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Stimulated Raman scattering effect on femtosecond pulse generation using a parabolic amplification and a pulse compressor

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Abstract: An explicit analytical form for the Stokes pulse evolution in parabolic amplification is derived for the first time. In order to achieve efficient pulse compression, the parabolic amplifier should be operated in the small Stokes pulse regime where the signal pulse is not seriously deteriorated. An analytical expression to obtain the critical fibre length for small Stokes pulse regime is also derived. The pulse compression of the output signal at various fiber lengths also confirms that the output signal pulse at the derived critical fiber length provides a compressed pulse with the maximum peak power and shortest pulse width. The results are verified through numerical simulations using split-step Fourier method.

Keywords: Stimulated Raman scattering, parabolic amplification, femtosecond

1. Introduction

High power femtosecond sources enable numerous applications in bio-optics, fundamental science studies, and security scanning spectroscopy. A combination of a parabolic amplifier in the normal dispersion and a grating pair pulse compressor can generate high power femtosecond pulses [1, 2]. However, the Stokes pulses caused by stimulated Raman scattering severely limits the parabolic amplification process, by degrading the signal pulse and the pulse compression efficiency. In order to achieve a short compressed pulse with large peak power, it is critical to maintain the parabolic signal pulse intact since even small distortions of a parabolic pulse degrades the compression efficiency. Since stimulated Raman scattering builds up along the fibre, there will be an upper bound of fibre length, within which the signal pulse maintains the parabolic shape. In order to investigate this, an explicit analytical expression of the Raman Stokes pulse is needed, which however have not been presented before. For this, we derived an exact analytical solution for the signal and Stokes pulses. We also present expressions for the critical length over which the signal may maintain a parabolic shape.

2. Theory

The nonlinear Schrödinger equation can be used to describe pulse propagation in fibres as follows [3].

$$\frac{\partial\psi_s}{\partial z}+\frac{i}{2}\beta_{2s}\frac{\partial^2\psi_s}{\partial T^2}=i\gamma_s\left[|\psi_s|^2+(2-f_R)|\psi_r|^2\right]\psi_s-\frac{g_s}{2}|\psi_r|^2\psi_s+\frac{\alpha_s}{2}\psi_s, \tag{1}$$

$$\frac{\partial\psi_r}{\partial z}-d\frac{\partial\psi_r}{\partial T}+\frac{i}{2}\beta_{2r}\frac{\partial^2\psi_r}{\partial T^2}=i\gamma_r\left[|\psi_r|^2+(2-f_R)|\psi_s|^2\right]\psi_r+\frac{g_r}{2}|\psi_s|^2\psi_r+\frac{\alpha_r}{2}\psi_r, \tag{2}$$

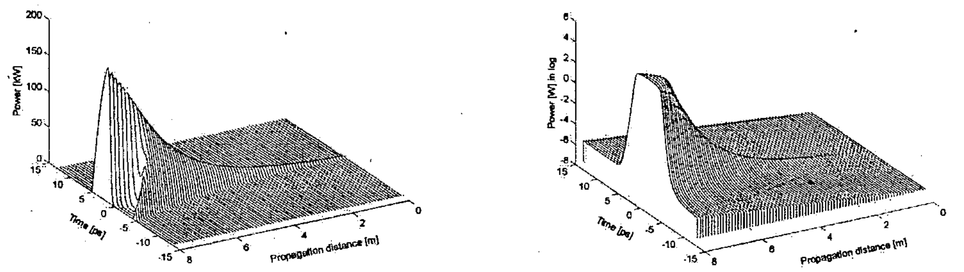
where ψ_s, ψ_r represent the slowly varying envelopes of pulses of signal and Raman Stokes pulse. Then, it can be shown that the evolution of the Stokes wave pulse can be divided into four different regime: namely, Gaussian small Stokes pulse regime, asymmetric small Stokes pulse regime, signal pulse depletion regime, and finally, parabolic Stokes pulse regime. The critical fibre length can be defined as the point where the signal depletion starts. This critical fibre length (z_0) is obtained through following algebraic equation:

$$T_p^2(z_0)-\frac{9d^2}{4\alpha^2}W\left(\frac{2\alpha}{3d}T_p(z_0)\right)\left\{1+\frac{2}{3\alpha d}W\left(\frac{2\alpha}{3d}T_p(z_0)\right)\right\}=\frac{2\alpha_s B^2}{3A_0^2}\ln\left(\frac{2\alpha_s}{g_s P_{r0}}-\alpha_r z_0\right), \tag{3}$$

