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Stimulated Raman scattering in a fiber with bending loss

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Abstract

Stimulated Raman scattering is investigated in a 100-m long single mode fiber with bend-induced loss which has a steep wavelength dependence. The wavelength dependent loss can be used to suppress the second Stokes conversion resulting in an increased first Stokes intensity. Our experiments with a Q-switch Nd:YAG laser produced a rectangular first Stokes pulse at the fiber output. © 1999 Published by Elsevier Science B.V. All rights reserved.

Stimulated Raman scattering in an optical fiber has been the subject of intense research for over two decades; since SRS processes are relevant to many aspects of optical communication systems, optical data processing systems, optical amplifiers etc. [1–3]. At high power level SRS leads to scattering of pump photons to first Stokes photons, then first Stokes acting as a pump generates second Stokes and so on. For many applications the suppression of higher-order Stokes or even first Stokes is desired. Various techniques to perform this have been used; among them are methods based on dual-frequency pumping or four-wave mixing [4,5]. Conventional filters have been used for optical loop memory based on stimulated Raman scattering in fibers [6].

An examination of the equations describing SRS [1] reveals that SRS can be suppressed by high Stokes attenuation distributed along the fiber. SRS in fibers with attenuation has been numerically examined; the results show that the loss for higher-order Stokes can significantly increase the power of low-order Stokes [8]. The distributed fiber loss must depend strongly on wavelength for this technique to be effective. Wavelength dependent loss was realized in capillary optical fibers [7]. In these experiments high attenuation for the second Stokes and low for first Stokes have been achieved because the index refraction of liquid was higher then that for glass for pump and first Stokes but lower for the second Stokes. So for the second Stokes the fiber no longer guides the wave. The suppression of the second Stokes was observed with a corresponding increase of the first Stokes power. However, this technique is too complicated.

The simplest way to introduce wavelength dependent distributed losses is to bend a fiber. The bend-induced loss depends strongly on the wavelength and bend radius [9], and by appropriate selection of the

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bend diameter we can achieve high loss for second and higher-order Stokes and low loss for first Stokes and pump. The results presented here show that the bend-induced loss for the same bend diameter is highly efficient for suppressing second Stokes generation and at the same time negligible for the first Stokes. Implementing this concept allows an increase of the first Stokes energy and rectangular first Stokes pulse generation at the fiber output.

The equations for SRS can be written as follows [1]:

$$\frac{dP_P}{dz} + \alpha_P P_P = -gP_P(P_{S1} + p)/A_{eff},$$

$$\frac{dP_{S1}}{dz} + \alpha_{S1} P_{S1} = g(\lambda_P/\lambda_{S1}) P_P (P_{S1} + p) /A_{eff} - gP_{S1}(P_{S2} + p)/A_{eff},$$

$$\frac{dP_{S2}}{dz} + \alpha_{S2} P_{S2} = g(\lambda_{S1}/\lambda_{S2}) P_{S1} (P_{S2} + p) /A_{eff} - gP_{S2}(P_{S3} + p)/A_{eff} \quad (1)$$

where: P_P, P_{S1}, P_{S2} are pump, first Stokes, and second Stokes powers; λ_P, λ_{S1}, λ_{S2} are wavelengths of the pump, first Stokes and second Stokes; α_P, α_{S1}, α_{S2} are corresponding attenuation coefficients; g is the Raman gain and A_{eff} is the effective area of the fiber mode. Effective input power p is introduced to take into account spontaneous Raman scattering from which SRS is started. We consider here first and second Stokes only. This corresponds to the conditions used in the experiments at which the third Stokes was suppressed very strongly and can be neglected. We have used the value of g equal to 10^{-11} cm/W.

To determine the required strength of the second Stokes attenuation we have simulated the SRS in a 100-m long fiber. The attenuation for pump and first Stokes was considered to be equal to 0, and the attenuation for the second Stokes was changed in the range 0–2 $\times 10^{-3}$ cm^{-1}. The value of p was taken equal to 10^{-6} W. Fig. 1a, Fig. 1b, and Fig. 1c show intensities of the pump and Stokes along the fiber when there is no attenuation of second Stokes (a), attenuation is equal to 4×10^{-4} cm^{-1} (b), and attenuation is equal to 2×10^{-3} cm^{-1} (c). Input pump intensity is equal to 0.7×10^9 W/cm^2. The typical multiple Stokes SRS process is observed in the fiber without attenuation. In this case the first Stokes does not propagate through the fiber because

