulses is carried out. The parameters of pump pulses are important to generate net gain and <7dB NF in silicon waveguides.

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1. Introduction

Intrinsic high optical nonlinearity fortified by tight mode confinement and prospect of dense on-chip integration with microelectronics made silicon photonics a rapidly growing field. In fact, nonlinear silicon photonic functional devices, such as Raman lasing and amplification [1], optical modulation [2], wavelength conversion [3], and so on, have been successfully demonstrated. In modern optical fiber communication systems, wavelength division multiplexing is adopted to facilitate high capacity broadband communication. However, the relatively narrow Raman gain bandwidth in silicon (100GHz) can only amplify a few wavelength channels with one pump laser. Optical parametric amplifiers (OPAs), on the other hand, provide large and flexible gain bandwidth with promising multifunctional capabilities such as phase conjugation. Recently, by tailoring the cross-sectional size and shape, the waveguide geometries that allow for anomalous group velocity dispersion (GVD) were investigated, and parametric amplification over 28 nm using pulsed pump with a 75-MHz repetition rate is demonstrated in suitably designed silicon waveguides [4]. To gain further understanding of the OPA in silicon waveguides and especially for its applications in high-speed optical communications, it is necessary to investigate the high-repetition-rate pulsed pump amplifier more thoroughly.

In this paper, we provide a numerical investigation on the noise figure (NF) evolution inside 1 cm silicon waveguides with high-repetition-rate pulsed pump, in the presence of two photon absorption (TPA), TPA-induced free-carrier absorption (FCA), free-carrier-induced dispersion and linear loss. The dependence of the NF on pulsed pump parameters (including peak power, repetition rate and pulse width etc) is analyzed.

2. Analysis

By combing a strong pump wave at angular frequency (ω_p) with a signal at another frequency (ω_s) into a silicon waveguide, FWM parametric process can occur. This can result in amplification of the signal as well as generation of an idler wave (ω_i) at the frequency $\omega_i=2\omega_p-\omega_s$ at the same time. The evolution process of the pump A_p, signal A_s and idler A_i field amplitudes along the silicon waveguide can be described by the coupled equations [5]. For the the silicon waveguide with effective mode area of 0.1 μm^2 and GVD of 600 ps/km/nm at 1550 nm, the linear loss is α=140 dB/m , $\beta=0.75\times10^{-11}$ m/W is the TPA coefficient, and $\gamma_j=n_2\omega_j/c$ with nonlinear refractive index $n_2=5.5\times10^{-18}$ m^2/W is the nonlinear coefficient ($j=p,s,i$) . Δk is the phase mismatch among three waves. The TPA-induced FCA loss is given as $\alpha_j^{FCA}(z)=1.45\times10^{-17}(\lambda_j/1550)^2N$, where λ_j is the wavelength (nm), and N (cm^{-3}) is carrier density generated by TPA. For pulsed pump $I(t,x)=I_0(z)\exp(-4\ln2t^2/T_0^2)$, N meets the following equation

$$\frac{dN(t,z)}{dt}=\frac{\beta}{2h\nu}I^2(t,z)-\frac{N(t,z)}{\tau} \quad (1)$$

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, which changes with the waveguide geometry to enhance the carrier recombination. The repetition rate, R, of the pulsed pump is an important factor impacting N. In the optical amplifier, the noise in the amplified output signal is mainly affected by gain and loss in the medium. For OPAs in silicon waveguides, the gain is generated by FWM process and the loss includes all of nonlinear losses of TPA and FCA, and linear loss. The noise figure (NF) of the OPA can be attained by evaluating mean output photon number and mean photon number fluctuation through the silicon waveguide[6-7]. In order to achieve large pump power, optical pump sources around 1550 nm telecommunication widow often are amplified with Erbium-dope fiber amplifier (EDFA). The amplified spontaneous emission (ASE) of the EDFA together with the pump laser's relative intensity noise significantly influences OPA's noise performance. With a 1 cm silicon waveguide pumped, the typical gain and NF spectra of the OPA pumped with 1 ps pulses

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operating at 1550 nm and the repetition rate of 10 GHz are given in Fig.1.

