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High-power cw visible lasers pumped by Raman fibre lasers

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Abstract. **This paper describes cw visible lasers having an output power above 10 W and emitting at wavelengths of 561, 589 and 623 nm. An approach is proposed for obtaining single-mode cw visible laser light with a power above 10 W at any wavelength in the range 560 – 660 nm.**

Keywords: *stimulated Raman scattering, Raman laser, second harmonic generation, periodically poled crystals, visible laser.*

1. Introduction

High-power cw visible lasers operating at particular wavelengths and offering good beam quality are much in demand for making laser projectors and shows, in holography and adaptive optics and for a variety of medical and scientific applications. Nevertheless, such sources are still difficult to find among familiar visible lasers. Semiconductor lasers have limitations on their output power (several watts) and low beam quality; dye lasers are difficult to manufacture and require constant maintenance, which limits their utility for practical applications; and metal vapour lasers are bulky and inefficient. Another approach to producing visible laser light is the generation of harmonics in nonlinear optical crystals under pumping by IR lasers. However, efficient frequency conversion typically requires the use of either pulsed light sources with peak powers of several kilowatts [1] or a resonator scheme requiring very accurate positioning of optical components.

Georgiev et al. [2] proposed an easy-to-implement approach for obtaining intense cw visible laser light at any particular wavelength in the range 560 – 770 nm. Their approach builds on single-pass SHG in a periodically poled crystal pumped by a Raman fibre laser. They observed considerable broadening of the Raman laser emission line, which limited the second harmonic power and conversion efficiency. For this reason, the maximum yellow light power obtained at a wavelength of 589 nm was just 3 W, at a 12% SHG efficiency. As a result, relatively cheap and easy-to-fabricate single-mode cw visible lasers with an output power above 10 W remained the subject of a scientific and technological search. We continued to develop the approach in question [2] with the aim of obtaining higher powers and efficiencies. As a result, the yellow light power reached at a wavelength of 589 nm exceeded 14 W and the SHG efficiency was 24% [3, 4]. Later, in addition to the laser operating at $\lambda = 589$ nm, high-power lasers emitting at wavelengths of 561 nm (green laser) and 623 nm (red laser) were demonstrated [5, 6]. In this paper, we review this range of colour lasers.

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2. Raman pump laser

Fibre lasers with an ytterbium-doped gain medium offer record high output powers in combination with high beam quality ($M^2 < 1.1$), high efficiency (above 35%) and compact design [7]. However, the wavelengths covered by the optical transitions of active ytterbium ions are limited to the range 1.03 – 1.15 μm. Light at longer wavelengths can be generated using photonic crystals fibres [8], bismuth-doped fibres [9] and chromium-doped materials [10], but the simplest and most efficient approach is SRS conversion [11].

A typical Raman fibre laser configuration comprises a pump fibre laser and internal cavities for one or a few sequential wavelengths (Fig. 1) corresponding to the Raman shift. The active medium in the case of SRS conversion is a passive fibre, and the cavity is formed by fibre Bragg gratings. Figure 1 shows a schematic of a laser emitting at $\lambda = 1178$ nm.

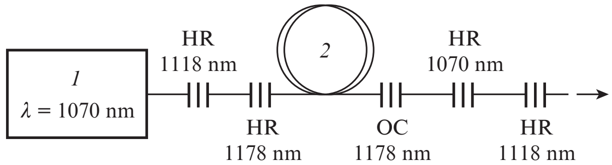

Figure 1. Schematic of a Raman laser emitting at 1178 nm: (*1*) cw ytterbium-doped fibre pump laser providing linearly polarised light; (*2*) polarisation-maintaining passive fibre; HR, high-reflectivity Bragg gratings; OC, output Bragg grating.

A laser source comprising an ytterbium-doped fibre pump laser and Raman converter makes it possible to generate light in the range 1.1 – 2.2 μm [12]. Zhang et al. [13] reported a Raman laser with a record high output power of 1.3 kW at a wavelength of 1.12 μm, and Supradeepa and Nicholson [14] demonstrated a Raman laser of 300-W power at $\lambda = 1.48$ μm.

