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Volume 65, number 4 OPTICS COMMUNICATIONS 15 February 1988

A SYNCHRONOUSLY PUMPED WAVEGUIDE CH_4 RAMAN LASER AT 1.54 μm

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Received 2 October 1987; revised manuscipt received 20 November 1987

The threshold for stimulated Raman scattering (SRS) in CH_4 gas with a 1.06 μm pump has been reduced to only ~50 kW using an arrangement involving synchronous pumping and confinement in a capillary waveguide. This corresponds to a threshold reduction of ~50 compared to an unguided, single pass device. This Raman laser has produced stable mode-locked 1.54 μm pulses of ~12 kW power and pulse duration ~100 ps.

1. Introduction

The use of a capillary waveguide to reduce the threshold of stimulated Raman scattering in gases has been the subject of a number of publications [1–5]. In particular it has been shown that stimulated Raman scattering in CH_4 gas can be achieved with the output power available from a continuously pumped Nd:YAG laser, when Q-switched and mode-locked [6]. In this paper we describe a synchronously pumped waveguide Raman laser in CH_4 gas where the introduction of synchronous pumping has led to a further factor of four reduction of threshold. The overall reduction of threshold compared with a single pass unguided arrangement is ~50, and the threshold power requirement for a 1.06 μm pump is now ~50 kW. Agreement between predicted and observed threshold is good. Output pulses of ~12 kW and 100 ps are obtained at the 1.54 μm 1st Stokes wavelength.

2. Background

Following ref. [6], the stimulated Raman threshold power P_{th} for a single pass arrangement in a capillary waveguide of length l is

$$P_{th} + F A_{eff}(G_{th} + \alpha_s l)/g_R l_{eff}, \qquad (1)$$

where α_s, α_p are the Stokes and pump attenuation coefficients respectively, the effective length $l_{eff} = [1 - \exp(-\alpha_p l)]/\alpha_p$, and the effective area $A_{eff} = \pi W_0^2$ where W_0 is the spot size of the EH_{11} mode. G_{th} is the gain exponent needed to reach threshold, usually taken to be $G_{th} = 25$. F is a factor which takes account of the increase in threshold relative to the steady state value, due to the transience of the medium response. The value of F as a function of the ratio of pump pulse duration to the medium T_2 is given in ref. [5]. g_R is the Raman gain coefficient [7,6].

Expression (1) for the single-pass case can be readily extended to the synchronously pumped case by noting that the net gain of Stokes power after n round trips is

$$P_{sn}/P_{s0} = (R)^{n-1} \times \exp\left((g_R l_{eff}/F A_{eff}) \sum_{i=1}^{n} P_{pi} - n\alpha_s l \right), \qquad (2)$$

where P_{pi} is the pump in the ith pulse of the pump train and R is the fraction of Stokes power fed back into the capillary entrance as a result of mirror and launching losses. The threshold power is expressed as the value reached by P_{pi} at the peak of the pump train envelope, where $P_{sn}/P_{s0} = \exp(G_{th})$.

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3. Experimental arrangement

The pump laser was a continuously pumped Nd:YAG laser (Spectra Physics 3000), operating at 1.06 μm and producing a ~ 1.6 mJ Q-switched mode-locked train of 200 ns (fwhm), with mode-locked pulse duration measured to be 120 ps. The peak pulse power was thus calculated to be ~700 kW. The Raman cell consisted of a fused silica capillary of bore diameter $2a=200$ μm and length 75 cm, supported and held straight inside another capillary, which in turn was held inside a pressure cell with fused silica windows. Operating pressures up to 70 atm of CH_4 were used. High pressures are advantageous in reducing the threshold since this result in a shorter T_2 and hence a smaller factor F. At 70 atm, with 120 ps pump pulses, F is estimated to be ~ 1.4 [5]. It should be noted that with the short T_2, ~9 ps at 70 atm, the vibrational excitation of the medium decays virtually completely between pump pulses (~12 ns separation).

