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FEMTOSECOND NATURE OF STIMULATED RAMAN SCATTERING IN OPTICAL FIBRES : THE POSSIBILITY OF "DARK" SOLITON GENERATION

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One of the most outstanding achievements of laser physics in recent years is, undoubtedly, the development of methods for the generation and formation of optical pulses containing only a few periods of optical oscillation within their envelopes[1-3].

Penetration into the area of the femtosecond time scale is the result of the intense work of both physicists and engineers that has been carried out over the last fifteen years. An important aspect of this progress has been the widespread use of nonlinear optical methods and optical fibres which are almost the ideal media for effective nonlinear interactions.

Of the many nonlinear effects that occur in a single-mode fibre, stimulated Raman scattering (SRS) is one of the most useful effects for light amplification, frequency conversion and pulsewidth reduction. Under certain conditions, the addition of the optical Kerr effect can induce self-phase modulation which leads to the formation of Raman solitons[3-5].

Nonlinear pulse propagation in an optical fibre is described by the nonlinear Schrodinger equation which predicts the existence of bright solitons (envelope solitons) in the region of negative chromatic dispersion of an optical fibre and dark solitons (a dip in the constant radiation level) in a region of positive dispersion. Since SRS starts from spontaneous emission then it seems quite reasonable to investigate the temporal nature of the radiation in order to establish a symmetry between the positive and negative regions of the group velocity dispersion of an optical fibre.

Towards this goal the temporal characteristics of SRS in a single-mode optical fibre have been studied. The experimental set up included a CW mode-locked and Q-switched Nd:YAG laser ($\lambda = 1.064\mu m$) the radiation from which was launched into a single-mode optical fibre with LP_{11}-mode cutoff wavelength of $1.1\mu m$ and a zero chromatic dispersion wavelength of $1.36\mu m$. Peak pump power was 10kW with a pump pulse duration of 150ps.

The temporal characteristics of the output radiation were analysed by using the zero-background second-harmonic autocorrelation technique with a time resolution 10-15fs. Temporal measurements have been done at wavelengths corresponding to the Stokes components i.e. 1.12, 1.18, 1.24, 1.30 and $1.36\mu m$. The fibre length was varied from 850m to 10m.

Fig. 1 shows an autocorrelation trace from a 450m length of single-mode fibre at $1.18\mu m$. This autocorrelation shape corresponds to a pulse with a noise substructure. Pulse duration is defined by a pedestal duration while noise characteristics are given by the

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amplitude and width of the autocorrelation trace central spike (ACS), which is shown more clearly in the insertion.

The results of the pulse duration measurements are in good agreement with our recent work in which the pulse duration at the Stokes wavelengths was measured with a streak camera[6].

As far as ACS describes femtosecond nature of the Raman scattering, it makes sense to investigate the ACS characteristics more carefully.

Before describing our results we would like to emphasize two points. At first, the autocorrelation function contrast (peak to pedestal ratio) is defined by a noise spike duration τ_s and an average time interval between spikes τ_a. Secondly, a signal with noise spikes has the same autocorrelation trace as a signal with noise dips.

Fig. 2 shows the z-dependence of the ACS at 1.18μm. We would like to pay attention on the smooth increase of the ACS duration. This fact is not characteristic for linear propagation of a noise spike (duration does not depend on a length) or for nonlinear propagation either (duration decreases).

The spectral dependence of the ACS duration and contrast is shown in Fig. 3 by curves 1 and 2 (fibre length = 400m). These results show that the central spike disappears near the zero chromatic dispersion wavelength, i.e. the Stokes pulse has no noise substructure at this wavelength. So, autocorrelation measurements of the Stokes radiation in an optical fibre allow us to define the zero chromatic dispersion wavelength. That is a new but not very convenient method of chromatic dispersion measurement.

As for results interpretation then from our point of view it seems quite reasonable to assume that during cascade SRS, stable femtosecond dips or dark solitons are formatted on a picosecond envelope.