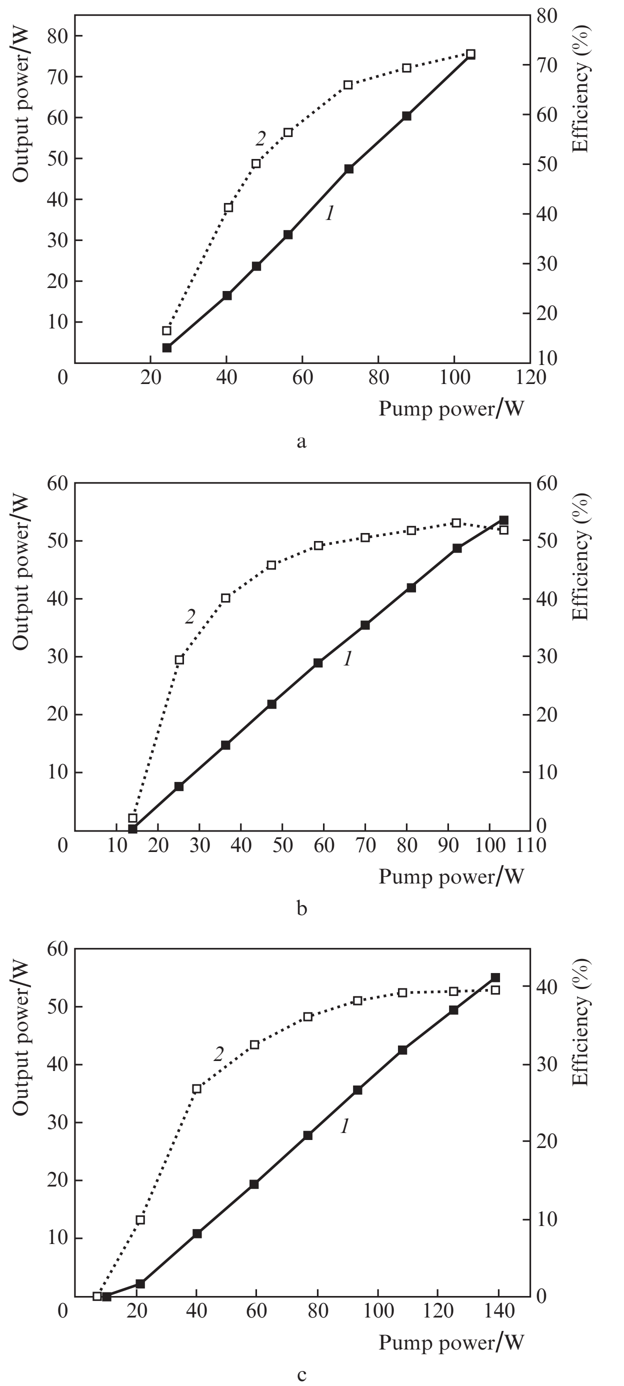

Figure 2. (*1*) Output power and (*2*) efficiency as functions of pump power at $\lambda = 1070$ nm for germanosilicate Raman lasers emitting at $\lambda =$ (a) 1122, (b) 1178 and (c) 1246 nm.

At the same time, not only the pump power is important for efficient nonlinear conversion of IR radiation in a nonlinear optical crystal (in particular, in a periodically poled crystal). The Raman laser output should be linearly polarised and its spectrum should be narrower than the phase matching bandwidth of the crystal. The phase matching bandwidth of a periodically poled lithium tantalate (PPLT) crystal is 0.4 nm cm for second harmonic generation at a wavelength of 589 nm [15, 16]. The limitations on the second harmonic power and conversion efficiency in Ref. [2] were related to the well-known problem of the broadening of the Raman fibre laser emission line [17–19].

In this work, we considerably raised the spectral output power and reduced the emission bandwidth owing to the narrow reflection spectra of the fibre Bragg gratings (FBGs) that formed the Raman resonator at a signal wavelength. The reflection bandwidth of the FBGs did not exceed 0.05 nm, and it was measured with an accuracy that was limited by the resolution of our spectrum analyser. For comparison, in Ref. [2] at an output power of 23 W at $\lambda = 1178$ nm, the full width at half maximum (FWHM) of the emission line was $\Delta\lambda = 0.37$ nm, and in Ref. [4] the FWHM was 0.1 nm at an output power of

