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On the generation of ultrabroad bandwidth light for inertial confinement fusion

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Abstract. Symmetric bichromatic pumping in stimulated Raman scattering is predicted to lead to the generation of a multifrequency beam consisting of nearly 50 Raman lines of comparable amplitude. Such a beam may have application in laser fusion. We show that ultrabroad bandwidth may be generated in a time much less than the dephasing time of the nonlinear medium and that two distinct regimes of multifrequency generation exist - the coherent and incoherent regimes. In the coherent regime we have discovered that a large number of long-lived soliton pulse trains are spontaneously generated at the distinct Raman frequencies.

1. Introduction

In nearly all previous studies of stimulated Raman scattering (SRS), higher order Stokes and anti-Stokes waves are assumed to be of negligible amplitude. Remarkably, SRS with symmetric bichromatic pumping (identical input pump and Stokes field envelopes) has only very recently been examined in detail [1, 2]. Modelling 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 (ICF) where high gain targets require collisional absorption to be the dominant process in the laser-target coupling. Experiments have shown that reducing the coherence of the incident light can suppress laser-driven plasma instabilities [3,4]. However, a simple increase in the bandwidth of the incident light can also increase thresholds and lower growth rates for such instabilities [5-7]. This approach, as an alternative to or in combination with the use of incoherent sources, has therefore been suggested for ICF [8, 9].

2. The model

To model broadband SRS, the total electric field is expanded in terms of constituent plane waves whose carrier frequencies are given by $\omega_n = \omega_o + n\omega_R$ ($n = 0, \pm 1, \pm 2, \dots$) where ω_o and ω_R are the pump frequency and Stokes shift, respectively. To study the essential physics of the broadband generation process, we recast the governing equations into dimensionless form. For the propagation of the n^{th} normalised electric field envelope, A_n , and the dynamics of the polarisation wave, P , one finds [2, 10]

$$\frac{\partial A_n}{\partial Z} = \frac{\omega_n}{2\omega_o} [P^* A_{n+1} e^{-i\gamma_{n+1}Z} - P A_{n-1} e^{i\gamma_n Z}] \quad (1)$$

$$\left(\frac{T_2}{t_p}\right) \frac{\partial P}{\partial \tau} = -P + \sum_j A_j A_{j-1}^* e^{-i\gamma_j Z} \quad (2)$$

$Z = gI_0z$ is the gain-length product, g is the Raman gain coefficient, I_0 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 normalised mistuning, γ_n , which can be parametrised by a single value, $\gamma_1 = (k_1 + k_{-1} - 2k_0)/gI_0$. The input fields are assumed to drive a resonant transition and, for pumping with Gaussian pulses, are taken as $A_0(\tau) = A_{-1}(\tau) = \exp(-\tau^2)$. We also consider here square input pulses, defined as $A_0 = A_{-1} = 1$ for $0 \leq \tau \leq 1$ and $A_0 = A_{-1} = 0$ for $\tau < 0$ and $\tau > 1$. Results are presented for rotational SRS in H_2 gas pumped by the second harmonic of a Nd:YAG laser, $\omega_R/(2\pi c) = 587\text{cm}^{-1}$ and $\omega_o/(2\pi c) = 18900\text{cm}^{-1}$. However, we expect that our overall conclusions will have much wider applicability.

3. Incoherent and coherent regimes

Towards the steady-state limit, $T_2/t_p \rightarrow 0$, distinct temporal regions become decoupled (incoherent) and are, ultimately, independent. One finds that the generated Raman waves can be modulated with rapidly-varying envelopes which are a direct consequence of the input pulse shapes. In this limit, square input pulses lead to square output pulses. In dispersionless propagation, and for large Z , a broad temporal region exists where the system reaches a stationary state, corresponding to saturation of the Raman conversion processes [1, 2]. Generated bandwidth shows a strong dependency on input amplitude and its peak value is found to coincide with the pump frequency, $32\omega_R$ [1]. The incorporation of finite dispersion greatly increases the complexity of the temporal profiles of the interacting waves, imposing phase effects that cause rapid oscillations in the time domain. However, in this case, the conversion processes remain Z -dependent and unsaturated, which can result in bandwidth greater than the pump frequency.

A finite value of T_2/t_p introduces memory effects and allows the polarisation wave to grow even while the magnitude of the polarisation source term falls to zero. For dispersionless propagation we have found that the effect of transiency, alone, can be to increase the bandwidth generated. The presence of both finite coherence time and finite dispersion can result in highly complex patterns in the time domain - see Fig. 1(a). The profiles of the interacting waves exhibit irregular and rapidly varying oscillations. However, the combined effect results in a smooth, high amplitude polarisation wave which can mediate efficient Raman conversion processes, not saturating at low Z , and

