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Time-Domain Pulse Property of Stimulated Raman Scattering in a Multimode Optical Fiber

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Abstract. The time-domain pulse property of quasi-steady stimulated Raman scattering (SRS) in a multimode optical fiber, pumped by an A – O Q-switched Nd:YAG laser, is studied both experimentally and theoretically. Good agreement has been achieved between theory and experiment. Discussion shows that the variation of the Stokes pulse width (FWHM) t_s depends on the shape of input pump pulse.

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Owing to the long interaction length and high optical intensity, nonlinear optical effects can be largely enhanced in low-loss optical fibers. Thus, nonlinear optics of optical fibers has attracted more and more attention [1].

Stimulated Raman scattering (SRS) [2], which has been widely studied experimentally and theoretically, is one of most important nonlinear optical phenomena frequently observed in optical fibers. But, to the authers' knowledge, little study has been reported in the literature about the time-domain pulse property of quasi-steady SRS.

In this paper, an experimental and theoretical study about the time-domain pulse property of quasi-steady SRS, pumped by wide pulses from an acousto-optic (A – O) Q-switched Nd:YAG laser, is given. We place emphasis on the variation of the FWHM widths of the Stokes pulses as a function of the peak power of the input pump pulses. Good agreement has been achieved between the theoretical and experimental results.

1. Experiment

The experimental arrangement is shown in Fig. 1. The cw pumped Nd:YAG laser, operated at 1.06 µm, is Q-switched with an A – O modulater. We can change the FWHM width t_p of the output pulses simply by changing the diameter of an intracavity aperature. With the diameter of 2 mm, t_p is 260 ns, and the corresponding peak power is about 7 kW.

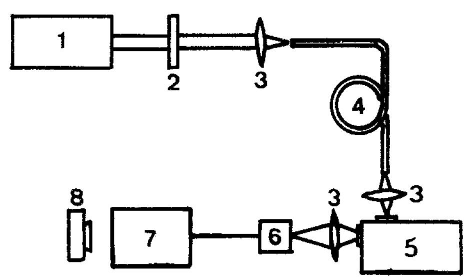

Fig. 1. Experimental arrangement. *1* A–O Q-switched Nd : YAG laser, *2* variable attenuator, *3* objective lenses, *4* multimode optical fiber, *5* gratting monochrometer, *6* photodetector, *7* oscilloscope, *8* camera

The optical fiber used in the experiment is a graded-index multimode optical fiber with $GeO_2 - SiO_2$ core and SiO_2 cladding. It has the core and cladding diameters of 50 µm and 120 µm, respectively. The length L of the fiber is 1.1 km, and the linear loss at 1 µm is about 1 dB/km.

The output pulses from the optical fiber are received by a photo-detector, which has a time constant of less than 10 ns. Reducing the pump power coupled into the fiber to a proper level, and changing the input power with a variable attenuator, we can observe the variation of the FWHM width t_s of the Stokes pulses as a function of the input pump peak power P_p directly on the screen of an oscilloscope. The measured Stokes pulse widths t_s, normalized by the pump pulse width t_p, are shown as circles in Fig. 2.

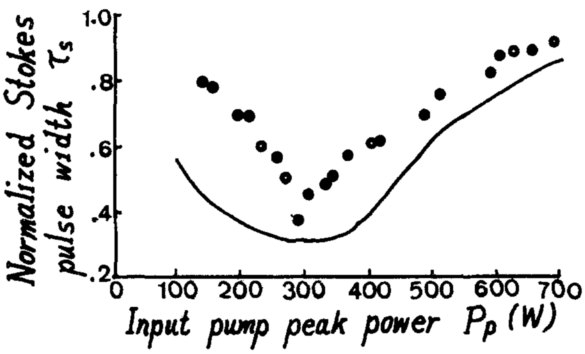

Fig. 2. Variation of Stokes pulse with input pump peak power. Circles ($t_p = 260$ ns) and dots ($t_p = 420$ ns) are the experimental results; Solid line is a theoretical plot

The experimental results show that the width t_s shortens in the small-signal area and broadens, after having passed a minimum of t_s, in the saturation area with the increasing P_p, but never exceeds the pump pulse width t_p, i.e., the normalized Stokes pulse width τ_s is always less than unity. Due to the rapid buildup of the Stokes wave, pump depletion is first observed at the peak of the pump pulse, then a dip is formed at the center of the pump pulse. The further increase in input pump power makes the center part of the output pump pulse from the optical fiber almost deplete completely. As a result, a two-peak structure pulse is observed. We note that the minimum of t_s occurs at a critical pump power P_{cr} at which input power the output pump pulse begins to dip at its peak.

