# Low-threshold operation of a waveguide $CH_4$ Raman laser at 1.54 $\mu$m

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**Abstract:** A convenient source of high-power ($\sim$20 kW) stable mode-locked pulses at 1.54 $\mu$m, suitable for pulse-compression studies in the negative group-velocity-dispersion region of optical fibres, is described. The source is based on a capillary-waveguide Raman laser, using $CH_4$ gas, and pumped by a mode-locked $Q$-switched CW Nd : YAG laser. Initial results for a synchronously pumped Raman laser are also presented.

## 1 Introduction

The spectral region around 1.5 $\mu$m is of particular interest in optical communications since fused-silica fibres have very low loss in this region. The negative group-velocity dispersion in this region is also of interest since it offers the possibility of soliton pulse propagation. There are few sources of mode-locked pulses of sufficient power to induce nonlinear propagation effects in this 1.5 $\mu$m region, and studies of soliton behaviour have so far relied on colour-centre lasers [1, 2]. In this paper we report the development of a rather simple source of high-power mode-locked pulses at 1.54 $\mu$m which should prove suitable for studies of nonlinear propagation behaviour.

The source is based on stimulated Raman scattering (SRS) in $CH_4$ gas, pumped by the 1.06 $\mu$m output from a mode-locked $Q$-switched continuously pumped Nd : YAG laser (Spectra Physics 3000). To reduce the threshold to a level that could be reached by the output from such a CW pumped laser, the $CH_4$ gas was contained in a capillary waveguide, thus providing guidance for both the pump and Stokes waves [3–7]. Working at a $CH_4$ gas pressure of 7 MPa (70 atmospheres), the threshold pump power was measured to be $\sim$200 kW; an order of magnitude reduction in threshold compared with an unguided geometry, and more than a factor of two lower than the available output power from the pump laser. Peak power of the generated 1.54 $\mu$m pulses was $\sim$20 kW with amplitude stability equal to that of the pump laser. The output beam was diffraction limited. Since this type of Nd : YAG laser is widely used in optical-communications research laboratories and since operation is in principle possible up to $\sim$1 kHz, this Raman laser provides a potentially attractive and simple source.

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## 2 Background

Under plane-wave pumping conditions the steady-state power gain for the scattered Stokes wave, of frequency $\omega_s$, is exp $G$, where $G = g_R I_p l$. Here $I_p$ is the pump intensity, $l$ is the length of medium and $g_R$, the Raman gain coefficient, is given by [8]

$$g_R = \frac{16\pi^2 c^2 \Delta N}{n_s^2 \hbar \omega_s^3 \Delta\omega_R}\left(\frac{d\sigma}{d\Omega}\right) \tag{1}$$

Here $\Delta N$ is the difference in population density between the initial and final levels (in this case simply the number density of $CH_4$ molecules), $\Delta\omega_R$ is the Raman linewidth and $(d\sigma/d\Omega)$ is the Raman-scattering cross-section. For $CH_4$ it has been shown that the linewidth $\Delta\omega_R$ is given by [9]

$$\Delta\omega_R = \pi c(64 + 2.4P) \tag{2}$$

where $P$ is the pressure in atmospheres. The Raman cross-section $(d\sigma/d\Omega)$ is here defined in terms of the ratio of scattered to incident intensity as in Reference 3. The threshold for stimulated Raman scattering is reached when $G_{th} = 25$. From eqn. 1 and the relation $G = g_R I_p l$, the threshold pump intensity can be calculated. In practice, two further modifications to the analysis are needed, to account for the nonuniform intensity within the pump beam and the transient character of the Raman scattering when the pump pulse durations are comparable to the inverse of the Raman linewidth. With these modifications the threshold pump power, for an unguided beam focused at the centre of a Raman medium of length $l$ to give a confocal parameter $b$, is given by Reference 3:

$$P_{th} = \frac{F\lambda_s}{4g_R}\left[1 + \left(1 + \frac{G_{th}\lambda p}{\lambda_s \tan^{-1}(l/b)}\right)^{1/2}\right]^2 \tag{3}$$

The numerical factor $F$ accounts for the transient behaviour, and the procedure for calculating $F$ is given in Reference 3. Using eqn. 3, it is found that the predicted threshold pump intensity, for a 1.06 $\mu$m pump of $\sim$100 ps duration generating 1.54 $\mu$m 1st Stokes radiation in $CH_4$ gas at $\sim$7 MPa, is $\sim$2 MW, in good agreement with experimental results [3]. This is significantly greater than the 0.5 MW peak power available from a typical CW pumped Nd : YAG laser. The necessary reduction in threshold can however be achieved by an appropriate choice of capillary waveguide [4, 5].