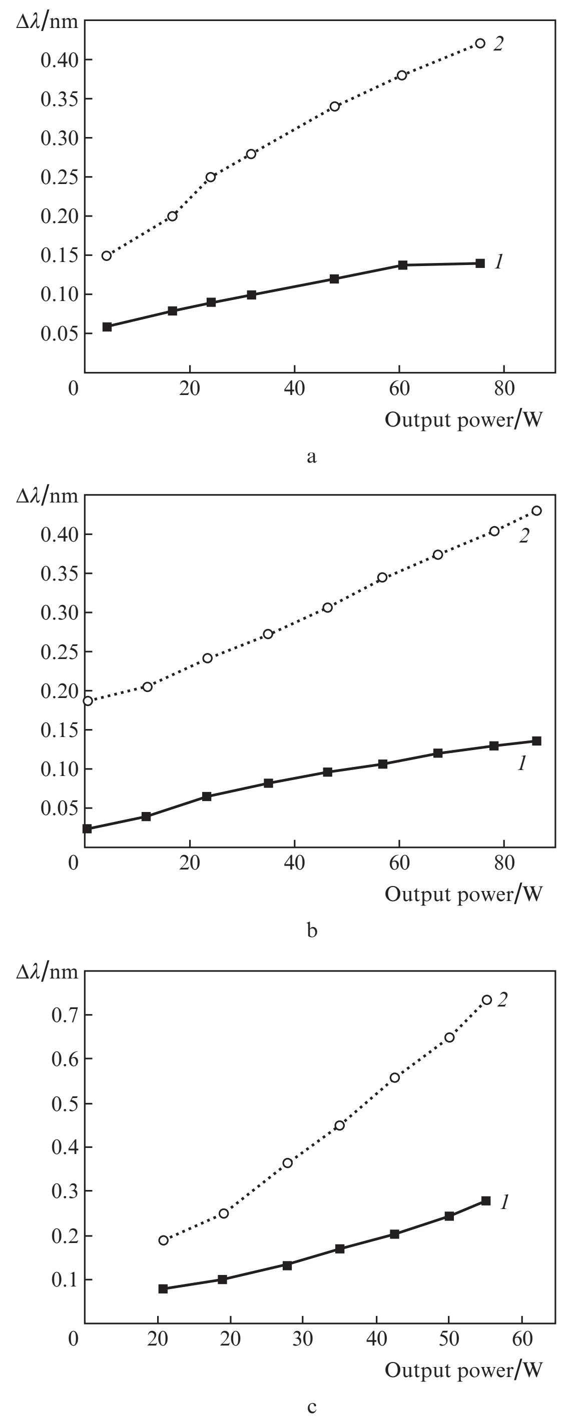

Figure 3. (*1*) 3- and (*2*) 10-dB emission bandwidths $\Delta\lambda$ as functions of output power for Raman lasers emitting at $\lambda =$ (a) 1122, (b) 1178 and (c) 1246 nm.

60 W. It is well known that intense light heats up FBGs, causing their reflection spectrum to shift to longer wavelengths, with a temperature coefficient of about 0.01 nm °C^{-1}. Thus, in our case heating of one grating by just 5 °C relative to the other would lead to a complete mismatch between them. To resolve this issue, the gratings were placed in a thermostat, which maintained a constant temperature.

Using the improved Raman converter configuration, we obtained laser light at wavelengths of 1122 (single-cascade SRS conversion in a germanosilicate fibre), 1178 (two-cascade conversion) and 1246 nm (three-cascade conversion). Figure 2 shows the output powers of the lasers as functions of pump power and Fig. 3 presents their spectral characteristics. The three lasers had an output power above 50 W. At the maximum output power, the FWHM of the emission line of the lasers operating at λ = 1122 and 1178 nm was under 0.15 nm and that of the laser operating at λ = 1246 nm was under 0.25 nm.

In addition, linearly polarised cw light at λ = 1246 nm was obtained using a single-cascade resonator for SRS in phosphosilicate fibre [11]. As a result, conversion efficiency increased only slightly, whereas the emission bandwidth at 50 W of output power was just 0.15 nm. Figure 4 presents spectral and power characteristics of the phosphosilicate fibre Raman laser emitting at λ = 1246 nm.