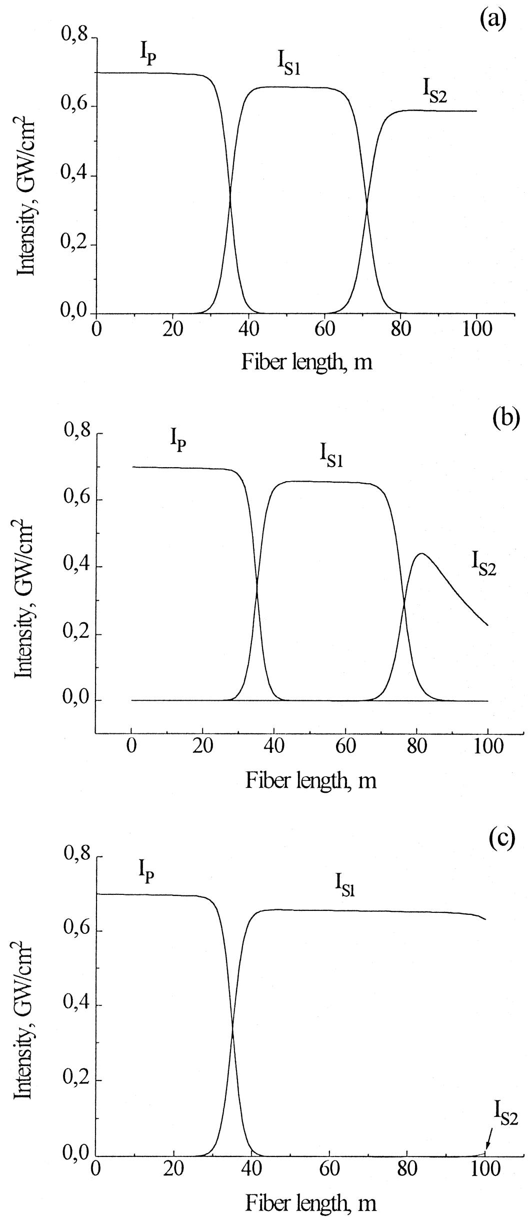

Fig. 1. Calculated dependencies of the pump, first Stokes, and second Stokes intensity on the fiber length. The attenuation of the second Stokes is equal to 0.2×10^{-2} m^{-2}, and 2×10^{-1} m^{-1} for parts (b), and (c) respectively.

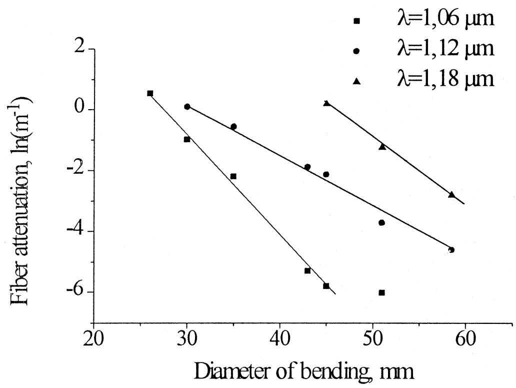

Fig. 2. Dependence of the attenuation on the bend diameter for the pump ($\lambda = 1.06$ μm), first Stokes ($\lambda = 1.12$ μm), and second Stokes ($\lambda = 1.18$ μm).

of efficient energy conversion to the second Stokes. An attenuation equal to 4×10^{-4} cm^{-1} results in a decrease of the second Stokes, but is not yet sufficient to affect the first Stokes. An increase of the attenuation coefficient to 2×10^{-3} cm^{-1} results in the considerable change in the SRS. Now the first Stokes is transmitted through the fiber without attenuation. At the same time the second Stokes at the fiber output has very low intensity. The total attenuation of the 100-m long fiber with the attenuation coefficient $\alpha = 2 \times 10^{-3}$ cm^{-1} is equal to exp(20), this corresponds to the typical Raman gain required for the high power Stokes to appear at the fiber output. To avoid the first Stokes loss, the attenuation coefficient for it must be less then 10^{-4} cm^{-1}.

To find an appropriate bend diameter we have measured wavelength-dependent attenuation of various fibers with different bend diameters. Fig. 2 presents the dependence of the attenuation on the bend diameter for the Newport F–SF single mode fiber. The fiber has a 750 nm cut-off wavelength and a 5.4 μm mode field diameter. The attenuation was measured for wavelength equal to 1.06 μm, 1.12 μm, and 1.18 μm These wavelengths correspond to pump, first and second Stokes when Nd:YAG laser is used as a pump pulse source. On a logarithmic scale the dependencies are quite close to linear. From these results it is clear that the pump attenuation is not affected by bend if the diameter is more then 45 mm. The bend with diameter equal to 50 mm results in high attenuation for the second Stokes equal to 0.38 m^{-1}, and respectively low attenuation for the first Stokes equal to 0.05 m^{-1}. These values are in agreement with those calculated above. So we can expect remarkable changes of the first Stokes parameters in the fiber with the bend diameter close to 50 mm.

