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Characteristics of gain and pump-to-signal RIN transfer in a dual-pump SOPA with Raman effect*

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We investigate the spectra of the gain and pump-to-signal relative intensity noise (RIN) transfer in silicon optical parametric amplifier (SOPA) with Raman effect, and draw a conclusion that Raman effect makes the spectra narrower from 260 nm to 180 nm. A maximum gain also appears at 1622 nm. Moreover, the effects of the related parameters in SOPA on the gain and the pump-to-signal RIN transfer characteristics are also discussed. The high gain (16 dB) and low pump-to-signal RIN transfer (7 dB) can be obtained by using the appropriate parameters of pump and silicon waveguide.

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Fiber optical parametric amplifiers (FOPAs) have attracted wide attention because of the potential for achieving the high gain, large bandwidth and low noise for the past decades[1,2]. Recently, because of the intrinsic high optical nonlinearity and the prospect of dense on-chip integration with microelectronics in silicon, the nonlinear photonic phenomena and devices based on the silicon waveguide, such as Raman amplification and lasing, all-optical switching, wavelength conversion and optical modulation, have been successfully demonstrated.

Moreover, it is possible to achieve the anomalous group velocity dispersion (GVD) through appropriately tailoring the cross-sectional size and shape of the core waveguide[3], and it makes the silicon waveguide be applied in the parametric amplification. The net gain and large bandwidth are obtained in the silicon waveguide, and the noise figures (NFs) both in single-pump and dual-pump configurations are studied[4,5]. In addition, the net gain of optical amplifier plays an important role in the pump-to-signal RIN transfer[6]. However, the pump-to-signal RIN transfer in dual-pump silicon optical parametric amplifier (SOPA) has been excluded at present, and the influence of Raman effect on the gain and pump-to-signal relative intensity noise (RIN) transfer characteristics is also unsolved.

In this paper, we analyze the characteristics of gain and pump-to-signal RIN transfer in a dual-pump SOPA with Raman effect. It is demonstrated that the length of the waveguide, free carrier lifetime in the waveguide, and the power, pulse width, as well as pulse repetition rate of the pumps have great effects on the maximum gain and the corresponding pump-to-signal RIN transfer.

As two strong pumps with frequencies of ω_l and ω_h and a signal wave with frequency of ω_s are launched into a silicon waveguide, the parametric process of four-wave mixing (FWM) can occur, and an idler wave generates at the frequency of $\omega_i=\omega_l+\omega_h-\omega_s$ simultaneously. It generally describes this process in the situation of non-depleted pump by the coupled equations, in which the influences of two-photon absorption (TPA) and TPA-induced free-carrier absorption (FCA) are taken into account, but the Raman effect is ignored. However, it is necessary to combine Raman effects to the parametric amplification when considering a wide gain bandwidth. Under this circumstance, we can easily know that the Raman contribution fraction f_R (f_R=0.043 in SOPA) and the Raman response function $F(f)$[7] both play an important role during calculation. The imaginary part of $F(f)$ is an odd function and the real part of $F(f)$ is an even function, which can change the position of the maximum gain and the nonlinear index, respectively. Considering an analytical math method, we can obtain two vital factors, which are the total phase mismatch k and the parametric gain coefficient g in SOPA with Raman effect as follows[8]:

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$$k=[H(f)+H^{*}(-f)]I_{\mathrm{p}}-\Delta\beta\ , \tag{1}$$

$$g^{2}=H(f)H^{*}(-f)I_{\mathrm{p}}^{2}-k^{2}/4\ , \tag{2}$$

where $H(f)=\gamma_0[1-f_{\mathrm{R}}+f_{\mathrm{R}}F(f)]$ and $\Delta\beta\approx\beta_{2\mathrm{c}}(\omega_{\mathrm{sc}}^{2}-\omega_{\mathrm{d}}^{2})+\beta_{4\mathrm{c}}(\omega_{\mathrm{sc}}^{4}-\omega_{\mathrm{d}}^{4})$. $\beta_{2\mathrm{c}}$ and $\beta_{4\mathrm{c}}$ are the second- and fourth-order dispersion parameters at $\omega_{\mathrm{c}}(\omega_{\mathrm{c}}=\frac{\omega_1+\omega_{\mathrm{h}}}{2})$. Based on the analyses above, we can get the net gain in the presence of nonlinear losses from the expression[9]

