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Noise investigation of dispersion compensating photonic crystal fiber Raman amplifiers

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Noise induced by gain and loss in photonic crystal fibers and pump-to-signal RIN transfer in Raman amplifiers is investigated. We show that transmission loss and low-frequency RIN transfer noise significantly influences the final noise figure.

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*Keywords:*Photonic crystal fiber, Raman amplifier, Noise

1. Introduction

Photonic crystal fibers (PCFs) have progressed rapidly in the last ten years, and their prominent properties have led to the development of novel functional devices [1-2]. PCF is one of the potential candidates for dispersion compensation because it can provide larger negative dispersion and dispersion slope contrary to that of the standard single mode fiber [3-4]. However, dispersion compensating PCFs exhibit significant insertion loss, which degrades the signal power. Raman amplification is a powerful technology to improve the system performance, and PCFs exhibit efficient Raman amplification [5-6]. Recently, gain characteristics of dispersion compensating PCF Raman amplifiers have been discussed [7-8]. During Raman amplification, noise occurs and degrades the optical signal. Therefore, the noise performances in dispersion compensating PCF Raman amplifiers should be elevated.

In an optical amplifier, the transmission noise can be analyzed by the quantum-mechanical model based Langevin noise sources, which are associated with photon fluctuation created by the gain and the loss [9-10]. For Raman amplifiers, small amplitude perturbations residing on the pump wave characterized as the relative intensity noise (RIN), are transferred to the Stokes wave during Raman amplification [11-12]. Here, we investigate noise characteristics of dispersion compensating PCF Raman amplifiers by analyzing the photon fluctuations along the PCFs and RIN transferred from the pump to the signal.

2. Analyses and discussion

Assuming that pump and signal waves travel in the PCF with different group velocities, we can write the Raman interaction equations between two waves as :

$$\frac{\partial P_s}{\partial z}+\frac{1}{v_s}\frac{\partial P_s}{\partial t}=-(\alpha_s+\alpha_{Rs})P_s+\frac{g_R}{A_{eff}}P_{p\pm}P_s \tag{1}$$

$$\pm\frac{\partial P_{p\pm}}{\partial z}+\frac{1}{v_p}\frac{\partial P_{p\pm}}{\partial t}=-(\alpha_p+\alpha_{Rp})P_p-\frac{\omega_p}{\omega_s}\frac{g_R}{A_{eff}}P_sP_{p\pm} \tag{2}$$

The parameters $P_{s,p}$ represent the signal and the pump powers, g_R is the Raman gain coefficient, $v_{s,p}$ are the group velocities of the Stokes and pump waves, $\alpha_{s,p}$ are the attenuation coefficients, $\alpha_{Rs,\,Rp}$ are the Rayleigh attenuation coefficients induced by the Rayleigh scattering effect, $\omega_{s,p}$ are the angular optical frequencies, A_{eff} is the effective mode area. The upper and lower signs of $\pm$ and $\mp$ correspond to the co-propagating and counter-propagating configurations, respectively.

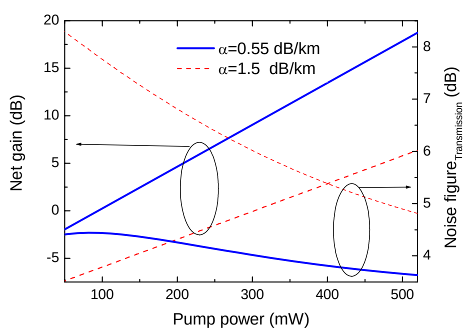
To estimate the noise figure during Raman amplification process, mean output photon number and mean photon number fluctuation along PCFs are calculated by using the signal wave Eq. (1)-(2) [9-10]. The noise figure due to Raman amplification based on photon fluctuations will be:

$$NF_{silicon}=\frac{T+N_{loss}+N_{gain}}{T}+\frac{N_{gain}(T+N_{loss})}{T^2\,|a|^2}, \tag{3}$$

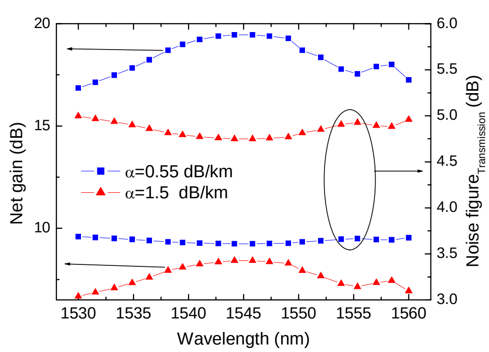
where $T=\exp\left(\int_0^L (g(z)-l(z))dz\right)$ is the net gain, $N_{gain}=\int_0^L g(z)\exp\left(\int_z^L (g(x)-l(x))dx\right)dz$ and $N_{loss}=\int_0^L l(z)\exp\left(\int_z^L (g(x)-l(x))dx\right)dz$ are photon fluctuations due to gain and loss. Parameter L is the PCF length, $g(z)=P_p(z)\cdot g_R/\,A_{eff}$ is the local optical Raman gain calculated from Eq.(1) and Eq.(2),

$l(z) = \alpha_s + \alpha_{Rs}$ is the experienced loss coefficient, $|a|^2$ is the photon number at the input frequency. Assuming that the input signal power is large enough, so the second term in Eq. (3) is negligible and Eq. (3) can be numerically solved.