The experimental setup used for SRS investigations is shown in Fig. 3. The pump pulses were produced by a repetitively Q-switched Nd:YAG laser. The pulse width was typically 19 ns (full-width at half-maximum), and the pulses typically contained multiple longitudinal modes. The 100-m long fiber was wound on the cylinder. In the experiments, cylinders with diameter of 50 mm, 53 mm, and 110 mm were used. The pump power introduced to the fiber was changed by mechanical alignment of the fiber. A 1 cm diameter loop of the fiber at the distance about 2 m from the fiber end was put into the integrated sphere. We used it to measure the input pump. The pump and Stokes at the fiber output were separated by a monochromator with resolution of 10 nm and detected by a fast Ge-detector with bandwidth equal to 300 MHz.

Fig. 4a and Fig. 4b present typical pulses of the first Stokes measured at the diameter of the fiber bend equal to 53 mm, and 50 mm, respectively. The input pump power was equal to 190 W for both cases. The SRS threshold pump level was found to be equal to 20 W. The first Stokes pulse presented in the Fig. 4a displays the typical shape of an intensity hole at its center, i.e. U-type pulse form. The hole appears due to the energy conversion from the first

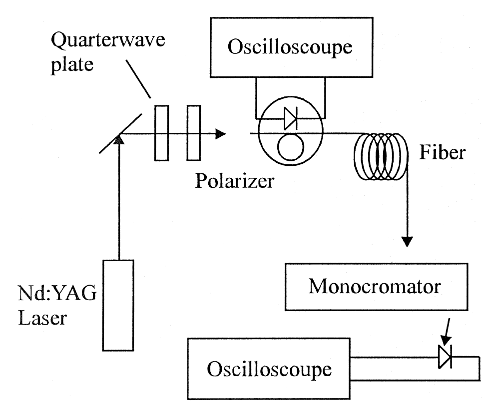

Fig. 3. Experimental set up for SRS measurements.

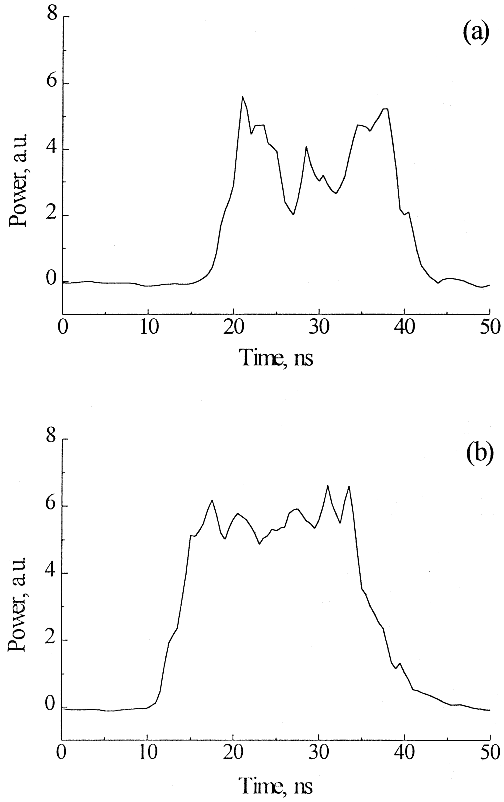

Fig. 4. Experimentally measured first Stokes pulse shapes for the fiber bending diameter of 53 mm (a), and 50 mm (b). Input pump power is equal to 190 W (a) and 210 W (b).

Stokes to the second Stokes. The attenuation for the second Stokes in the fiber with the bend diameter equal to 53 mm is 0.16 m^{-1}, see Fig. 2, and we observed that this loss does not suppress the second Stokes generation. For the smaller bend diameter in Fig. 4b the Stokes pulse is close to rectangular. It demonstrates that second Stokes generation is suppressed by fiber loss introduced by the fiber bend with diameter of 50 mm. The attenuation coefficient is equal to 0.38 m^{-1} in this case. Nevertheless the first Stokes pulse is not Gaussian, which may be expected if the first Stokes does not suffer any losses. It means that some loss for the first Stokes still exists. Two reasons for loss are possible: energy transformation to the second Stokes, and attenuation.

