49.

Short Communication

Dependence of stimulated Raman threshold on the pump bandwidth

The question of Raman gain (or threshold) dependence on pump laser bandwidth, $\Delta\nu_L$, has received considerable attention, both theoretical and experimental ([1, 2] and references therein). One aspect of this question has been particularly emphasized, namely the comparison between Raman gain for a single-mode pump pulse and for a multi-mode pump pulse. To be specific, let us consider the case of a single-mode pump pulse having a bandwidth much less than the Raman medium linewidth, $\Delta\nu_L \ll \Delta\nu_R$, and a multi-mode pump pulse for which the inequality is reversed, i.e. $\Delta\nu_L \gg \Delta\nu_R$. Let us also consider these two pulses (temporally smooth in the single-mode case and deeply modulated in the multi-mode case) to have envelopes of the same overall duration. Then the conclusion reached by theoretical analysis and confirmed by experiments [1, 2] is that for forward Raman scattering in a dispersionless medium the threshold pump energy is the same in each of these two cases.

This is a useful result since it indicates that in some circumstances the requirements on frequency selection of the pump laser can be greatly relaxed. It is important to note however that the Raman gain is not entirely independent of the pumping laser bandwidth [3], a fact that is in danger of being overlooked. We refer to a situation, which is quite likely to be encountered experimentally, where the laser output is in more than one mode but still with a bandwidth $\Delta\nu_L$ less than $\Delta\nu_R$. We shall refer to this as a multi-mode narrowband pump. In this case the threshold will be less than for the single-mode and multi-mode broadband ($\Delta\nu_L \gg \Delta\nu_R$) cases. A simple explanation of this can be given by considering the behaviour in the time domain. Temporal structure in the pump pulse cannot be shorter than $\sim 1/\Delta\nu_L$ and provided this structure is long in duration compared to the characteristic response time ($\sim 1/\Delta\nu_R$) of the Raman medium, i.e. $\Delta\nu_L \ll \Delta\nu_R$, then the medium will show a steady state response to the intensity variations within the pulse. (Strictly, one should also take account of the highly nonlinear dependence of Stokes wave growth on the pump intensity, so the above inequality becomes $\Delta\nu_L \ll \Delta\nu_R/G$ where G is the gain exponent [4]). Since a multi-mode pulse contains peaks of greater intensity than a single-mode pulse of the same energy, the multi-mode narrowband pulse will yield a lower energy threshold for forward stimulated Raman scattering. This situation was not explicitly considered in the various experimental investigations into threshold dependence on pump bandwidth [1, 2, 5]. To clarify this point we have therefore measured the stimulated vibrational Raman scattering threshold in hydrogen gas for 1.06 μm pump pulses with the following characteristics: 1. single mode, $\Delta\nu_L \ll \Delta\nu_R$, 2. two-modes, $\Delta\nu_L \ll \Delta\nu_R$, 3. multi-mode broadband, $\Delta\nu_L \gg \Delta\nu_R$. As expected we have found the threshold to be the same for cases 1 and 3. For case 2 the threshold was found to be lower by a factor of ~ 1.5, in principle a factor of 2 would be expected if steady state conditions had been achieved since the peaks are twice as intense as in a single-mode pulse.

The laser used in these measurements has been described in [6–8]. It provided a TEM_{00} output and when Q-switched in a conventional way its output linewidth was ~ 0.3 cm^{-1}, thus satisfying the requirement for multi-mode broadband pumping. When operated with prelase-triggered Q-switching [8], single-longitudinal mode (SLM) operation was obtained, with pulses free from intensity modulation. The periods of SLM operation, which lasted for typically 1–2 min, were separated by periods of 10–20 s during which the pulses showed a sinusoidal intensity modulation. The modulation frequency corresponded to adjacent mode beating, i.e. at a frequency $C/2L$ = 115 MHz, and the depth of modulation varied from shot to shot, occasionally reaching the base line when the two modes were of equal intensity. The lowest Raman threshold was observed, as expected, with these deeply modulated pulses.