The TEM_{00} pump beam was launched into the capillary with a waist spot size at the guide input chosen to satisfy $3W_0=2a$ [8]. The theoretical transmission T of the capillary guide for the EH_{11} mode is given by [9]

$$T=\exp(-\alpha_p l) , \tag{3}$$

where $\alpha_p=0.43\ \lambda_p^2/a^3$. In practice we achieve a measured transmission of 57%, compared to the theoretical value of 70%. Slight bending of the capillary and/or imperfect launch may have accounted for the slight discrepancy. In calculation of threshold we have used an empirical α_p value which, when substituted in eq. (3) gives the observed transmission. The transmitted pump beam was in the form of a clean circular spot of diffraction-limited divergence.

Results obtained for the single pass arrangement gave a threshold of ~190 kW, in excellent agreement with the theoretical value from eq. (1). Fig. 1(a) shows a typical depleted pump pulse observed at the capillary output and fig. 1(b) shows the corresponding 1st Stokes 1.54 μm output pulses. The Stokes output has good amplitude stability, similar to that of the pump, when the Raman medium is pumped well above threshold. Energy measurements indicated that single mode-locked pulse energies of ~7 μJ were generated.

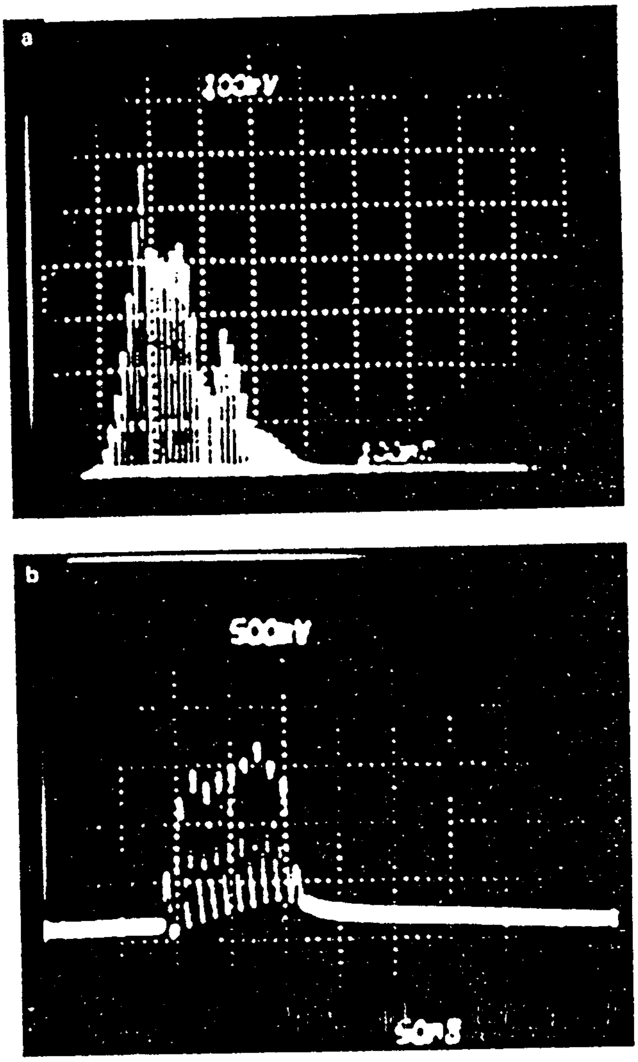

Fig. 1. (a) Depleted pump pulse for single pass Raman laser. (100 ns/division). (b) 1st Stokes 1.54 μm output pulses. (50 ns/division).

The single pass arrangement was then modified to the synchronously pumped arrangement shown in fig. 2. The 1st Stokes pulses were fed back to the capillary entrance via the prisms P_1, P_2, P_3 and the beam-

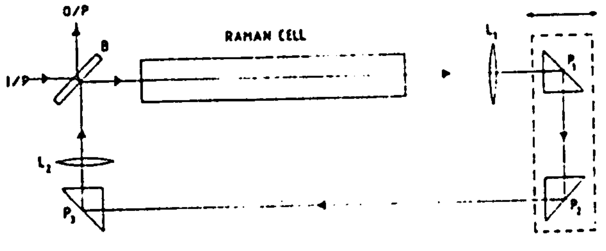

Fig. 2. The synchronously pumped Raman laser resonator with beamsplitter (B), lenses (L_1, L_2) and prisms (P_1, P_2, P_3). The pump input is denoted by I/P and the Raman output by O/P.

