Ultrabroad-bandwidth multifrequency Raman soliton pulse trains

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Ultrabroad-bandwidth multifrequency
Raman soliton pulse trains

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I have discovered that in the coherent regime of ultrabroad-bandwidth Raman generation, a large number
of long-lived soliton pulse trains are spontaneously generated. This novel solution of the dispersionless
and highly transient regime, involving more than 40 distinct Raman lines of comparable amplitude, is
found to be a strong attractor in the nonlinear dynamics, even when the system is initially far from
this limit.

During the past three decades, stimulated Raman scattering (SRS) has been the subject of many
investigations. It has been known for some time that the equations describing dispersionless
two-wave SRS (the interaction of the pump and first Stokes fields) have a soliton solution in the extreme
transient limit. Initially, it was believed that an instantaneous π phase shift had to be imposed on the
input Stokes field for this soliton solution to be realized experimentally. It was then discovered that
Raman solitons could arise spontaneously from vacuum phase fluctuations of the Stokes field. Physically,
the presence of a π phase shift can reverse the Stokes gain and result in a brief temporal period
of pump repletion. During this repletion period an ultrashort soliton pulse in the pump field can
be generated. Experimentally, however, it turns out to be difficult to control the total number and
the amplitudes of the solitons generated. This instability is partly due to a critical sensitivity of the
soliton formation process on the Stokes phase shift. Any deviation of the initial phase shift from exactly
π results in unstable solitons that decay during propagation. Because these solitons strictly exist only in
the extreme transient limit, their generation can be problematic because the phase modulation of the
input Stokes pulse is required to be essentially instantaneous. In addition, it was proved in Ref. 12 that
the conventional two-wave SRS soliton, where the pump retains a large fraction of its initial energy,
cannot exist for finite energy pulses and, instead, propagates away from the main pulse and disappears.

In nearly all previous studies of SRS, higher-order Stokes and anti-Stokes waves were assumed to be of
negligible amplitude. Remarkably, SRS with symmetric pumping (identical input pump and Stokes
field envelopes) has only recently been examined in detail. Modeling of this regime has led to the
prediction that multifrequency beams consisting of nearly 50 distinct Raman waves of comparable
amplitude may be generated. Such broadband multifrequency beams may have application in
inertial confinement fusion. During their generation, all the constituent waves are coupled together
in nonlinear interaction, and thus the vast majority of previous analyses of SRS are no longer valid.
No analytic solutions fully describing this novel broadband phenomenon are known, and systematic
numerical investigations of the model equations are necessary. In this Letter I present an account
of the temporal characteristics of broadband SRS and report the discovery of robust multifrequency
Raman soliton pulse trains.

To model SRS, the electric field is expanded in terms of plane waves whose frequencies are given
by ω_n = ω_0 + nω_R (n = 0, ±1, ±2, ...), where ω_0 and ω_R are the pump and the Stokes frequencies, respectively.
We recast the governing equations into dimensionless form14-19 and find for the propagation
of the nth normalized electric-field envelope, A_n, and the dynamics of the polarization wave, P,

\[ \frac{\partial A_n}{\partial Z} = \frac{\omega_n}{2\omega_0} [P^* A_{n+1} \exp(-i\gamma_n Z)] - PA_{n-1} \exp(i\gamma_n Z), \]

(1)

\[ \left( \frac{T_2}{t_p} \right) \frac{\partial P}{\partial \tau} = -P + S, \quad S = \sum_j A_j A_{j-1}^* \exp(-i\gamma_j Z). \]

(2)

Z = gI_o z is the gain–length product, g is the Raman gain coefficient, I_o is the peak input intensity,
τ is local time (in units of input pulse width t_p), and T_2 is the medium dephasing time. Dispersion gives
rise to a set of finite values of normalized mistuning, γ_j, which can be parameterized by a single value, γ_1.
The input fields are assumed to drive a resonant transition and, for pumping with Gaussian pulses, are
taken as A_0(τ) = A_1(τ) = \exp(-τ^2). I also consider here square input pulses, defined as A_0 = A_1 = 1
for 0 ≤ τ ≤ 1 and A_0 = A_1 = 0 for τ < 0 and τ > 1. Results are presented for rotational SRS in H_2 gas
pumped by the second harmonic of an Nd:YAG laser, ω_0/2πc = 587 cm⁻¹ and ω_0/2πc = 18 900 cm⁻¹.

Toward the steady-state limit, T_2/t_p → 0, distinct temporal regions become decoupled (incoherent) and
are, ultimately, independent. A finite value of T_2/t_p introduces memory effects (temporal asymmetries).
Fig. 1. Generated intensity profiles of (a) third anti-Stokes, (b) third Stokes, (c) eighth anti-Stokes, and (d) eighth Stokes waves ($\gamma_1 = 0, T_2/t_p = 4, Z = 250,$ and square input pulses). Each profile is plotted normalized to its peak value.

Fig. 2. Collective characteristics of the Raman soliton pulse trains of Fig. 1: (a) source term for the polarization wave, (b) magnitude of the polarization (in units of $10^{-3}$), (c) sum of the wave intensities, (d) bandwidth generated (in units of the Stokes shift).

Fig. 3. As in Fig. 1, except that $T_2/t_p = 10$ and Gaussian input pulses are used.
Fig. 4. As in Fig. 2, except that $T_2/t_p = 10$, Gaussian input pulses are used, and $|S|^2$ is in units of $10^{-1}$.

in units of $t_p$, is 4 or 10. Thus, contrary to previous expectations, we find that bandwidth, which in our case is ultrabroad, can be switched on in a time much less than $T_2$.

In a recent numerical study of three-wave SRS, it was found that, by introduction of a $\pi$ phase shift in the input Stokes field, a single soliton can form at the anti-Stokes frequency. It was also shown that dispersive phase mismatch can lead to the decay of such solitons. We have found that, even when such phase modulation is included, the global (broadband) solution is still attracted to a set of Raman soliton pulse trains. Solitons of two-wave SRS have been shown to exhibit instabilities, and their formation can be triggered by small fluctuations of the Stokes field. Because solitonic zero crossings appear from large $\tau$, one might expect that the presence of noise would have a strong influence on the formation and stability of multifrequency pulse trains. We have also investigated the consequences of including complex noise in the input pump and Stokes fields and have found that soliton pulse trains are robust attractors of the nonlinear dynamics.

In conclusion, I have discovered that Raman soliton pulse trains form spontaneously and dominate the temporal characteristics of multifrequency SRS in the coherent regime. I attribute this feature to a global SRS soliton train solution of the highly transient regime, to which the full solution is strongly attracted, even when the system is initially far from this limit. I have presented results for SRS in H$_2$ gas, but it is expected that my overall conclusions will have much wider applicability. In addition to considerations of other Raman media, there may be application to related phenomena such as stimulated Brillouin scattering and beat-wave generation of intense plasma waves.

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References