Since the pulse width of the A – O Q-switched laser is dependent on the transition time of the acoustic wave crossing the laser beam, the pulse width t_p increases to about 420 ns when the intracavity aperature is opened with 4 mm in diameter. Keeping the other parameters unchanged an experimental plot of t_s vs. P_p at this t_p is given as dots in Fig. 2. The comparison of the plots at two different pump pulse widths indicates that, as expected, the variation of t_p has little effect on the normalized Stokes pulse width $\tau_s = t_s/t_p$ in the quasi-steady case.

As the pump power P_p increases to a higher level we have observed multi-order Stokes and anti-Stokes components and the two-peak structure not only in pump pulse but also in some lower-order Stokes pulses.

2. Theoretical Analysis

For an A – O Q-switched pulse (usually $t_p \geqq 100$ ns) the SRS interaction can be treated as a steady process at any instant although the pump power may vary rapidly in time during a pulse because the pulse width t_p is much larger than the relaxation time of molecular vibration in Raman medium and the vibration can follow with the variation of optical field to reach the steady state instaneously.

The pulsed-pumping Raman gain at the peak is higher than that at the leading and falling edges, and the Raman exponential gain is proportional to the pump power in the steady state. This gain difference causes the generated Stokes pulse to steepen on its leading and falling edges so that the Stokes pulse is shorter than the input pulse and narrows furthermore with the growth of P_p in the small-signal area. When the Stokes wave is built up, obviously the pump depletion will occur first at its peak to form a dip, and the gain difference will be inverted. Therefore the Stokes pulse begins to broaden as the pump power increases in the saturation area. We can conclude immediately from the above qualitative discussion that the minimum of t_s will occur at a critical pump power P_{cr} at which the output pump pulse from the optical fiber will dip at its peak.

A quantitative analysis of the experimental results can be based on the classical SRS theory. Assuming plane waves for the pump and Stokes waves, the coupled equations are obtained as following for the pump and the Stokes pulse power from the nonlinear wave equations at the standard slow-varying-amplitude approximation.

$$\frac{dP_p(z',t')}{dz'} = -\frac{g_p}{A_{\text{eff}}} P_p(z',t') \cdot P_s(z',t') - \alpha P_p(z',t'), \tag{1a}$$

$$\frac{dP_s(z',t')}{dz'} = \frac{g_s}{A_{\text{eff}}} P_p(z',t') \cdot P_s(z',t') - \alpha P_s(z',t'), \tag{1b}$$

where g_p is the Raman gain which is proportional to the Raman scattering section and the optical frequency. For a SiO_2 glass fiber $g_p = 9.2 \times 10^{-14}$ (m/W) [3], pumped at 1.06 μm, and $g_s = (\omega_s/\omega_p) g_p = 8.7 \times 10^{-14}$ (m/W). Transmission loss of the optical fiber: $\alpha = 1$ dB/km $= 2.3 \times 10^{-4}$ m^{-1}.

In the derivation of (1) we have made the travelling-wave transformation

$$z' = z, \quad t' = t - z/v_g$$

where $v_g = c/n$ is the group velocity in the optical fiber. The group dispersion is neglected since its influence on the process is very small in the quasi-steady case.

