Fibre-optic tunable CW Raman laser operating around 1.3 μm

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Abstract

We describe an integrated fibre-optic, CW, broadly tunable Raman laser operating around 1.3 μm. This laser was pumped by a cascaded-Raman fibre laser at a wavelength of 1.24 μm, which was pumped at a fundamental wavelength of 1.06 μm derived from a multi-clad, high-power Yb-fibre laser. Tunability from 1.29 μm to 1.33 μm was achieved with a maximum output power of 140 mW.

1. Introduction

Stimulated Raman scattering in glass optical fibres has been shown to be an efficient means of wavelength conversion in the visible and near infrared. The Raman gain in glasses is typically two orders of magnitude less than in crystals or liquids, however the highly confined optical field and the low loss of glass optical fibres permit long interaction lengths and the construction of Raman oscillators pumped by relatively low laser powers. In addition, the large gain bandwidth (~ 600 cm⁻¹) allows tuning over a broad range of frequencies.

Previously, CW Raman fibre lasers have been demonstrated at visible [1,2] and near infra-red [3,4] wavelengths. These systems used Ar⁺ or Nd:YAG pump lasers. Both ring and Fabry–Perot cavities were employed and tuning was achieved using either prisms in combination with rotating mirrors or diffraction gratings. As a result of the necessary use of bulk optics for coupling, apart from the problems that arise from mechanical instability, the considerable loss introduced gave rise to low efficiencies and high threshold powers. Threshold pump powers for Raman oscillation of 1.5 W were reported in the visible [1] and 1 W in the infrared [4]. In the majority of the previously reported schemes, as a result of losses and inefficiency the output powers were at the milliwatt level, however, in exceptional cases powers at 100 mW level in a single Stokes order has been obtained but only at intracavity c.w. pump powers around 20 W [5].

Recent developments in fibre laser design [6–9] mean that high power cascaded-Raman fibre-laser sources are now available wavelengths from 1.1–1.9 μm. These lasers use multiple-Stokes-order cascaded Raman scattering inside the laser cavity to generate the desired wavelength. Based on these it is now possible to construct tunable CW Raman lasers without the need for bulk optical components or large frame pump lasers. Consequently these laser sources are simple to use, highly compact, robust and stable.

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They have the additional advantage of an optical fibre output making them easily compatible with other fibre-optic systems.

In this paper an all-fibre-optic CW tunable Raman laser is demonstrated. We have developed an all-fibre cascaded Raman resonator operating at 1.24 μm. This CW pump scheme permits previously unprecedented levels of stability, simplicity of operation and efficiency to be achieved in a fibre Raman laser. The broad wavelength tunability over the range 1.288–1.330 μm, a wavelength range as yet to be reported, was achieved using an in-line filter. The laser had a linewidth of ~35 GHz and a maximum output power of 140 mW.

2. Experiment

The experimental arrangement is shown in Fig. 1. It consisted of a ring cavity with counter-propagating pump and Stokes fields. Uni-directional operation resulted from the use of three port optical circulators (OC1 and OC2). These had an insertion loss of 1 dB in the forward direction and greater than 25 dB isolation in the reverse direction. A 10 km dispersion-shifted single-mode optical fibre was used to provide the Raman gain. The pump laser emitted a maximum power of 1.5 W at a wavelength of 1.24 μm. The linewidth of this laser was broad enough to suppress stimulated Brillouin scattering. Pump light was coupled into the gain fibre through the left-hand circulator (OC1 see Fig. 1 and any residual pump light was absorbed at the right-hand circulator, OC2. An in-line filter, tunable over the wavelength range 1.288–1.330 μm and with a spectral half width of 3 nm, was used for wavelength selection. A fibre-loop reflector provided output coupling and feedback for the generated Stokes radiation.

3. Results

The range of lasing wavelengths and the output power depended on the choice of output coupler. Using a broadband reflector with a reflectivity which varied approximately linearly with wavelength from 0.37 at 1.290 μm to a value 0.75 at 1.320 μm lasing took place from 1.288 μm to 1.330 μm. The output power is plotted against wavelength in Fig. 2. A typical output spectrum is shown in Fig. 3. The linewidth of 30 GHz reflects the highly multimode operation of this laser. No detectable power was measured at other wavelengths. When operated at 1.305 μm a few 500 mw pump power was required for the Raman lasing threshold. From a knowledge of the losses of the fibre, the circulators, the filter and the reflector, the round-trip cavity loss is expected to be at least 10 dB for the Stokes light. The single-pass small-signal gain was calculated at threshold and the cavity loss was estimated from this to be 11.5 dB giving good agreement with the above value. The system was found to be extremely stable as expected from the counter propagating pump and signal configuration and all-fibre format.

The pump power was increased from threshold up to 1.5 W and the output power and linewidth were
It was found that the output power increased linearly with the pump power when the laser was tuned to a wavelength close to the gain peak at 1.311 μm as well as towards the edge of the tuning range at 1.291 μm. An increase by a factor of two of the linewidth, which also varied linearly with pump power, was observed when the pump power was increased over the same range.

The output coupling was not optimal in this configuration. In order to find the output coupling at which the output power is a maximum a number of different reflectors were used. It was found that the output power was a maximum at a reflectivity of approximately 0.4. A broadband reflector with this output coupling was not available. Using a reflector with an output coupling of approximately 0.4 over a range of 2 nm centred on 1.318 μm an output power of 140 mW was measured over this range of wavelengths. It is expected that by optimising the output coupling a corresponding increase in the output power could be achieved at those wavelengths in Fig. 2 where the output coupling is not optimal. The increase would be most significant for wavelengths at the long wavelength end of the tuning range where the output coupling is furthest from the ideal value.

Additional tunability can be expected from this system by using a filter with a broader tuning range. If the laser were tuned over all wavelengths where the Raman gain exceeds the minimum value at which we have shown that it will lase then the total tuning range would be approximately 80 nm (500 cm⁻¹) which covers almost the entire Raman gain bandwidth.

4. Conclusion

We have demonstrated a high power, all-fibre CW tunable Raman laser that has been tuned over a 42 nm range, at wavelengths around 1.3 μm, with the potential for an 80 nm tuning range. This system shows the practicality of compact and efficient, high power CW tunable laser sources based on stimulated Raman scattering in optical fibres. By employing different orders of Stokes radiation in the pump laser an extensive wavelength range can be readily covered at moderately high output powers using similar configurations.

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