The estimated attenuation coefficient of 0.55 dB/km is used in Ref.[7]. However, the real attenuation coefficients of PCFs for dispersion compensation and Raman amplification are often larger than 1 dB/km [3, 13]. Therefore, we adopt both attenuation coefficient of 0.55 dB/km and 1.5 dB/km in the following calculations. In addition, the Rayleigh attenuation coefficient is calculated from the Rayleigh scattering coefficient of 1 dB·μm^4/km.The other parameters is the same as that in Ref.[7] With increasing the pump power, transmission noise figure and gain evolutions at 1550 nm are shown in Fig. 1(a) with Raman gain efficiency $\gamma_R = g_R/A_{eff}$ of 4.17 $W^{-1}\cdot km^{-1}$ and the pump wavelength of 1455 nm. The transmission noise figure and gain at different wavelengths are depicted in Fig. 1(b) with the pump power of 520 mW. From Fig. 1(b), we can know that the net gain decreases ~11 dB and the transmission noise figure increases ~1.5 dB when the attenuation coefficient increases from 0.55 dB/km to 1.5 dB/km.



(a)



(b)

Fig. 1. (a) Transmission noise figure and net gain versus the pump power at 1550 nm; (b) Transmission noise figure and net gain at different wavelengths with the pump power of 520 mW.

Assuming that the intensity fluctuations have sinusoidal time dependence and the modulation indices can be separated, we can write the intensity of the pump and Stokes wave at any location along the silicon waveguide as:

$$P_s(z,t) = \overline{P}_s(z)\left[1+M(z,t)\right] = \overline{P}_s(z)\left[1+m(z)\exp(i\Omega t)\right] \qquad (3)$$

$$P_{p\pm}(z,t) = \overline{P}_{p\pm}(z)\left[1+N_\pm(z,t)\right] = \overline{P}_{p\pm}(z)\left[1+n_\pm(z)\exp(i\Omega t)\right] \qquad (4)$$

where $m(z)$ and $n_\pm(z)$ are the perturbing complex spatial modulation indices, and Ω is the angular frequency of the modulation. Substituting Eqs. (3) and (4) into Eqs. (1) and (2) we obtain the following differential equations for the complex spatial modulation indices:

$$\frac{dm}{dz} = i\Omega d_\pm m + \frac{g_R}{A_{eff}}\overline{P}_p n_\pm \qquad (5)$$

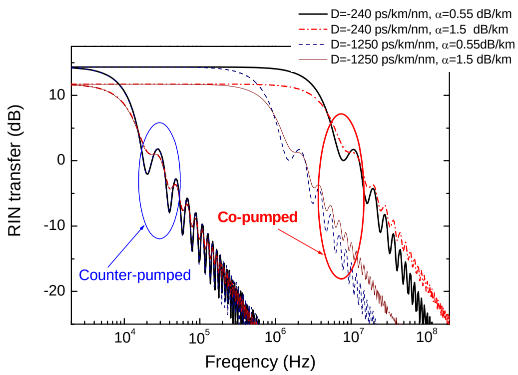
$$\frac{dn_\pm}{dz} = \mp\frac{\omega_p}{\omega_s}\frac{g_R}{A_{eff}}\overline{P}_s m \qquad (6)$$

where $d_\pm = 1/v_p \mp 1/v_s$ is the “walk-off” between pump and the signal. Here we assume quadratic modulation terms can be neglected due to small fluctuations, i.e. $|m \bullet n_\pm| \ll 1$. The RIN transfer can be calculated for co-propagating and counter-propagating configurations as [8]:

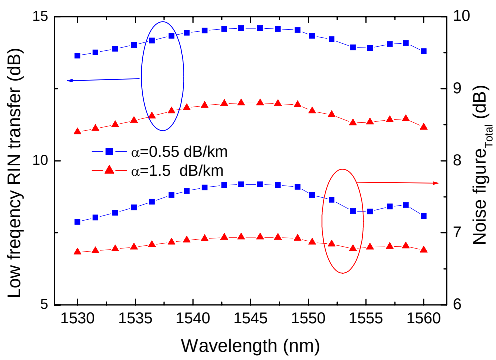
$$T_+(L,\Omega) = \frac{|M(L,\Omega)|^2}{|N_+(0,\Omega)|^2} \qquad (7)$$

$$T_-(L,\Omega) = \frac{|M(L,\Omega)|^2}{|N_-(L,\Omega)|^2} \qquad (8)$$

The dispersion value of ~-240 ps/km/nm is achieved in Ref.[7]. Through proper design, the dispersion of the PCF can be smaller than -1000 ps/km/nm [13]. Therefore, the dispersion value of -1250 ps/km/nm is also used to analyze the RIN transfer characteristics of the dispersion compensating PCF Raman amplifiers. Fig. 2(a) shows the pump to signal RIN transfer spectra at 1550 nm for co-pumped and counter-pumped configurations with the pump power of 520 mW. We can see that the -3 dB cutoff frequency decreases with a larger negative dispersion value, and the low frequency RIN transfer value decreases with a larger attenuation coefficient. Typical pump lasers used for Raman amplification are rather noisier than lasers used for optical communication systems (>20dB worse RIN), and here the pump RIN value of -130 dB/Hz is used. The final noise figure will increase linearly with increasing RIN transfer rate as $\Delta NF = \Delta RIN \bullet P_{s,input}/(2h\nu)$[11]. Fig. 2(b) gives the total noise figure including the transmission noise and the pump to signal RIN transfer noise at low frequency.



(a)



(b)

Fig. 2. (a) Pump to signal RIN transfer and (b) Low frequency RIN transfer and the total noise figure at different wavelengths.

3. Conclusions

We analyzed the noise properties of dispersion compensating PCF Raman amplifiers by considering different actual conditions. Our results indicate that the transmission loss and pump to signal RIN transfer have significant influence on the final noise figure.

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