Take the input pump pulse $P_p(0,t')$ to be $P_p f(t')$ where P_p and $f(t')$ are the peak power and the pulse profile function, respectively. The input of Stokes wave is given by an effective input generated by spontaneous Raman scattering [4]

$$P_s(0,t') = N(h\nu_s) B_{\text{eff}} \tag{2}$$

where $h\nu_s$ is the energy of a Stokes photon; N is the mode number of the optical fiber and is about 200 for the fiber used here. The effective gain bandwidth B_{eff} has the form [4]

$$B_{\text{eff}}=\frac{\sqrt{\pi}}{2}\cdot\frac{\Delta\nu_R}{\sqrt{G_sP_p(0,t)}}. \tag{3}$$

Dividing (1a) by g_p and (1b) by g_s and then adding them leads to the well-known Maley-Rowe relation

$$\frac{P_p(z',t')}{\omega_p}+\frac{P_s(z',t')}{\omega_s}=\frac{P_p(0,t')}{\omega_p}e^{-\alpha z'}. \tag{4}$$

Finding P_p from (2) and substituting it into (1b), we have the equation for P_s:

$$\frac{dP_s}{dz'}=\left[\frac{g_s}{A_{\text{eff}}}P_p(0)e^{-\alpha z'}-\alpha\right]P_s-\frac{g_p}{A_{\text{eff}}}P_s^2. \tag{5}$$

Using transformation $X=P_s^{-1}$, Eq. (3) becomes

$$\frac{dX}{dz'}=-X\left[\frac{g_s}{A_{\text{eff}}}P_s(0)e^{-\alpha z'}-\alpha\right]+\frac{g_p}{A_{\text{eff}}}. \tag{6}$$

This linear equation is easy to solve.
With the solution of (4) and the relations $P_s=X^{-1}$ and $P_p=P_p(0)\exp(-\alpha z')-(\omega_p/\omega_s)P_s$, we can find the analytical solutions for the pump and Stokes pulses at the exist of the optical fiber.

$$P_s(z',t')=\frac{P_s(0,t')\exp(G_sP_p(0,t')z_{\text{eff}})\exp(-\alpha z')}{1+\frac{\lambda_s}{\lambda_p}\cdot\frac{P_s(0,t')}{P_p(0,t')}\exp[G_sP_p(0,t')z_{\text{eff}}]}, \tag{7a}$$

$$P_p(z',t')=\frac{P_p(0,t')\exp(-\alpha z')}{1+\frac{\lambda_s}{\lambda_p}\cdot\frac{P_s(0,t')}{P_p(0,t')}\exp[G_sP_p(0,t')z_{\text{eff}}]}. \tag{7b}$$

When the Stokes conversion is small, the second term in the denominator of (7) is much less than unity, and the solutions reduce to the small-signal expressions.

Substituting the effective Stokes input (2) into the solutions we have

$$P_p(L,t')=\frac{P_pf(t')\exp(-\alpha L)}{1+CP_p^{3/2}f^{3/2}(t')\exp[-G_sP_pf(t')]}, \tag{8a}$$

$$P_s(L,t')=\frac{P_pf(t')\exp(-\alpha L)}{1+1/CP_p^{3/2}f^{3/2}(t')\exp[-G_sP_pf(t')]}, \tag{8b}$$

with the constant $C=(2/Nh\nu_s\Delta\nu_R)\,(g_pL_{\text{eff}}/A_{\text{eff}})^{1/2}$ and the gain coefficient $G_s=g_sL_{\text{eff}}/A_{\text{eff}}$. $\Delta\nu_R$ is the Raman linewidth, for SiO_2 glass $\Delta\nu_R=300\,\text{cm}^{-1}$. L_{eff} and A_{eff} are effective interacting length and area, respectively. $L_{\text{eff}}=[1-\exp(-\alpha L)]/L$, and A_{eff} is equal to the core area of the multimode optical fiber.
The solutions (4) are now used to analysis the time-domain properties of the pump and Stokes pulses. Assuming a Gaussian function for the input pump pulse profile $f(t)$, i.e.

$$f(t)=\exp[-\ln 2\cdot(t/t_p)^2] \tag{9}$$

an iterative formula for the normalized Stokes pulse width (FWHM) is obtained.

$$y=\frac{1+CP_p^{3/2}y^{3/2}\exp(-G_sP_py)}{2(1+CP_p^{3/2})},\qquad \tau_s=t_s/t_p=[\ln(1/y/\ln 2]^{1/2}. \tag{10}$$