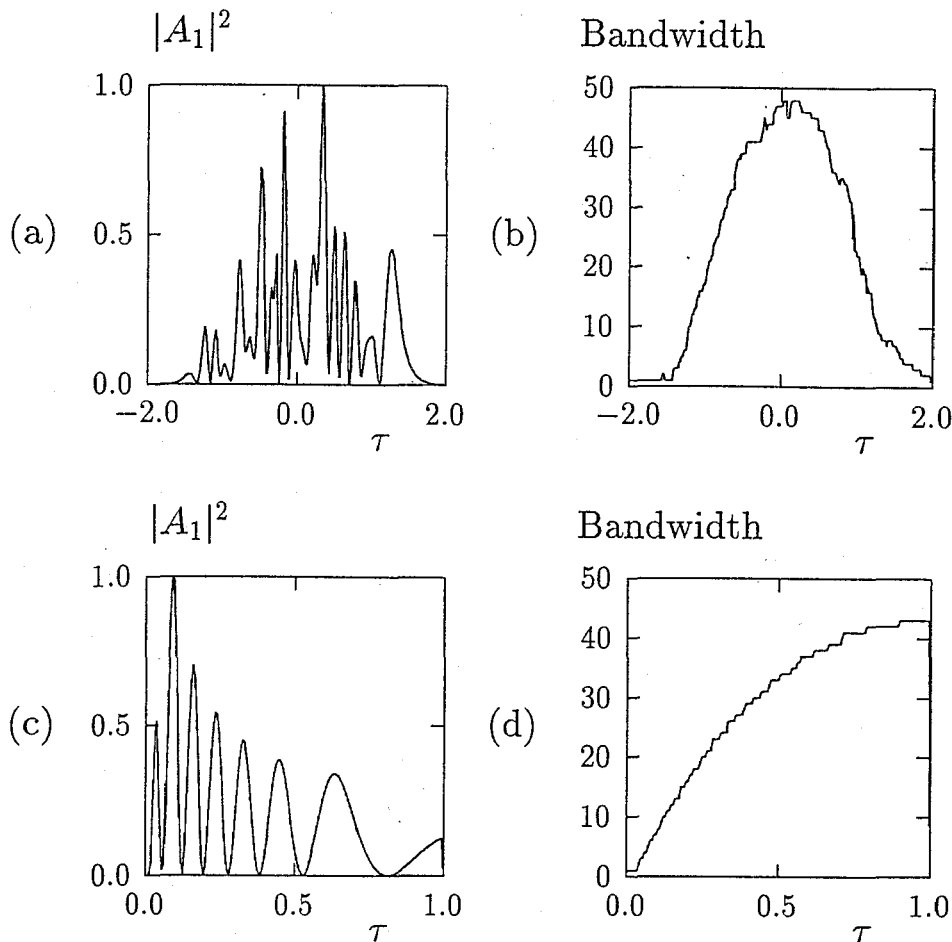


Figure 1. Characteristics of the generated Raman spectra: the normalised intensity profile at the anti-Stokes frequency ($n = +1$) and the generated bandwidth (in units of the Stokes shift). (a) and (b) show results for Gaussian input pulses in the incoherent regime with $T_2/t_p = 0.25$, $Z = 250$ and $\gamma_1 \approx 2 \times 10^{-3}$ ($gI_0 = 1\text{cm}^{-1}$, 1 atmosphere of H_2 gas) while (c) and (d) are for the coherent regime with $T_2/t_p = 4$, $Z = 250$ and $\gamma_1 = 0$.

enabling the generation of a peak bandwidth of nearly $50\omega_R$ - see Fig. 1(b). An optimal (dispersive) phase mismatch between the interacting waves and the collectively-written polarisation grating is shown to increase output bandwidth by 50%.

Considering cases where $T_2 > t_p$ (the coherent regime), we find, in contrast to some of the highly complex patterns found in the incoherent regime, that well-defined pulse trains dominate both the Stokes and anti-Stokes orders. For square input pulses, the complexity of the generated waveforms is further reduced - see Fig. 1(c) and (d). In fully transient SRS, pulse trains appear for both Gaussian and square input pulses; they are intrinsic to the nonlinear dynamics of the system and are not a simple consequence of input pulse shape. These *spontaneous* structures are robust Raman soliton pulse trains, resulting from the collective self-organisation of the interacting waves. Note that, in units of τ , T_2 is 4 here and thus, contrary to previous expectations [9], we find that ultrabroad bandwidth may be switched on in a time much less than T_2 . In applications, bandwidth switch on time can be a crucial parameter [11].

4. Concluding remarks

An important consideration is the distribution of *energy* across the orders. In [2] we outlined the dependency of energy bandwidth on T_2/t_p for calculations with finite dispersion ($\gamma_1 \approx 2 \times 10^{-3}$). It was shown that, in this case, there is an overall increase in energy bandwidth with decreasing T_2/t_p and that, at the same time, the bandwidth switch on time is lowered. Considering target instabilities, if the instability growth rate is smaller than ω_R then each frequency can drive its own instability. Alternatively, if this growth rate is much larger than ω_R then the discrete spectrum can be considered as continuous [9, 11]. In either regime, the use of broadband spectra can be highly advantageous. For applications in ICF, the incoherent regime appears optimal for $\gamma_1 \approx 2 \times 10^{-3}$, allowing the *rapid* generation of *larger* bandwidth and also enhancing the temporal bandwidth of each wave. However, as $\gamma_1 \rightarrow 0$ and for small T_2/t_p we have found that saturation of the conversion processes occurs at moderate values of gain-length product. For $\gamma_1 = 0$ and large Z we can report that energy bandwidth is optimised in the coherent regime. In this case the global solution is strongly "locked" to a set of soliton pulse trains. This latter consideration may be an important feature if these results are to be applied to other Raman media, such as N_2 [11], where the Stokes shift can be much smaller.

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