The Raman scattering medium was hydrogen gas, contained in a cell of 58 cm length. The cell was equipped with Brewster-angle windows to suppress any Stokes or pump feedback. This is an important precaution to take since the backward

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Raman gain is very different for narrowband and broadband pumping (see e.g. [9]), and the presence of any feedback between forward and backward waves could lead to a spurious dependence of threshold on pump linewidth. The laser beam was tightly focussed into the cell, with the beam waist at the cell centre having a confocal parameter of 2.5 cm. The laser was operated at the same flashlamp input for all measurements and the laser energy input to the cell was varied by means of an attenuator consisting of a pair of tilted glass plates. This arrangement ensured that the beam profile and pulse duration were unchanged as the intensity was adjusted. The stimulated Raman scattering (SRS) threshold was detected by visual observation of the appearance of a green beam (564 nm) resulting from the second anti-Stokes scattering and the threshold pump energy was measured by a calorimeter at the input to the cell.

Fig. 1 shows the results of these threshold measurements for a range of hydrogen pressures. The threshold power is defined as (threshold energy) × 0.94/pulse envelope duration (full width at half maximum, FWHM), the factor 0.94 being appropriate to a Gaussian time dependence. The pulse duration was found to have the following values: (a) 32 ns for SLM operation and two-mode operation and; (b) 29 ns for broadband operation. The abscissa in Fig. 1 includes some calculated values (using data from [5]) for the Raman linewidth $\Delta\nu_R$ (FWHM). The upper solid curve in the figure shows the calculated threshold for SLM pumping assuming a steady state response. It can be seen that the experimental results for both SLM and broadband pumping agree well with the calculation. Fig. 1 also clearly indicates a significantly lower threshold for the two-mode pumping. What is also apparent is that the threshold reduction for two-mode pumping is less significant at lower pressures. The explanation for this probably lies in the fact that for narrower Raman linewidths (e.g. ~ 450 MHz at 10 atm pressure) the requirement for steady state response to the variations of intensity of the two-mode pump is clearly not satisfied. In fact it is likely that steady state conditions were not fully reached even at the highest pressure used and this could account for the fact that the two-mode threshold reduction was less than the expected factor of two.

In conclusion, we have given a direct experimental confirmation of the fact that although the Raman threshold is the same for single-mode and broadband pumping ($\Delta\nu_L > \Delta\nu_R$) it is reduced when the pump laser is narrowband ($\Delta\nu_L < \Delta\nu_R$) but not single-mode.

It is important to note, therefore, that in measurements of Raman threshold where a narrowband pump laser is used ($\Delta\nu_L < \Delta\nu_R$), the laser must be single-mode if the results are to be unambiguous. On the other hand, it is also clear that if the aim is to achieve SRS for a minimum pump energy then it is advantageous to use a narrowband ($\Delta\nu_L < \Delta\nu_R$) but multi-mode pump.

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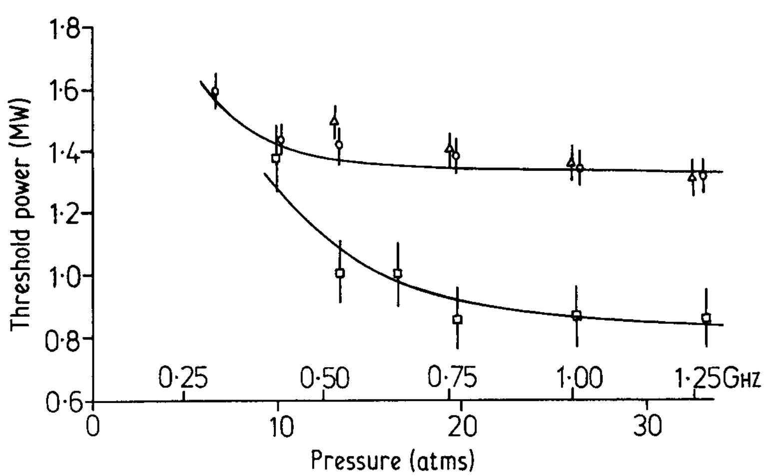

Figure 1 Stimulated vibrational Raman threshold power for a 1.06 μm pump in hydrogen gas, as a function of gas pressure. Linewidths (FWHM) of the Raman transition in GHz are also indicated. Threshold power is defined here as (threshold energy) × 0.94/pulse duration (FWHM). The upper solid curve is a theoretical calculation assuming steady state response. Experimental points correspond to; ○ – SLM pump, □ – two-mode pump, △ – broadband pump.

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