The capillary used in this work was a thin-walled capillary made of fused silica, with a bore diameter of $2a = 180\ \mu m$. To support the capillary and hold it straight, it was fitted inside another glass capillary of large outside diameter ($\sim 6$ mm) and then placed inside a high-pressure cell. The end windows of the pressure cell were of fused silica, $\sim 12$ mm thick, allowing operation up to $CH_4$ gas pressures of 7 MPa.

The pump laser provided an output energy of $\sim 1.4$ mJ in a $Q$-switched envelope of $\sim 200$ ns duration. Within this envelope the mode-locked pulses had a repetition rate of 82 MHz. The duration of these pulses was measured, see Fig. 1, using a background-free second-

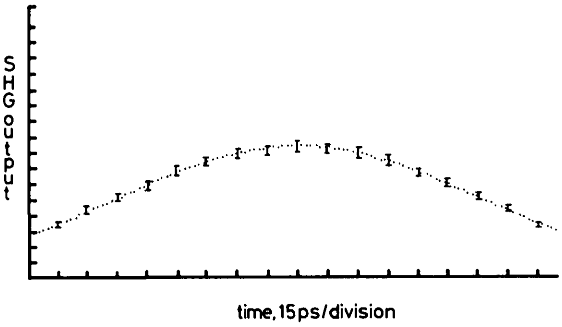



**Fig. 1** *Pump-pulse autocorrelation*
FWHM = $150 \pm 1$ ps

harmonic autocorrelation technique, and found to be $\sim 150$ ps (assuming a Gaussian temporal profile), thus implying a peak power of 0.5 MW in the most energetic pulses. This autocorrelation was performed over the full $Q$-switched pulse envelope, and so represents an average pulse duration. Measurements on a single pulse in the train were not made. The output was in the form of a clean $TEM_{00}$ mode. This is important for efficient launching into the $EH_{11}$ mode of the capillary. The beam was focused to a waist of spot size $w_0 = 60\ \mu m$ at the capillary entrance, thus satisfying the launch condition [10].

$$3w_0 = 2a \tag{4}$$

The theoretical transmission $T$ of the capillary for the $EH_{11}$ mode is given by [11]

$$T = \exp(-\alpha_p l) \tag{5}$$

where $\alpha_p = 0.43\lambda_p^2/a^3$ is the pump attenuation coefficient. For Raman scattering in the capillary waveguide of length $l$ the power gain exponent $G$ is given by [3]

$$G = g_R I_p l_{eff} - \alpha_s l \tag{6}$$

where $\alpha_s$ is the Stokes attenuation coefficient and the 'effective length' $l_{eff}$ is given by [3]

$$l_{eff} = (1 - T)/\alpha_p \tag{7}$$

The threshold pump power $P_{th}$ for SRS is therefore

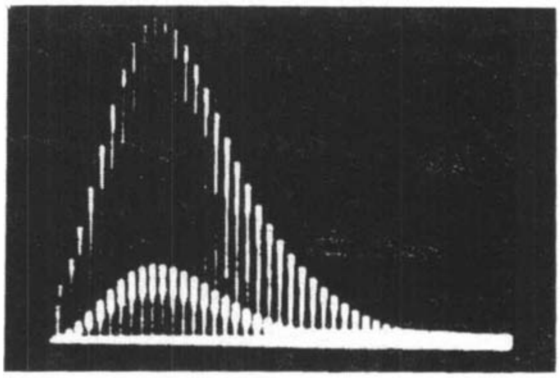
$$P_{th} = F A_{eff}(G + \alpha_s l)/g_R l_{eff} \tag{8}$$

where, following Reference 5, $A_{eff} = \pi w_0^2$.

The capillary waveguide allows a small threshold to be achieved by virtue of the fact that even if $A_{eff}$ is made small, $l_{eff}$ can be kept significantly longer than the effective length of approximately one confocal parameter ($\equiv 2\pi w_0^2/\lambda$) that would apply for unguided conditions.