To reveal which of these reasons is most important, a numerical simulation was done with experimentally measured losses for the pump, first Stokes

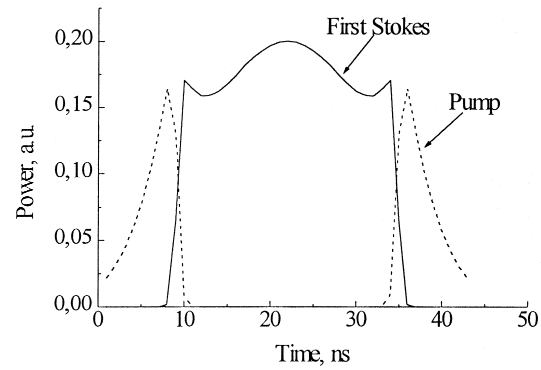

Fig. 5. Calculated first Stokes pulse for the with attenuation corresponding to the bend diameter equal to 50 mm.

and second Stokes. Fig. 5 presents the pulse shape when the fiber attenuation for the pump pulse, first Stokes pulse and second Stokes pulse were $\alpha_P = 0$, $\alpha_{S1} = 5 \times 10^{-2}$ m^{-1}, $\alpha_{S2} = 0.38 \times 10^{-1}$ m^{-1} re-

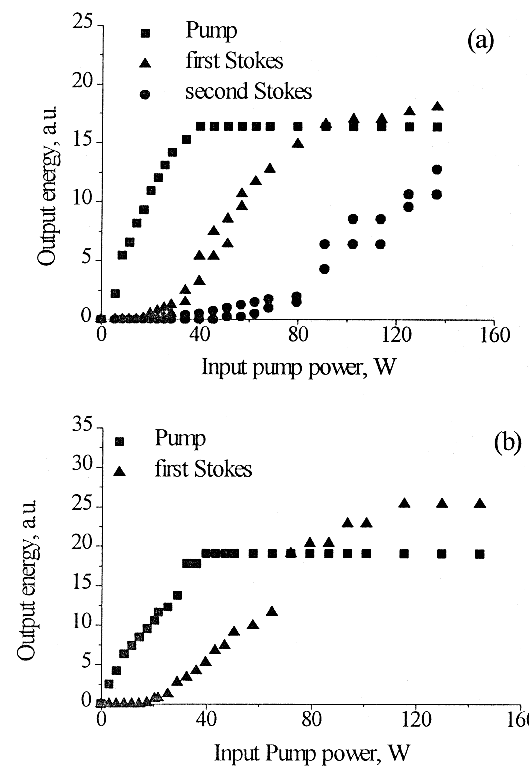

Fig. 6. Experimental dependencies of pump, first Stokes, and second Stokes energies on the input pump power. The bend diameter is equal to 53 mm (a), and 50 mm (b).

spectively. These losses correspond to a bend diameter equal to 50 mm. The input pump power was equal to the threshold power multiplied by 10. We see the same rectangular pulse for the first Stokes as it was observed in the experiments. The simulation has been performed also for the set of equations including pump and first Stokes only. In this case second Stokes is eliminated, and energy conversion to the second Stokes does not occur. The first Stokes pulse was found to be exactly the same. So the second Stokes generation most probably did not affect the first Stokes in the experiments, and the first Stokes had some loss due to the bend-induced attenuation.

The pulse energies at the fiber output were measured as well. Fig. 6a and Fig. 6b present the dependencies of the output pulses energy on the input pump power for the bend diameters equal to 53 mm, and 50 mm respectively. At bend diameter equal to 53 mm both first Stokes and second Stokes appear at the fiber output. For this bend diameter pump attenuation is negligible, third Stokes attenuation is very high, and first Stokes and second Stokes both have low attenuation. For the bend diameter equal to 50 mm, only the first Stokes appears at the fiber output. The attenuation for this case is high for second- and higher-order Stokes. The pump energy at the fiber output was the same for both bend diameters and can be used as a reference level. Comparing the pump and first Stokes energies at the fiber output we can conclude that the first Stokes energy is higher at the bend diameter equal to 50 mm then that at the bend diameter equal to 53 mm.

In conclusion, we have shown that stimulated Raman scattering can be effectively controlled by a fiber bend resulting in spectral dependence of the fiber attenuation. Simulation guided experiment and unraveled the importance of fiber bending losses. In the experiment the complete suppression of second and higher order Stokes, and an increase of the first Stokes was achieved. The suppression of the higher order Stokes resulted in a rectangular first Stokes pulse at the fiber output.

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