splitter B. The ability to achieve single pass operation with the feedback loop misaligned proved a considerable help in setting up the synchronous pumping. Lenses L_1 and L_2 were used respectively to collimate and focus the Stokes beam for relaunch, again taking $3W_0=2a$ as the launch condition. Fine control of the cavity length, to achieve synchronism, was achieved with a micrometer adjustment on the common mounting or prisms P_1, P_2. When correctly adjusted the observed threshold was found to be ~50 kW, a factor of four less than for the single pass arrangement, and in fair agreement with the value of 58 kW predicted via eq. (2). At threshold the largest Stokes pulse occurs after the peak of the pump envelope, as predicted by eq. (2).

The effect that Stokes feedback has on pump depletion is shown in fig. 3(a) and 3(b). Fig. 3(a) shows the transmitted pump when just above the single pass threshold and with the feedback blocked, while fig. 3(b) shows the heavily depleted transmitted pump when, under the same pump conditions, the feedback is restored. Fig. 4 shows the train of 1st Stokes pulses for an input pump power of 310 kW. The pulses show good amplitude stability, as good as that of the pump pulse, and a measurement of pulse energy indicated ~1.3 μJ in each mode-locked pulse. The mode selection of the waveguide and feedback resonator ensure diffraction limited output. The pulsewidth, averaged over the whole output pulse train, was measured by a background free second harmonic autocorrelation measurement using a $LiIO_3$ doubling crystal. Pulse duration, assuming a gaussian temporal shape, was found to be ~100 ps, see fig. 5, implying peak powers of ~12 kW.

Anti-Stokes radiation ($\lambda=812$ nm) was also observed in the output, but 2nd Stokes radiation at $\lambda=2.8$ μm was not detected, despite it probably being generated in significant amounts, as the 12 mm thick fused silica windows had a very low transmission at that wavelength.

Two features of the Stokes behaviour are as yet unexplained. One is the fact that typically a maximum of ~10 pulses are observed in the Stokes output train, whereas a simultaneous observation of pump depletion indicates that ~20 or more pump pulses are strongly depleted. This is seen by comparing figs. 3(a) and (b), which were taken under identical pump conditions, and differing only in that fig. 3(a) corresponds to the feedback being blocked. After the first 6 or 7 pump pulses, all remaining pulses are heavily depleted, many to the base line, and even the late pulses in eq. 3(b) are depleted to below the 20% level. It appears that the Stokes output correponds to the initial part of the pump depletion. A second observation, found in single pass operation, is that depletion of the pump train is not symmetric about the envelope peak (fig. 1(a)), as one might have expected since pump pulses of the same power would be expected to produce the same behaviour.