where T_p, A_0 is defined in reference [1] and $B=6(A_0/\alpha_s)\sqrt{\gamma_s\beta_{2s}/2}$. W is the Lambert W-function. Before the signal pulse reaches the critical fibre length z_0, the signal pulse remains parabolic. Therefore, the optimum fibre length for efficient parabolic amplification is $L=z_0$. Within the small Stokes pulse regime ($z<z_0$), the Stokes pulse is divided into two regimes: Gaussian Stokes pulse regime ($z<2B/d$), and the asymmetric Stokes pulse regime ($2B/d<z<z_0$). Once the pulses pass the critical length z_0, the signal pulse becomes depleted over a relatively short distance due to the fast growth of the Stokes pulse. After this, the Stokes pulse itself propagates as a parabolic pulse. Although we derived the exact pulse shape of the Stokes pulse for each regime, those are omitted here due to the limited space.

3. Numerical simulations

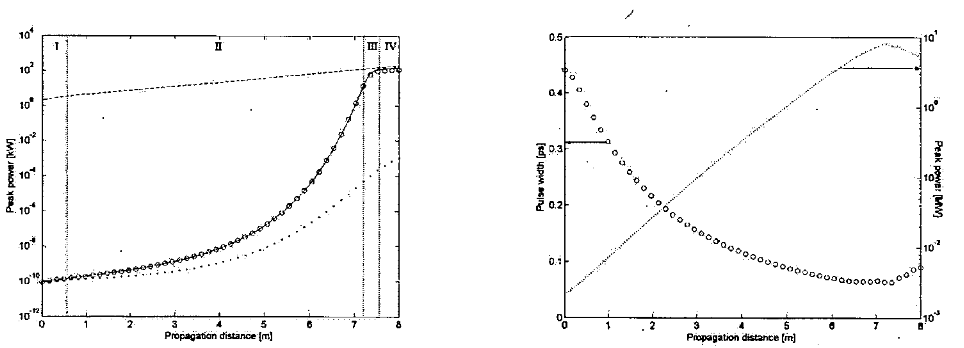
In order to verify the validity of our analytical Raman Stokes pulse energy formula, we simulated the nonlinear Schrödinger equation in equation (1) and (2), using the split-step Fourier method.[4] For simulations, we assumed a 27 μm mode-field diameter and silica-fused fibre with $\beta_2 = 20\ ps^2/km$ and $\gamma_s = 0.27\ W^{-1}km^{-1}$.The signal wavelength is 1.06 μm. The seed signal is assumed to be a 533 fs (FWHM) Gaussian pulse with energy of 1 nJ. Then, the Gaussian Stokes pulse regime is $z < 2B/d = 0.532\ m$ from analysis. The signal depletion starts from z_0 which is calculated from equation (3) giving 7.23 m. The gain was assumed to be 4 dB/m.



(a) (b)

Figure 1. Numerical simulation. (a) Signal pulse, (b) Stokes pulse.

Figure 1 shows the evolution of the signal and Stokes pulses. As is expected from theory, the signal starts being depleted from 7.23 m. The depletion of signal takes place within 0.35 m, which coincides with theoretical calculation. After that, the Stokes pulse propagates as a parabolic pulse as in the figure.



(a) (b)

Figure 2. (a) The peak power of pulses, (b) the peak power and pulse width of compressed pulse.

In figure 2(a), the peak power of signal and Stokes pulse are shown. The figure shows that the analytical solution of Stokes pulse (O mark) is almost indistinguishable from the numerical solution (solid line). The Roman figures indicate the different regimes, namely, I: Gaussian small Stokes pulse, II: asymmetric small Stokes pulse, III: signal depletion, IV: parabolic Stokes pulse. Figure 2(b) shows the optimum compression results for the signal pulse at various propagation distances by a grating pair compressor simulation. The graph clearly shows that the compressed pulse from the signal pulse at 7.2 m has maximum peak power of 8.38 MW as well as minimum pulse duration of 64 fs. Therefore, it is apparent that the desired fibre length should not exceed z_0 for efficient pulse compression.

4. Conclusion

We have derived an explicit analytical form for the Raman Stokes pulse and explained the pulse evolution by dividing it into four regimes. It was shown that the fibre length should not exceed the critical fibre length, which is given by equation (3), in order to achieve efficient pulse compression.

5. References

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