LOW THRESHOLD OPERATION OF A WAVEGUIDE H_2 RAMAN LASER

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The use of a fused silica capillary for reduction of stimulated Raman scattering threshold in H_2 gas has been investigated. A threshold pump power at 1.06 μm of 70 kW has been obtained, a twentyfold reduction over free space propagation. Further threshold reduction should be possible by taking care over capillary straightness.

Stimulated Raman Scattering (SRS) provides a convenient and efficient means of shifting the frequency of high power lasers [1]. This is particularly interesting in the case of tunable lasers since their tunability can then be extended to other regions of the spectrum. In this context high pressure H_2 gas has been widely used as a Raman medium since it offers a number of attractive features such as a large Raman shift, a narrow transition linewidth, a good transparency and freedom from problems caused by stimulated Brillouin scattering and self-focussing. Its drawback is that to reach SRS threshold, pump power levels of around 1 MW are typically required. A reduction of these threshold powers by one or two orders of magnitude could offer much more scope for the application of SRS, in particular to frequency down-conversion of various tunable near-infrared lasers operating at more modest power levels, e.g. vibronic lasers, colour centre lasers or optical parametric oscillators. A further advantage of achieving a low threshold is that one can divide the available pump power to drive a Raman oscillator and amplifier. This configuration can result in a more efficient channeling of the pump power into the intended Stokes radiation [2].

Techniques which have been applied to reduce the SRS threshold include the use of multiple pass configurations [3,4], the use of resonators to provide feedback of the Stokes radiation [5] and the use of hollow dielectric waveguides to guide the pump and Stokes radiation [6,7]. In fact a combination of waveguiding and feedback could be used, as in waveguide lasers [8] and this should in principle give a reduction of SRS threshold by something like two orders of magnitude. To investigate this possibility we chose first to address the question of how great a threshold reduction can be achieved in practice simply by using a capillary waveguide. The experiments described by Rabinowitz et al. [6] and Hartig and Schmidt [7] emphasized a comparison of conversion efficiency with and without guiding but they do not give an explicit comparison of threshold powers. In this letter we report results for the generation of 1.9 μm Stokes radiation from a 1.06 μm pump in H_2 gas contained in a capillary waveguide. A threshold pump power of 70 kW has been achieved, representing a factor of twenty reduction compared with unguided propagation. With better quality capillaries and with feedback of the Stokes wave a further significant reduction appears feasible.

The pump source used in our experiments was a Q-switched NdYAG laser providing a high output power in a clean TEM_{00} beam and in a single longitudinal mode [9,10]. This well-defined laser output is helpful for a careful comparison of measured and predicted thresholds. The use of a TEM_{00} beam also conferred other advantages. It allowed well-defined launching conditions into the capillary and this has enabled us to avoid optical damage even when operating with an on-axis beam intensity up to an order of magnitude higher than the damage threshold of the capillary material (fused silica). The TEM_{00} mode couples very efficiently into the lowest loss mode (EH_{11}) of the capillary [8]. The TEM_{00} beam was also helpful in the procedure for adjusting the capillary for optimum transmission, since this was based on the visual observation (via burn paper and phosphor card) of a clean beam of circular symmetry leaving the output end of the capillary. A photodiode array was used to confirm that the emerging beam was diffraction-limited.

Initial measurements of SRS threshold were made in H_2 gas in a high pressure cell of large bore (i.e. no guiding was involved). Brewster angle end windows were used to suppress pump and Stokes feedback. The cell length was 58 cm and the pump beam was focussed to a beamwaist at the centre of the cell, with a spot size (W_0 = 0.10 mm) chosen to make the confocal parameter ($b = 2\pi W_0^2/\lambda$) much less than the cell length. Using the value of plane wave Raman gain coefficient as calculated by Trutna and Byer [4], and the analysis of Cotter et al. [11] to account for the actual gaussian beam profile of pump and Stokes waves we have calculated the threshold pump power as a function of gas pressure. Above ~4 atmospheres the threshold is essentially independent of pressure and the predicted threshold (1.4 MW) and measured threshold (1.3 ± 0.15 MW; 35 mJ in a 25 ns FWHM pulse) are in good agreement. In the calculation of threshold it was assumed that a net single pass Stokes gain of exp(30) was required and this coincided with the experimentally defined criterion that a Stokes energy of ~10 μJ corresponded to threshold being exceeded. This criterion was found to correspond to the experimentally more convenient observation of a visually detectable green beam of 2nd antiStokes radiation (564 nm).

For the capillary waveguide measurements we have used a variety of capillary lengths and internal diameters, all made of fused silica. We confine ourselves mainly to a discussion of the results obtained from a 1 m length of capillary of 330 μm bore diameter and outside diameter of 5 mm. The high pressure cell made use of the capillary itself as the walls of the pressure vessel. This was an important feature of the design since it allowed the capillary to be clamped into a V-groove and thus some control could be exercised over the tube straightness. The end windows were held in high pressure metal fittings which were O-ring sealed to the outside of the capillary and also clamped to ensure they could not slide off the end. Unfortunately with the metal fittings available the distance from the window to the capillary end was only ~5 cm and the small pump spotsize on the window (W = 190 μm, corresponding to W_0 = 110 μm at the capillary) meant that the input energy was limited to <15 mJ to avoid window damage. In a separate measurement we have transmitted 50 mJ, 25 ns pulses through a 25 cm length of 300 μm bore capillary with no sign of damage, even though dust particles in the capillary cause air breakdown.