$$G(L)=\exp\{\int_0^L[g(z)-l(z)]\,\mathrm{d}z\}\ . \tag{3}$$

Besides, the pump wave should be amplified by erbium-doped fiber amplifier (EDFA) to obtain high pump power, which provides an additional source for the pump-to-signal RIN transfer. In SOPA, assuming the pump power is modulated by small fluctuation m_{p} as $P_{\mathrm{p}}=P_0(1+m_{\mathrm{p}})$, the pump fluctuations cause the parametric gain's fluctuation, and change the output signal as $P_{\mathrm{s,out}}=G_{\mathrm{s}}P_{\mathrm{s,in}}=G_{\mathrm{s0}}(1+m_{\mathrm{s}})P_{\mathrm{s,in}}$. The relationship between m_{p} and m_{s} is

$$G_{\mathrm{s}}=G_{\mathrm{s0}}+m_{\mathrm{p}}\frac{\mathrm{d}G_{\mathrm{s}}}{\mathrm{d}m_{\mathrm{p}}}=G_{\mathrm{s0}}+m_{\mathrm{p}}P_0\frac{\mathrm{d}G_{\mathrm{s}}}{\mathrm{d}P_{\mathrm{p}}}=G_{\mathrm{s0}}(1+m_{\mathrm{s}})\ . \tag{4}$$

The pump-to-signal RIN transfer is deduced by the radio of the output signal power to the pump power[9],

$$RIN_{\mathrm{transfer}}=(\frac{m_{\mathrm{s}}}{m_{\mathrm{p}}})^2=(\frac{p_0\,\mathrm{d}G_{\mathrm{s}}}{G_{\mathrm{s0}}\mathrm{d}P_{\mathrm{p}}})^2\ . \tag{5}$$

The derivation of the signal gain with respect to the pump power can be estimated by calculating the slope of SOPA gain as a function of the pump power from the coupled equations.

In FOPAs, the net gain is modulated by Raman response function $F(f)$[10,11]. The imaginary part of $F(f)$ is an odd function, which brings an asymmetry factor on the Stokes side of the gain spectrum. However, the real part is an even function, and it changes the nonlinear index and limits the spectrum flatness. We believe that these results can be used in SOPA and will give a detailed discussion following.

The chosen silicon waveguide is 2 cm-long with effective mode area of 0.38 μm^2. The zero-dispersion wavelength is 1551.3 nm with third- and fourth-order dispersion parameters of β_3 = 3.0 × 10^{-3} ps^3/m and β_4 =-1.87 × 10^{-5} ps^4/m. The free carrier lifetime is 1 ns, and the 8.6 ps-wide pulses with repetition rate of 1 GHz are used as the two pumps, set at 1512 nm and 1592 nm, respectively.

The gain amplitude modulation factors induced by the real and imaginary parts of $F(f)$ around the wavelength of 1512 nm, 1592 nm and the total superposition are clearly presented in Fig.1. There are two obvious dips near 1470 nm and 1640 nm for the modulation factors induced by real part of $F(f)$ as shown in Fig.1(a), and a minimum value appears at 1620 nm for the modulation factors induced by imaginary part of $F(f)$ as shown in Fig.1(b).

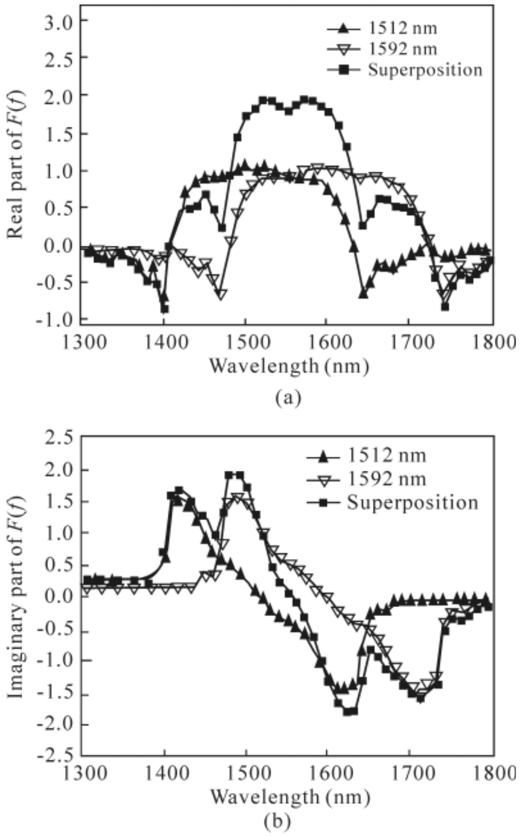


Fig.1 Gain amplitude modulation factors induced by (a) real part and (b) imaginary part of *F*(*f*)

We substitute $F(f)$ into Eqs.(1) and (2) to solve the equations. The spectra of gain and pump-to-signal RIN transfer with Raman effect are obtained, which are depicted in Fig.2. A simulation about the spectra of gain and pump-to-signal RIN transfer without Raman effect is also carried out. It can be clearly known that when the Raman effect is ignored, the pump-to-signal RIN transfer spectrum has the same trend with

