COHERENCE EFFECTS AND BANDWIDTH OPTIMISATION IN MULTIFREQUENCY RAMAN GENERATION

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INTRODUCTION

Stimulated Raman scattering (SRS) is well-established as a simple and efficient method of converting laser radiation to one or more lower (Stokes) frequencies. However, parametric Raman conversion to higher frequencies, or the simultaneous generation of multiple Raman lines, has generally been found to be much less efficient. The common assumption has been that, for optimal conversion of the input energy, the phase-matching conditions for the parametric processes dictate the geometry of the interacting waves. Radiation is therefore generated over a wide range of angles, resulting in low interaction lengths and a multifrequency "beam" that cannot be focused to a single spot. We have proposed that the collinear generation of higher orders, in the presence of finite dispersive phase mismatch and with fully symmetric pumping (input pulses of matching intensity and shape), has much greater potential than phase-matched generation. Results to date predict that the generation of a single multifrequency beam consisting of nearly 50 waves of comparable energy is possible[1,2,3]. The most immediate application of this work is in the field of inertial confinement fusion (ICF) where the use of a broadband light source may overcome several problems related to the transmission and delivery of high optical energy[4]. However, the predicted magnitude of bandwidth generated is such that our results may also find application in other areas such as plasma physics, measurement techniques, spectroscopy and sensing.

In multifrequency Raman generation, an optical beam initially containing 2 frequency components (ω_0 and ω_{-1}) drives a Raman resonance in a nonlinear medium at the difference frequency ω_R ($= \omega_0 - \omega_{-1}$). As a result, the incident energy is distributed among the Raman orders $\omega_n = \omega_0 + n\omega_R$, situated on both the red and blue sides of the incoming radiation ($n = 0, \pm 1, \pm 2, \ldots$). To model this process, the total electric field is expanded in terms of the constituent plane waves. For the propagation of the n^{th} normalised electric field envelope, A_n, and the dynamics of the polarisation wave, P, one finds

$$\begin{aligned} \frac{\partial A_n}{\partial Z} &= \frac{\omega_n}{2\omega_0}[P^* A_{n+1} e^{-i\Gamma_{n+1} Z} - P A_{n-1} e^{i\Gamma_n Z}] \\ (\frac{T_2}{t_p})\frac{\partial P}{\partial \tau} &= -P + \sum_j A_j A_{j-1}^* e^{-i\Gamma_j Z} \qquad (1) \end{aligned}$$

$Z = \gamma I_p z$ is a gain-length product, γ is the Raman gain coefficient, I_p 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, $\Gamma_1 = (k_1 + k_{-1} - 2k_0)/\gamma I_p$. Here, we take the input fields to be either Gaussian or square pulses and results are presented for rotational SRS in H_2 gas pumped by the second harmonic of a Nd:YAG laser.

COHERENCE EFFECTS

We have found that two distinct regimes of multifrequency generation exist - the coherent and incoherent regimes[5]. Towards the steady-state limit, $t_p/T_2 \to \infty$, distinct temporal regions become decoupled (incoherent) and are, ultimately, independent. In this limit, square input pulses lead to square output pulses. However, for pumping with Gaussian pulses one finds that the generated Raman waves are modulated with rapidly-varying envelopes which are a direct consequence of the input pulse shapes. Furthermore, the presence of finite coherence time and finite dispersion can result in highly complex patterns in the time domain - see Fig 1(a). In ICF 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. On the other hand, analyses have predicted that a simple increase in the spectral bandwidth can also increase thresholds and lower growth rates for such instabilities. Thus the use of light which is both incoherent and ultra-broadband may be optimal for this application.

Considering cases where $T_2 > t_p$ (the coherent regime), we find that well-defined pulse trains dominate both the Stokes and anti-Stokes orders[6]. For square input pulses, the generated waveforms are further simplified - see Fig 1(b). These 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. Indeed, these spontaneous structures are robust Raman soliton pulse trains, which result from the self-organisation of many interacting waves[6].

BANDWIDTH OPTIMISATION

We have undertaken a full investigation of the roles played by dispersion, gain-length product, transiency and the temporal characteristics of the incident light fields. For dispersionless propagation we find that the effect of transiency is to increase the bandwidth generated - see Fig 1(c). This follows from the fact that the polarisation wave is no longer constrained to follow its source term adiabatically and can continue to grow even while its driving term falls to zero. For sufficient Z, the bandwidth is maximised in the coherent regime where the broadband spectrum locks on to the soliton pulse train solution. In the incoherent regime, the combined effect of transiency and moderate dispersion enhances the output bandwidth since strong parametric and non-parametric processes can contribute to the frequency conversion[2]. As can be seen in the case of $t_p/T_2 = 4$, the generated bandwidth can be increased by around 50%. However, when either transiency or dispersion is too strong we find that the net effect is to suppress broadband generation.