The pump spot size W_0 at the capillary entrance was matched to the capillary diameter, $2a$, by arranging that $3W_0 = 2a$, for which condition the input gaussian beam should couple with 98% efficiency to the EH_{11} mode of the guide [12]. The entire assembly of V-groove and guide was then positioned by horizontal and vertical adjustments applied at the input and output ends (the former being the more critical), until the output beam was seen to have good circular symmetry. A maximum measured guide transmission of 60% was obtained in this way, and it was confirmed using a photodiode array that the exit beam was diffraction-limited. In fact a calculation of the guide transmission following the analysis of Marcatili and Schmeltzer [13] yields a transmission, T, of 86.5% for a straight guide ($T = \exp(-2\alpha_{11}l)$, $\alpha_{11} = 0.216\,\lambda^2/a^3$ for fused silica with n = 1.455). It is thought that most of the loss in this capillary arises from bends. Marcatili and Schmeltzer show that a bend of radius R gives rise to an additional loss (to be added to α_{11}) which, in the case of fused silica, is given by $19.4\,a^3/\lambda^2R^2$. To give some idea of the sensitivity to bends we note that a bend radius of 25 m (caused for example by the core oscillating transversely with an amplitude of 200 μm over a period of 0.2 m) would account for ~22% loss in this guide. These numbers underline the importance of holding the capillary straight. However it is also apparent that even a small, and difficult to detect, wander of the core relative to the outer capillary wall could introduce large losses.

Despite the imperfect transmission properties of this capillary (i.e. a measured loss α which is 3.5 times greater than predicted for a straight guide) the SRS threshold was found to be only 130 kW (3.5 mJ in 25 ns), an order of magnitude less than for the unguided situation. For a pump energy input of 12 mJ, the Stokes output of 1 mJ was measured in the forward direction (15% photon conversion efficiency). A rough estimate of the expected threshold reduction can be made by comparing the input powers, P, required to give the same product of medium length and on-axis intensity. For unguided propagation this product is given by

$$\int_{-l/2}^{+l/2} \frac{2P}{\pi W^2(z)}\,\mathrm{d}z = \frac{4P}{\lambda}\tan^{-1}(l/b)\,, \tag{1}$$

where $b \equiv 2\pi W_0^2/\lambda$ and $W_0 = W(0)$. When $l \gg b$ the integral has the value $2\pi P/\lambda$. For the case of guided propagation, we assume the power decays according to $P\exp(-2\alpha z)$ and the product is given by

$$\int_0^l \frac{2P\exp(-2\alpha z)}{\pi W_0^2}\,\mathrm{d}z = \frac{2Pl}{\pi(2a/3)^2}\,\frac{[1-\exp(-2\alpha l)]}{2\alpha l}\,, \tag{2}$$

where we have put $3W_0 = 2a$. Comparing this with $2\pi P/\lambda$, and putting in the values $l = 1$ m, $a = 165$ μm, $\exp(-2\alpha l) = 0.6$ yields a predicted threshold reduction of ~7, in reasonable agreement with the observed reduction. The discrepancy is probably due to the additional reduction which arises from Stokes guidance. More detailed calculations taking account of the radially varying gain distribution, and also Stokes diffraction and guiding will form the subject of a further publication [14].

Thus we have demonstrated experimentally that a reduction of SRS threshold by an order of magnitude can be achieved even with a capillary tube having significantly greater losses than predicted for a straight tube. If one considers the possibility of a perfectly straight capillary one can show [13] that a 60% transmission of a 1.06 μm beam over a 1 m length of guide would imply $a = 100$ μm, and hence from (1) (i.e. neglecting the effect of Stokes losses) a further reduction in threshold of $(165/100)^2 \sim 3$ is implied. We have carried out some further measurements which confirm the importance of capillary straightness and which also show that a reduction of bore diameter offers a further threshold reduction. The results discussed above were obtained when the capillary was held in a piece of extruded aluminium angle. The same when held in a precision V-groove (tolerance of <50 μm) gave a transmission of 75% instead of 60%, implying that the loss coefficient α had been further reduced by a factor of 1.8. Good results have also been obtained with thin wall fused silica capillaries of 300 μm diameter (outside diameter 400 μm). A He-Ne laser beam, at 633 nm, gave a measured transmission of 92% over a 1 m length of capillary held in the precision V-groove; theoretical transmission [13] is 95%, and this theoretical value does not include the ~2% loss due to launching [8]. Clearly a more systematic set of loss measurements is called for (as e.g. in [15]) to check how closely the observed losses approach the predictions of Marcatili and Schmeltzer [13]. We have observed SRS in H_2 contained in a thin walled capillary (150 μm bore, 270 μm outside diameter) by inserting the thin capillary into a thick walled capillary of 300 μm bore which was held in the precision V-groove and equipped with end windows as described above. The best transmission for the 1.06 μm pump was only 15%, nevertheless a threshold energy as low as 1.9 mJ (i.e. 70 kW power) was observed, corresponding to a twentyfold reduction compared with unguided propagation. These results confirm that with proper attention to capillary quality and straightness a very substantial threshold reduction is possible. It should be noted that the threshold power we have reached is already comparable to the power output available from some vibronic laser systems [15].

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