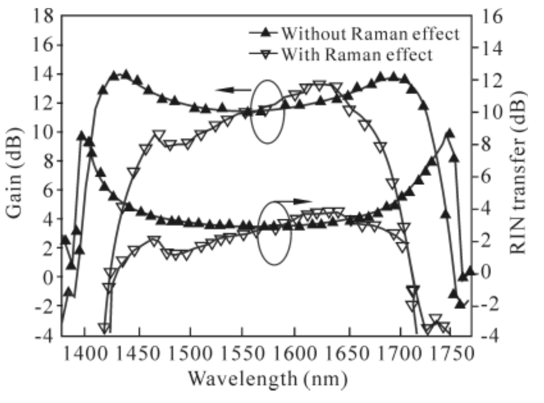


Fig.2 Spectra of gain and pump-to-signal RIN transfer with and without Raman effect

the net gain over a relatively wide gain bandwidth ranging from 1440 nm to 1700 nm. However, owing to considering the Raman effect, the relatively flat spectra of gain and pump-to-signal RIN transfer are narrower ranging from 1470 nm to 1650 nm. It agrees with the variation trend of the real part of $F(f)$ shown in Fig.1(a). Additionally, a maximum gain can be achieved near 1622 nm because of the inverse modulation of the imaginary part of $F(f)$.

To show the effect of the silicon length, we calculate the maximum gain and corresponding pump-to-signal RIN transfer (at 1622 nm) with the length changing from 0.5 cm to 7 cm. As shown in Fig.3, the pump-to-signal RIN transfer increases with the increase of waveguide length for a relatively short range, and then a large slope emerges, which is the same as the evolution of the gain. However, with the continuous increase of the silicon length, the pump-to-signal RIN transfer tends to a constant, which can be explained by the increased nonlinear losses including TPA and FCA.

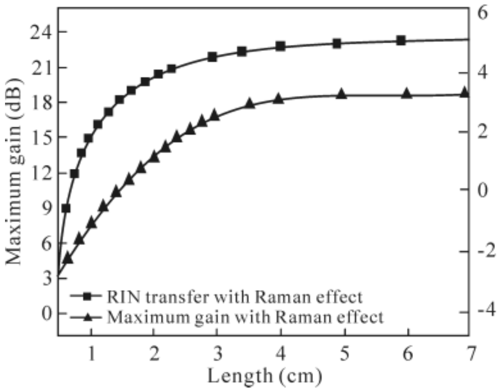


Fig.3 Maximum gain and corresponding pump-to-signal RIN transfer versus the silicon length with Raman effect

In addition, the free carrier lifetime also expresses significant influence for the performance of SOPA with Raman effect. To investigate this conclusion, we calculate the maximum gain and corresponding pump-to-signal RIN transfer (at 1622 nm) with the free carrier lifetime ranging from 10 ps to 2000 ps. Also, the different pulse widths of 0.5 ps, 1 ps and 5 ps are considered. Fig.4(a) and (b) show the evolutions of the gain and pump-to-signal RIN transfer. We find that the longer free carrier lifetime means the lower gain, which is due to the nonlinear losses induced by the free carriers. Thus, the pump-to-signal RIN transfer decreases noticeably with the increase of free carrier lifetime.

It can be clearly seen in Fig.5 that the pump-to-signal RIN transfer increases with the increase of pump power at first when TPA and FCA losses are low. However, with a continuous increase of the peak pump power, the gain is saturated, and the pump-to-signal RIN transfer decreases due to the presence of TPA and FCA losses. The pump-to-signal RIN transfer depending on the slope of the gain becomes lower, which is different from the result in FOPAs. So the high gain and low pump-to-signal RIN transfer can be obtained with the appropriate peak power.

