Effect of Raman-Induced Refractive Index Change on Multi-Pump Raman-assisted Four-Wave Mixing

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Abstract: We investigated the contribution of Raman-induced refractive index change on the conversion efficiency bandwidth in Raman-assisted four-wave mixing. The contribution of the Raman-induced refractive index change can be significant when multi-Raman pumps are used.

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1. Introduction

Wavelength conversion schemes based on four-wave mixing (FWM) are attractive because of the short excitation lifetime (~fs) and high transparency to bit rates and modulation formats [1]. In Raman-assisted FWM, stimulated Raman scattering (SRS) offer overall gain to the FWM process. In addition, SRS also contributes a nonlinear phase shift to the phase-matching condition and thus can affect the operating range of the FWM process [2]. We observed that the Raman-induced change in the nonlinear refractive index depends on the detune between the Raman pump and Stokes lines. In this paper, we investigate the effects of the Raman-induced nonlinear refractive index change on the phase matching condition, hence the operation bandwidth, in the FWM process.

2. Theory and Model

In SRS, the real and imaginary parts of the delayed Raman response function correspond to the Raman-induced nonlinear refractive index change and Raman gain, respectively [3]. Both of them are functions of the detune between the Raman pump and the Stoke lines. We studied the effect of Raman-induced refractive index change on Raman-assisted FWM process theoretically. We assumed that the Raman pump, the FWM pump, the signal and the idler are also collinearly polarized monochromatic waves. The chromatic dispersion can therefore be neglected. We also neglected the Raman amplification and absorption among the FWM pump, signal, idler. The evolution of the Raman pump, FWM pump, signal, and idler are given by

\[
\frac{dP_p}{dz} = -\alpha_p P_p \sum_i \frac{g_i}{A_{eff}} A_i^2 \frac{\partial}{\partial \omega} \left( \frac{\partial}{\partial \omega} \right) P_p, \quad (1)
\]

\[
\frac{dA_i}{dz} = G_i(z) A_i - 2\alpha_i A_i A_j \sin \phi, \quad (2)
\]

\[
\frac{dA_j}{dz} = G_j(z) A_j + \gamma \alpha_j A_i \sin \phi, \quad (3)
\]

\[
\frac{dA_i}{dz} = G_i(z) A_i + \gamma \alpha_i A_j \sin \phi, \quad (4)
\]

\[
\frac{d\phi}{dz} = \Delta k + \gamma \left[ 2a_j - \left( a_j^2 + a_i^2 \right) \right] + \gamma \left[ a_i \left( \frac{a_i}{a_j} + \frac{a_j}{a_i} \right) - 4a_i a_j \right] \cos \phi + \gamma \Delta \tilde{\eta}_i(\Omega) P_p, \quad (5)
\]

where, \( a_i(z) = |A_i|^2 \), \( i = 0, 1, 2 \) are the intensities of the FWM pump, signal and idler respectively. The parameters \( P_p \) is the total power of the Raman pump, \( \gamma \) is nonlinear coefficient, \( \Delta k \) is phase mismatch due to chromatic dispersion which can be approximately written as \( \beta_2 (\omega_i - \omega_p)^2 \), where \( \beta_2 \) is the group-velocity dispersion (GVD) parameter, and \( A_{eff} \) is the effective core area. The parameters \( \alpha_i, g_i, \) and \( G_i(z) = \left( g_i P_p / A_{eff} - \alpha_i / 2 \right), i = 0, 1, 2 \) are the fiber attenuation, Raman gain coefficients, and effective gains of the FWM pump, signal and idler respectively. \( \Delta \tilde{\eta}_i(\Omega) = \tilde{\eta}_i(\Omega) + \tilde{\eta}_i(\Omega) - 2\tilde{\eta}_i(\Omega) \) is the second order difference of the Raman-induced refractive index change \( \tilde{\eta}_i(\Omega) \) between the FWM pump, signal and idlers. In Eqs. (1)-(5), the phase \( \phi \) governs the energy exchange among
the FWM components. The last term on the right hand side of Eq. (5) can compensate the anomalous dispersion mismatch as well as contribute to the phase matching as $\Delta h'_R(\Omega)$ is positive.

Figure 1: The reminder of the Raman-induced refractive index change with the detunes between Raman pump and Stokes lines and the detunes between the FWM pump and signal.

Figure 2: Simulation results of (a) output conversion efficiencies and (b) phases versus wavelength detune between the signal and pump in Raman-assisted FWM with (solid line) and without (dashed line) contribution of the Raman-induced index change term. The Raman gain profile is assumed to be flat.

3. Discussions And Simulation Results

Figure 1 shows the quantity $\Delta \tilde{h}'_R(\Omega)$ at different detunes between the Raman pump and the Stokes line and the separation between the signal and the FWM pump using [4]. The maximum positive value and slope can be found at Raman-Stokes detune of 115 nm. Since this detune does not coincide with the peak of the Raman gain profile, the contribution of the quantity $\Delta \tilde{h}'_R(\Omega)$ is not important if a single Raman pump is used to assist the FWM process. However, if multiple Raman pumps are used to flatten the Raman gain profile, we can further enhance the FWM efficiency by optimizing the contribution of the difference of Raman-induced refractive index change $\Delta \tilde{h}'_R(\Omega)$. We study the maximum contribution of the quantity $\Delta \tilde{h}'_R(\Omega)$ by assuming a flat Raman gain profile. We use the gain value of the peak gain provided by a single Raman pump at 500 mW. We fix the Raman pump-FWM pump detune at 115 nm. Figure 2 shows the simulation results in which the total input power of the signal, pump and idler was set to be 10 mW and the input power of the signal was 1 mW. The initial phase is set to 0. The fiber is 12 km long with a nonlinear coefficient $\gamma = 2.0 \, W^{-1} \cdot km^{-1}$ and Raman gain coefficient of $1.0 \, W^{-1} \cdot km^{-1}$. We set the fiber attenuations to be 0.25 dB/km at 1550 nm and 0.35 dB/km at 1450 nm. The group velocity dispersion coefficient is $\beta_2 = -3 \times 10^{-3} \, ps^2/km$ at the FWM pump wavelength. Figure 2(a) shows the conversion efficiencies with (solid lines) and without (dashed lines) the quantity $\Delta \tilde{h}'_R(\Omega)$. We observed a difference of ~5 nm in the 3-dB full conversion bandwidth, which represents a 15% underestimate, when the contribution of $\Delta \tilde{h}'_R(\Omega)$ is not included. Figure 2(b) shows the relative output phase versus detune. Since the conversion efficiency curve and phase curve are symmetric at both sides of pump, we plotted only one side in Fig. 2.

4. Conclusion

We studied the contribution of the Raman-induced nonlinear refractive index change to the phase matching in Raman-assisted FWM. From our simulations, we found that this phase contribution has to be taken into account in when multiple Raman pumps are used to assist the FWM process.

5. Reference