## 3 Experimental results

A capillary transmission of 38% was achieved in practice for the 1.06 $\mu m$ pump, to be compared with a calculated theoretical transmission of 58%. The discrepancy was probably due to slight bending of the capillary [4] and imperfect launching, although care was taken to ensure the capillary ends were cleaved cleanly. The remaining transmitted pump beam was in the form of a clean circular spot of diffraction-limited divergence. The predicted threshold for SRS, $\sim 160$ kW, was in good agreement with the experimentally observed value of 205 kW. Fig. 2*a* shows the undepleted pump pulse train observed at



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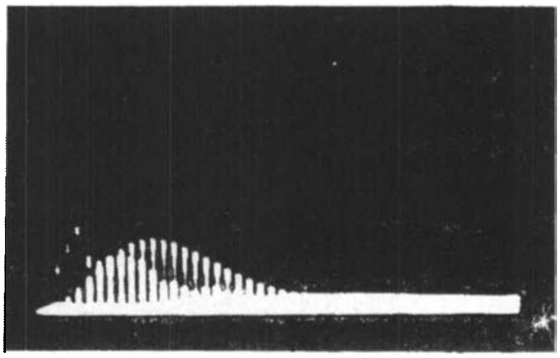

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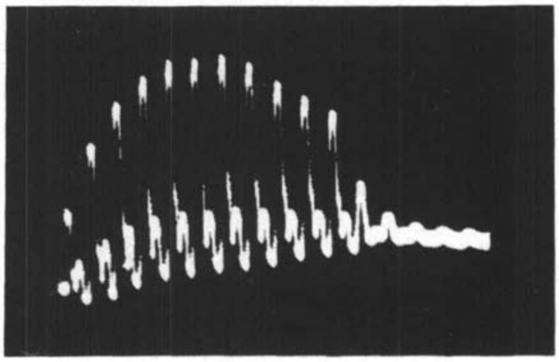

c

**Fig. 2** *Pulse trains*
*a* Undepleted pump transmitted by capillary. The smaller, interleaved pulses are due to pump light launched into the capillary walls. Mode-locked pulse separation is 12.2 ns
*b* Strong depletion of transmitted pump when operating at 2.5 times threshold power. The original interleaved pulses have the same intensity as in Fig. 2*b*
*c* Train of 1st Stokes pulses at 1.54 $\mu m$

the capillary output when the pump intensity was below the SRS threshold. The smaller interleaved train of pulses is due to pump light travelling through the walls of the capillary rather than down the bore and hence is delayed by $\sim 1$ ns. Fig. 2*b* shows the heavily depleted pump pulse train when the maximum available pump power was used ($\sim 2.5$ times the threshold). The pulses travelling through the capillary walls are unchanged in intensity (they enter the wall at the launch) and provide a useful reference to quantify the pump depletion. They are also useful for achieving optimum alignment by adjusting the capillary so that there intensity is minimised. Fig. 2*c* shows the corresponding 1.54 $\mu$m output pulses. These displayed excellent amplitude stability, with amplitude variations being no greater than those of the pump pulse itself. The DC level on the tail of these pulses is an artefact of the recording process. Second-harmonic autocorrelation measurement of the Stokes pulse duration gave a value of 130 ps (assuming Gaussian shape) for a 150 ps input pump pulse, see Fig. 3. A bandwidth measurement

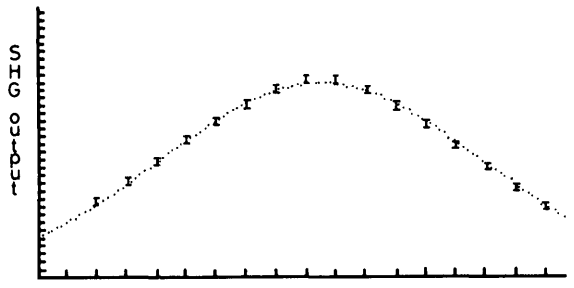


**Fig. 3** *Raman pulse autocorrelation*
FWHM = 133 ± 1 ps

of the generated Stokes radiation gave an upper limit of 5.5 GHz, although this was instrument limited owing to the low finesse of the spectrum analyser used. The pulses are therefore close to being bandwidth limited (within a factor of $\sim 2$). Peak output pulse energies of $\sim 3$ $\mu$J were observed implying peak output powers of $\sim 20$ kW.