Indeed, Stokes pulse intensity after passing the walkoff length of a fibre, i.e. the distance in which the Stokes and pump waves are interacted, is equal

$$I = \frac{D\Lambda G_{th}}{\tau_p\, g} \qquad (1)$$

where D is chromatic dispersion, Λ is wavelength difference between Stokes and pump pulses, g is SRS gain, G is threshold increment of the SRS (~16), τ_p is pump pulse duration. If one takes into account the linear loss of the fibre, a dispersion pulse spreading and the relationship between the duration and intensity of the dark solitons ($I\tau^2$ = const [7]) then it is easy to obtain the next expression for the dip duration:

$$\tau = \left[\frac{D\lambda^3 g\ \delta\lambda z}{1{,}288\pi^2 n_2 c\ G_{th}\ \Lambda} \right]^{0.5} e^{\alpha z/2} \qquad (2)$$

where $\delta\lambda$ is Stokes spectral width, α is linear loss. The dashed curves in Figs. 2 and 3 represent the corresponding dependences, which have been calculated using (2). One can see sufficiently good agreement between the experimental and calculated results that points out to the correct interpretation of the obtained results.

The nonlinear dynamics of the stationary dips formation can be described in the following manner.

High pump intensity in an optical fibre (~ 10^{10}W/cm^2) causes fast SRS development from spontaneous noise. At the walkoff length end the Stokes pulse is formatted, having noise substructure with an average noise spike duration of approximately 100fs. Simultaneous action of dispersion spreading and self-phase modulation leads to the neighbouring peaks interacting which results in the formation of nonlinear envelopes dips. The behaviour of these dark solitons is described by the nonlinear Schrodinger equation. Since the group velocity of dark solitons depends on their depth[7], then only dips up to zero level will be stable. Otherwise it should be "rolled-off" from the Stokes envelope.

In conclusion we would like to note two points. Firstly, we have investigated the temporal structure of stimulated Raman scattering in an optical fibre in order to establish a symmetry between positive and negative chromatic dispersion regions. Our results indicate that SRS in an optical fibre can be considered from one point of view - the existence of bright and dark solitons. Secondly, our measurements give an indirect proof of the existence of dark solitons and new, more complicated experiments are in progress.

References.

1. R.L. Fork, C.H. Brito-Cruz, P.C. Becker, and C.V. Shank: "Compression of optical pulses to 6fs using cubic phase compensation", Opt. Lett., 12, 483, (1987).
2. F.M. Mitschke and L.F. Mollenauer: "Ultrashort pulses from the soliton laser", Opt. Lett., 12, 407, (1987).
3. A.B. Grudinin, E.M. Dianov, D.V. Khaidarov, D.V. Korobkin, A.M. Prokhorov and V.N. Serkin: "SRS-generation optical pulses as short as 18fs at 1.6μm in an optical fibre", Sov. Phys. JETP Lett., 45, 211, (1987).
4. E.M. Dianov, A. Ya. Karasik, P.V. Mamyshev, A.M. Prokhorov, V.N. Serkin, M.F. Stelmakh, and A.A. Fomichev; "Stimulated Raman conversion of multisoliton pulses in quartz optical fibres", Sov. Phys. JETP Lett., 41, 294, (1985).
5. V.L. da Silva, A.S.L. Gomes, and J.R. Taylor; "High order cascade Raman generation and soliton-like pulse formation in a 1.06μm pumped fibre laser" Opt. Commun., 66, 231, (1988).
6. N.S. Vorobiyv, A.B. Grudinin, E.M. Dianov, A.M. Prokhorov, D.V. Khaidarov; "Direct measurements of Stokes pulses durations in a single-mode fibre", Sov. Phys. J. Tech. Phys. Lett., 13, 365, (1987)
7. V.I. Karpman; "Nonlinear waves in dispersive media", Pergamon Press, 1975.