With the corresponding parameter of the used optical fiber we obtain

$$C=750(1/W^{3/2}),\qquad G_s=0.0498(1/W). \tag{11}$$

Substituting the constant C and gain coefficient G_s into the iterative formula (10) we have calculated the normalized Stokes pulse width τ_s at different input pump peak power P_p. In Fig. 2 the theoretical result of the variation of τ_s vs. P_p is plotted (solid line) for comparison with the experimental results.
It can be seen from Fig. 2 that the theory agrees qualitatively with the experiments. A particular good agreement is achieved for the pump power $P_{\min}=300$ W at which the Stokes pulse has its minimum width.
By differentiation with respect to time we obtain the critical pump power $P_{\text{cr}}=310$ W from (8a), also in good agreement with the experimental result, i.e. $P_{\min}=P_{\text{cr}}$.
We note, however, that there is a quantitative deviation between the calculated and the measured results. We believe that the devitation comes from the fact that the actual input pump pulse is not a Gaussian but an asymmetrical pulse with a steeper leading edge, as shown in Fig. 3. In order to manifest the idea, we have made calculations on the variation of τ_s as a function of P_p for several asymmetrical input pump pulses. The results are given in Fig. 4. It is clear from the results that, as expected, the pump pulse profile has a significant influence on the variation of τ_s, but no

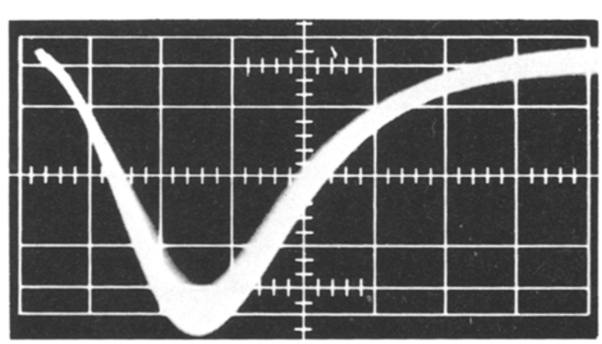

Fig. 3. Photograph of the input pump pulse. Time scale: 100 ns/div

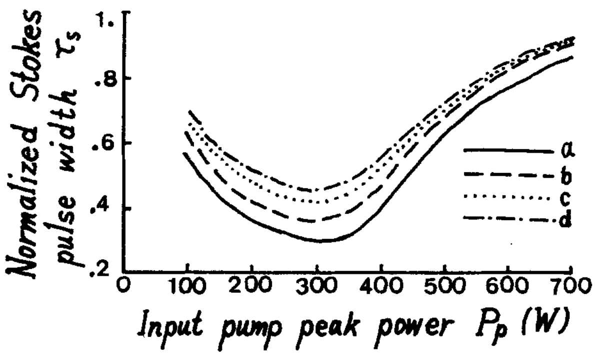

Fig. 4a–d. Plots of the variation of Stokes pulse width vs. input pump peak power for several input pump pulses.

$$f(t)=\begin{cases}\exp(-\ln 2\cdot\tau^n) & (\tau>0)\\ \exp(-\ln 2\cdot\tau^2)\quad \tau=t/t_p & (\tau<0).\end{cases}$$

(a) $n=2$, Gaussian; (b) $n=3$; (c) $n=4$; (d) $n=5$

influence on the pump power $P_{\min}$, at which τ_s is minimum. It also points out that the theoretical plots is approach to the experimental plots as the assumed $f(t)$ goes more asymmetrical.

3. Conclusion

The variation of the Stokes pulse width has been studied both experimentally and theoretically in a multimode optical fiber, as pumped by an A–O Q-switched Nd : YAG laser. The experimental results show:

1) The FWHM width of Stokes pulse t_s is always shorter than that of pump pulse t_p;
2) With the increase of imput pump peak power P_p, t_s shortens in the small-signal-area while broadens in the saturation-area;
3) The minimum of t_s occurs at a critical pump power P_{cr}, at which the output pump pulse from the optical fiber begins to dip at its peak;
4) Pump pulse width t_p has little effect on the variation of the normalized Stokes pulse width τ_s.

Analysis based on the quasi-steady SRS theory shows good agreement with the experimental results. Discussions indicate that the pump pulse profile has a significant influence on the variation of τ_s vs. P_p but no influence on the pump power $P_{\min}$ where τ_s achieves its minimum.

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