Although the $Q$-switched repetition rate can go up to $\sim 1$ kHz, all the measurements reported here have been carried out at 5 Hz. Initial measurements at the 1 kHz rate revealed a gas breakdown behaviour leading to a deposit of 'soot' on the inside surface of the window where the pump beam entered and also at the capillary entrance. The cause of this breakdown is not yet understood. It appears to depend on the average power of the pump and not the peak power. The maximum safe operating rate has not been established, although in view of the dependence on average power it is expected that if a single pulse switchout were used to take one pulse from each $Q$-switched envelope, repetition rates of several hundred hertz would be free from breakdown.

The single-pass Raman-scattering scheme described above has given threshold pump powers of 200 kW. A further reduction of threshold is possible by operating the Raman laser as a synchronously pumped oscillator. This involves feeding back the Stokes radiation to arrive at the entrance of the capillary in synchronism with the next pump pulse in the mode-locked train. We have used a ring configuration to achieve this. In this way the threshold pump power has been reduced to 54 kW, in good agreement with the predicted value of 40 kW, and thus almost an order of magnitude lower than the available pump power from our laser. This arrangement gave a stable 1st Stokes output, but at a lower peak power ($\sim 3$ kW) than the single-pass scheme. Further details of the operation of this synchronously pumped Raman oscillator are to be given in a further publication.

## 4 Conclusion

We have demonstrated a simple high-power source of mode-locked pulses at 1.54 $\mu$m. The good amplitude stability, diffraction-limited beam quality and high power make these pulses particularly interesting for studies of pulse-compression phenomena in fibres under conditions of very high soliton number.

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## 6 References

1 MOLLENAUER, L.F., STOLEN, R.H., and GORDEN, J.P.: 'Experimental observation of picosecond pulse narrowing and solitons in optical fibres', *Phys. Rev. Lett.*, 1980, **45**, pp. 1095–1098
2 MOLLENAUER, L.F., STOLEN, R.H., GORDEN, J.P., and TOMLINSON, W.J.: 'Extreme picosecond pulse narrowing by means of soliton effect in single-mode optical fibres', *Opt. Lett.*, 1983, **8**, pp. 289–291
3 HANNA, D.C., POINTER, D.J., and PRATT, D.J.: 'Stimulated Raman scattering of picosecond light pulses in hydrogen, deuterium, and methane', *IEEE J. Quantum. Electron.*, 1986, **QE-22**, pp. 332–336
4 BERRY, A.J., HANNA, D.C., and HEARN, D.B.: 'Low threshold operation of a waveguide $H_2$ Raman laser', *Opt. Commun.*, 1982, **43**, pp. 229–232
5 BERRY, A.J., and HANNA, D.C.: 'Stimulated Raman oscillation in capillary waveguide resonators', *Opt. Commun.*, 1983, **45**, pp. 357–360
6 RABINOWITZ, P., KALDOR, A., BRICKMAN, R., and SCHMIDT, W.: 'Waveguide $H_2$ Raman laser', *Appl. Opt.*, 1976, **15**, pp. 2005–2006
7 HARTIG, W., and SCHMIDT, W.: 'A broadly tunable IR waveguide Raman laser pumped by a dye laser', *Appl. Phys.*, 1979, **18**, pp. 235–241
8 MAIER, M.: 'Applications of stimulated Raman scattering', *Appl. Phys.*, 1976, **11**, pp. 209–231
9 TAIRA, Y., IDE, K., and TAKUMA, H.: 'Accurate measurement of the pressure broadening of the $v_1$ Raman line of $CH_4$ in the 1–50 atm region by inverse Raman spectroscopy', *Chem. Phys. Lett.*, 1982, **91**, pp. 299–302
10 ABRAMS, R.L.: 'Coupling lasers in hollow waveguide laser resonators', *IEEE J. Quantum. Electron.*, 1972, **QE-8**, pp. 838–843
11 MARCATILI, E.A.J., and SCHMELTZER, R.A.: 'Hollow metallic and dielectric waveguides for long distance optical transmission and lasers', *Bell Syst. Tech. J.*, 1964, **43**, pp. 1783–1809