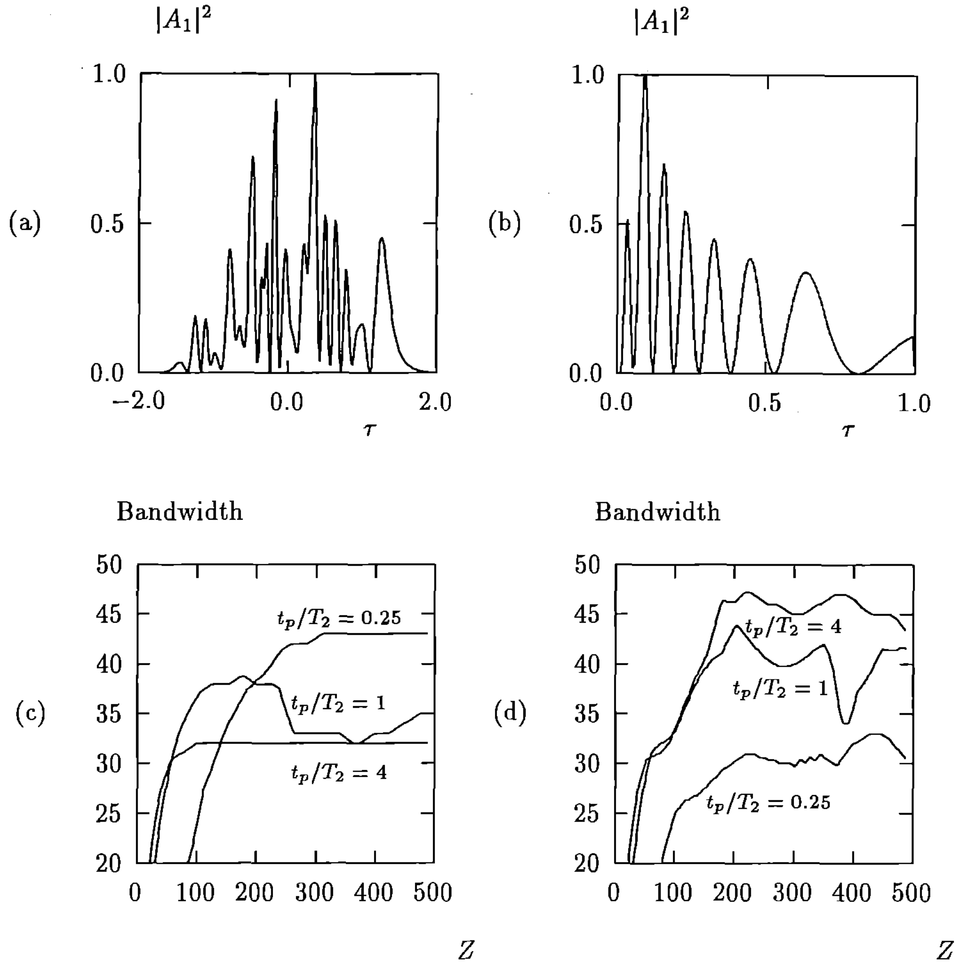

Fig 1 Characteristics of the generated Raman spectra. (a) and (b) show normalised intensity profiles at the anti-Stokes frequency ($n = +1$). (a) is for Gaussian input pulses in the incoherent regime with $t_p/T_2 = 4, Z = 250$ and $\Gamma_1 \approx 2 \times 10^{-3}$ ($\gamma I_p = 1\mathrm{cm}^{-1}$, 1 atmosphere of H_2 gas). (b) is for square input pulses in the coherent regime with $t_p/T_2 = 0.25, Z = 250$ and $\Gamma_1 = 0$. (c) and (d) show the generated bandwidth (in units of ω_R) as a function of the gain-length product, Z. Results for three levels of transiency, $t_p/T_2 = 4, 1$ and 0.25 are shown. In (c) $\Gamma_1 = 0$ (the dispersionless case) while (d) is for $\Gamma_1 \approx 2 \times 10^{-3}$. Note that for low Z bandwidth is relatively independent of moderate levels of dispersion.

In multifrequency generation the key quantity is the parametric gain[1]. A simple expression, which is proportional to the maximum possible value of this quantity, has been found to be a good qualitative predictor of the dependencies of the generated bandwidth in the regime of unsaturated amplification[7]. This expression is

$$P_{max}(T) = \exp(-T)\int_{-\infty}^{T} \exp(T')A_0(T')A_{-1}(T')dT' \qquad (2)$$

where T is local time in units of the dephasing time T_2. Simulations have been performed to examine dependencies on parameters such as the input Stokes amplitude, the input pulsewidth ratio and the relative timing of the pump pulses. The correlation of bandwidth generated with the above expression demonstrates the importance of spatiotemporal overlap of the input pulses for efficient multifrequency generation and, consequently, why symmetric pumping is optimal for maximising the output bandwidth.

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