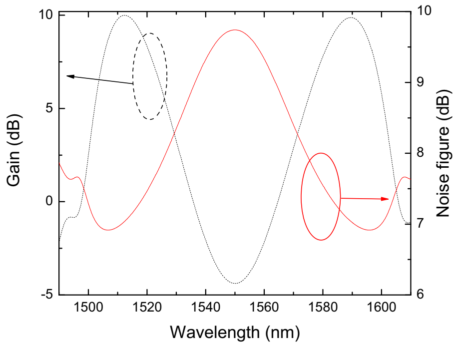

Fig.1 Typical gain and NF spectra of OPA in the silicon waveguide

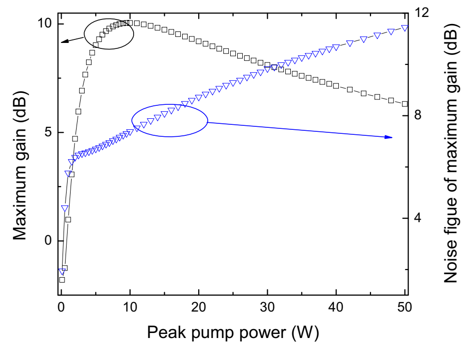

Fig.2 NF evolution at maximum gain

Pump power plays a significant role in OPA in silicon waveguides because TPA and FCA are both intensity-dependent. Maximum gain and relative NF evolutions versus the peak pump power are shown in Fig.2. With increasing the peak pump power, the maximum gain enters into saturation and then begins to decrease. We note that high peak pump power doesn't mean large gain due to presence of intensity-dependent TPA and FCA losses in the silicon waveguide. However, NF increases significantly with increasing peak pump power due to increase nonlinear losses by TPA and FCA. The repetition rate, and more important pump pulse width have significant impact on parametric gain and NF by influencing free carrier density. Fig.3 shows the maximum gain and corresponding NF evolutions versus the repetition rate at different pulse widths, with pump pulses with peak power of 5 W and repetition rate of 10 GHz. We estimate that the gain and NF have no significant changes when the repetition rate below 500 MHz, and the FCA loss is determined by the pulse width. With further increasing the repetition rage, the gain begins to decrease and the NF begins to increases. The net gain can even be achieved at 80 GHz when the pulse width is 0.5 ps, but there is no net gain for 10 ps at 5 GHz, as depicted in Fig.3 (a). In Fig.3 (b), which shows that lower NF can be achieved at shorter pulse and the NF increases with higher repetition rate when the repetition rate is above 1 GHz.

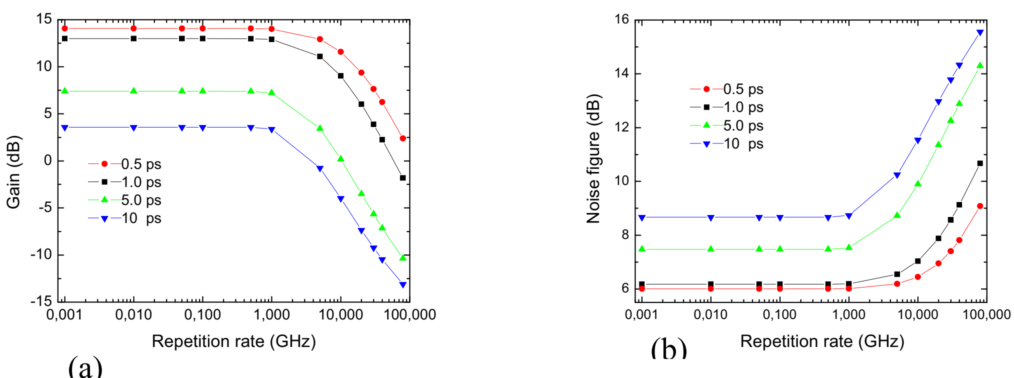

Fig.3 (a) Parametric gain and (b) NF versus the repetition rate for different pulse widths

3. Summary

The impact of pump parameters on the parametric gain and NF are discussed, and we show that shorter pump pulses can means higher gain, lower NF and wider gain bandwidth. So short pulse mode-locked lasers should be considered for pumping the optical silicon parametric amplifier.

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