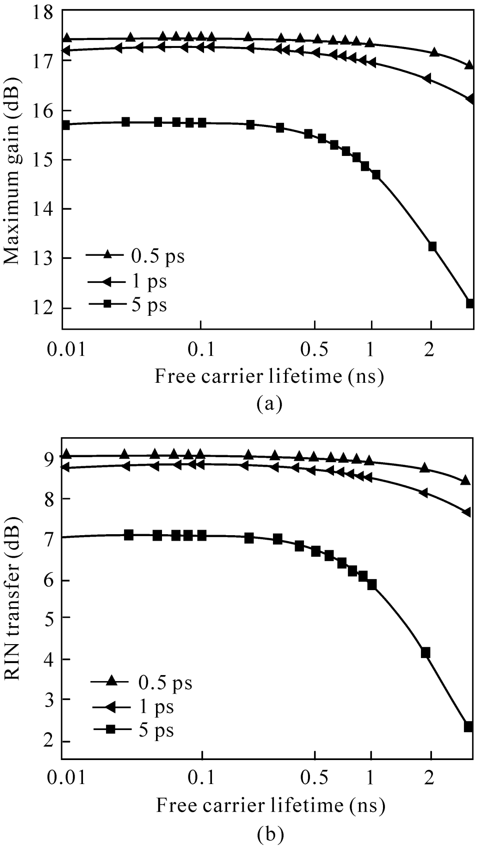


Fig.4(a) Maximum gain and (b) corresponding pump-to-signal RIN transfer versus the free carrier lifetime for different pulse widths with Raman effect

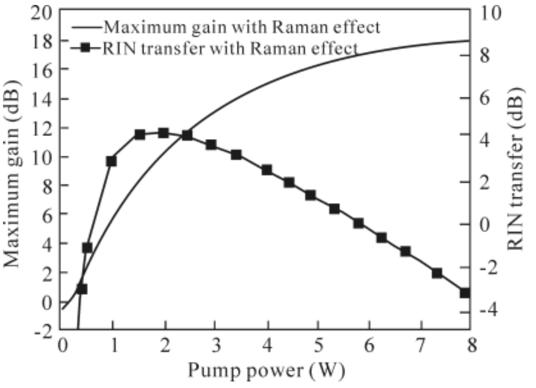
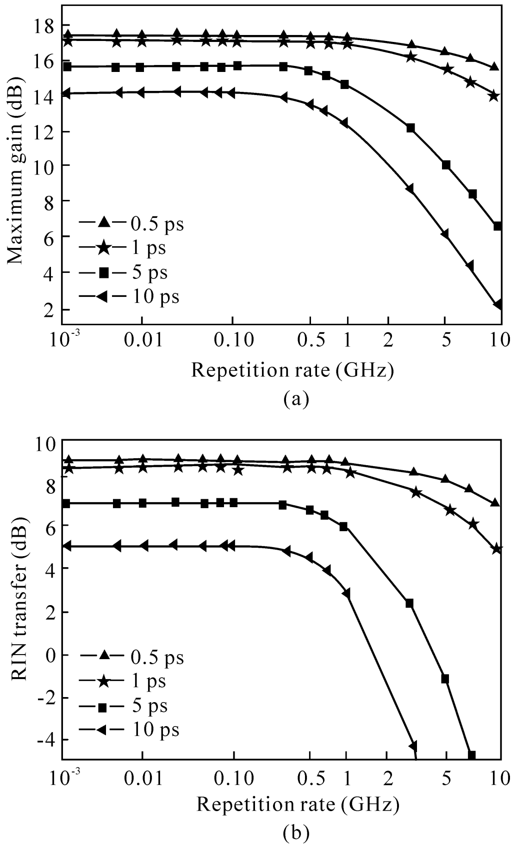


Fig.5 Maximum gain and corresponding pump-to-signal RIN transfer versus the pump power with Raman effect

Finally, to evaluate the effect of pump pulse repetition rate on the configuration with Raman effect, we calculate the maximum gain and corresponding pump-to-signal RIN transfer (at 1622 nm) with the repetition rate varying from 1 MHz to 10 GHz and with the different pulse widths of 0.5 ps, 1 ps, 5 ps and 10 ps. The results are depicted in Fig.6 (a) and (b), respectively. It is manifested that the maximum gain and corresponding pump-to-signal RIN transfer almost have no change when the repetition rate is below 600 MHz, but decrease with repetition rate further increasing. Moreover, the shorter pulse width means the higher gain and pump-to-signal RIN transfer.



(a)

(b)

Fig.6(a) Maximum gain and (b) corresponding pump-to-signal RIN transfer versus the repetition rate for different pulse widths with Raman effect

In summary, in order to achieve a more realistic simulation meeting with the experimental results, the Raman effect should be taken into account during calculating the gain and pump-to-signal RIN transfer in dual-pump SOPA. The flat gain bandwidth depends strongly on the Raman response function *F*(*f*). In dual-pump case, the gain modulation factor should be a superposed one, which makes the spectrum fluctuant, narrower and asymmetric. Analyses also show that there is a maximum gain located near 1622 nm. Then by calculating the gain and pump-to-signal RIN transfer at 1622 nm with different parameters of pump and silicon waveguides, we understand that the high gain and low pump-to-signal RIN transfer can be obtained with the appropriate pumps and silicon waveguides. The study of pump-to-signal RIN transfer in SOPA with Raman effect will make great contribution to the application of silicon photonics technology in many research areas.

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