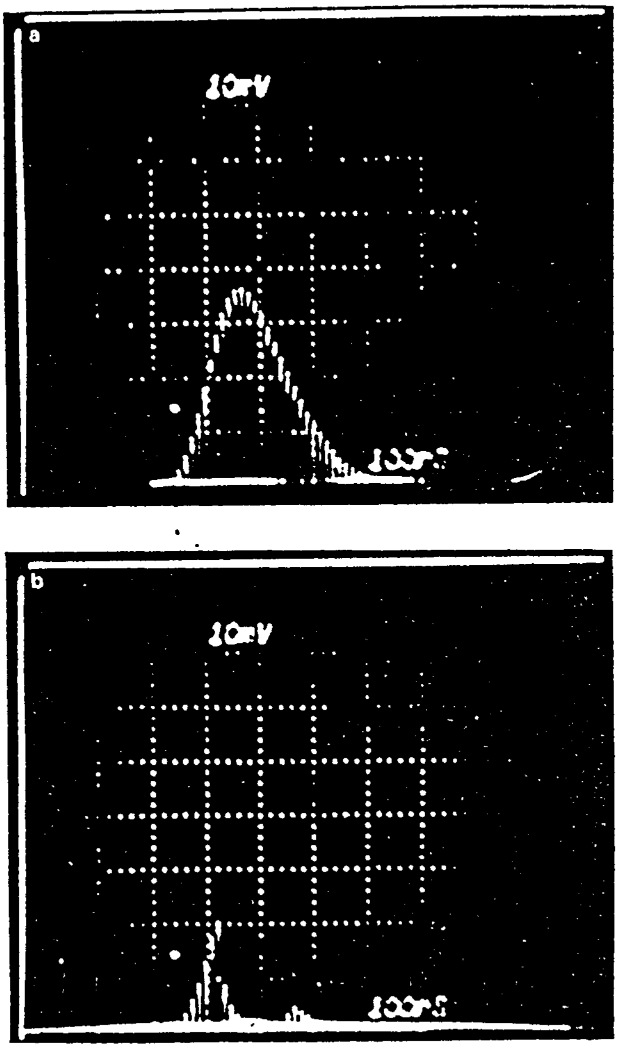

Fig. 3. (a) Transmitted pump pulse with feedback blocked. (b) Heavily depleted pump pulse with feedback operating.

A final comment is on a practical but important aspect of this source. We have found that when operating at higher repetition rates (the pump laser is capable of 1 kHz or more) the CH_4 gas rapidly undergoes decomposition, leading to a deposit of soot

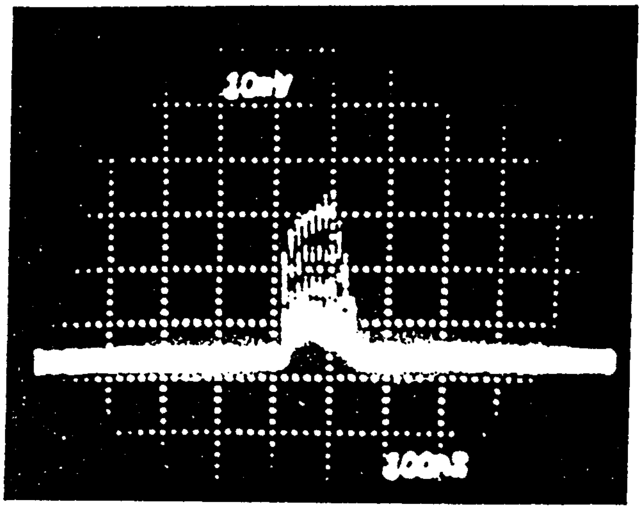

Fig. 4. 1st Stokes 1.54 μm output pulses for synchronously pumped Raman laser.

on the inside of the cell entrance window and at the entrance of the capillary guide. We have therefore confined our measurements to a repetition rate of 5 Hz, where operation over periods of many weeks is possible without such decomposition occurring. The underlying cause of this decomposition is not yet understood.

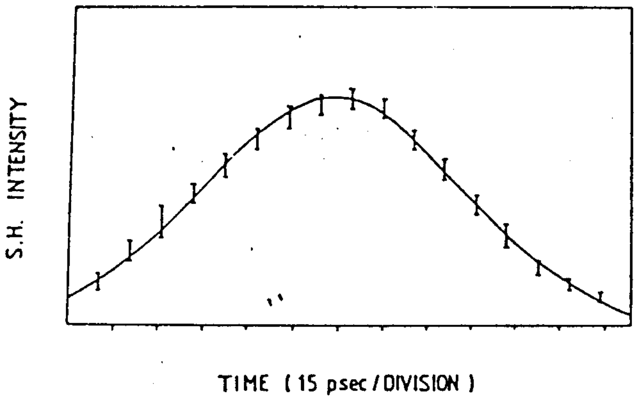

Fig. 5. Second harmonic autocorrelation measurement of pulse duration. FWHM = 104 ± 1ps.

4. Summary

We have demonstrated that very low threshold operation of a CH_4 Raman laser at 1.54 μm can be achieved by the combination of capillary waveguiding and synchronous pumping. Similar techniques should work successfully with a number of gases. The particular source based of CH_4 provides output at a wavelength, and in a form, which would be suitable for nonlinear propagation studies and measurements in the negative group velocity dispersion region of fused silica fibre.

Acknowledgements

This work has been supported by the SERC under the Joint Optoelectronics Research Scheme. D.P.S. wishes to acknowledge SERC and BTRL for support in the form of a Case studentship. We are grateful to Dr. A.I. Ferguson for a number of useful discussions.

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