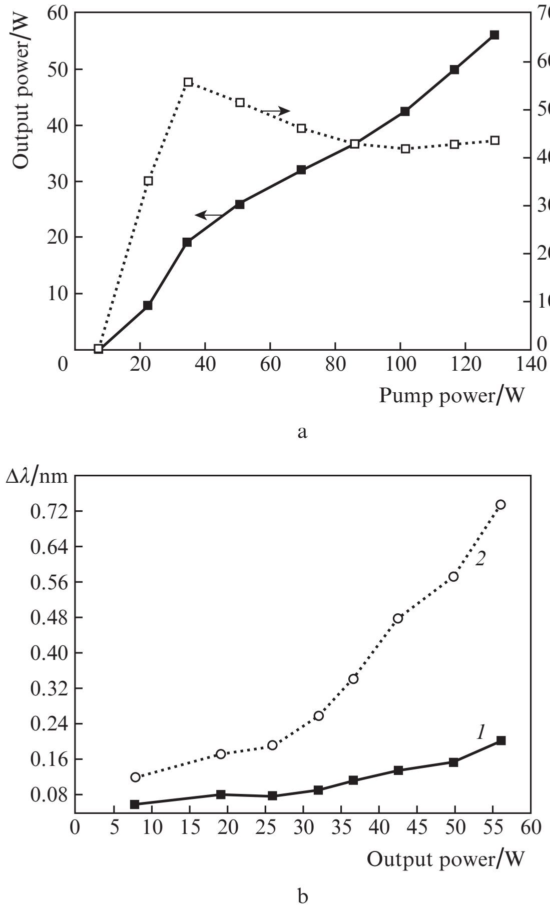

Figure 4. (a) Output power at λ = 1246 nm and efficiency as functions of pump power at λ = 1069 nm for a phosphosilicate fibre Raman laser; (b) (*1*) 3- and (*2*) 10-dB emission bandwidths as functions of output power for a Raman laser emitting at λ = 1246 nm.

3. Second harmonic generation

Among well-known periodically poled crystals (PPLN, PPLT and PPKTP), MgO-doped stoichiometric lithium tantalate crystals are the best suited to efficient conversion of intense IR radiation to its second harmonic [20–23]. Along with a relatively large effective nonlinearity coefficient ($d_{\rm eff}$ ≈ 10 pm V^{-1}), they possess a low optical absorption and high thermal conductivity (K = 8.4 W m^{-1} °C^{-1}) [24]. These properties are of key importance in obtaining high output powers and conversion efficiencies because laser light absorption and subsequent nonuniform heating of the crystal lead to a thermal phase mismatch, slowing down the growth of conversion efficiency [25–28]. Lim et al. [29] proposed a method for assessing the heat removal performance of a thermostat containing a crystal. They used a thin (300 μm) crystal and placed it in a copper thermostat, thereby optimising heat removal from the crystal. They obtained 19 W of output power at λ = 532 nm with a 26.5% conversion efficiency in a 10-mm-long MgO : PPsLT crystal.

All the above-mentioned studies dealt with lasing at a wavelength of 532 nm. In our work, using Raman laser pumping we demonstrated lasing at three wavelengths: 561, 589 and 623 nm. We used magnesium oxide-doped congruent lithium tantalate, MgO : PPcLT, crystals (8 mol% MgO) 20×3×0.5 mm in geometric dimensions (HC Photonics), with domain structure periods of 9.09, 10.43 and 12.13 μm for the above wavelengths, respectively. Figure 5 schematically illustrates the SHG process. IR radiation at λ = 1122, 1178 and 1246 nm was focused into the centre of the crystal to a waist diameter of 47, 48 and 49 μm, respectively.

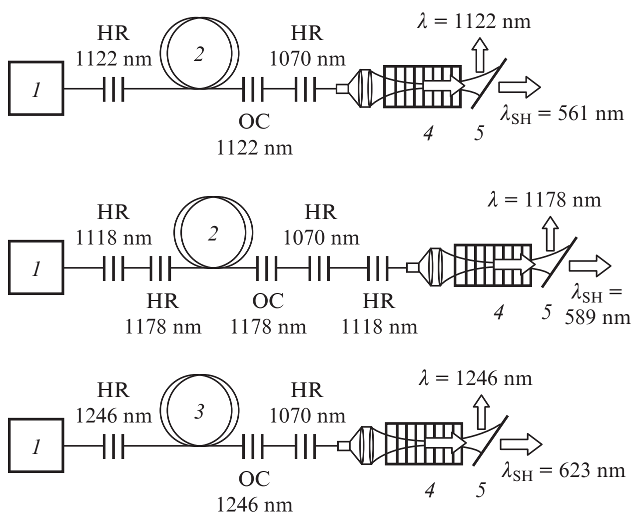

Figure 5. Schematics of visible lasers emitting at 561, 589 and 623 nm: (*1*) ytterbium-doped fibre laser (λ = 1070 nm); (*2*) polarisation-maintaining fibre; (*3*) polarisation-maintaining phosphate fibre; (*4*) MgO : PPcLT in a thermostat; (*5*) dichroic mirror.

Figure 6 shows the measured second harmonic power as a function of Raman laser pump power. The maximum powers obtained at wavelengths of 561, 589 and 623 nm were 8, 14 and 12 W, respectively.

The maximum SHG efficiency for narrow-band cw Raman laser light was 22% at 561 nm and above 25% at 589 and 623 nm. Also presented in Fig. 6 are theoretical dependences

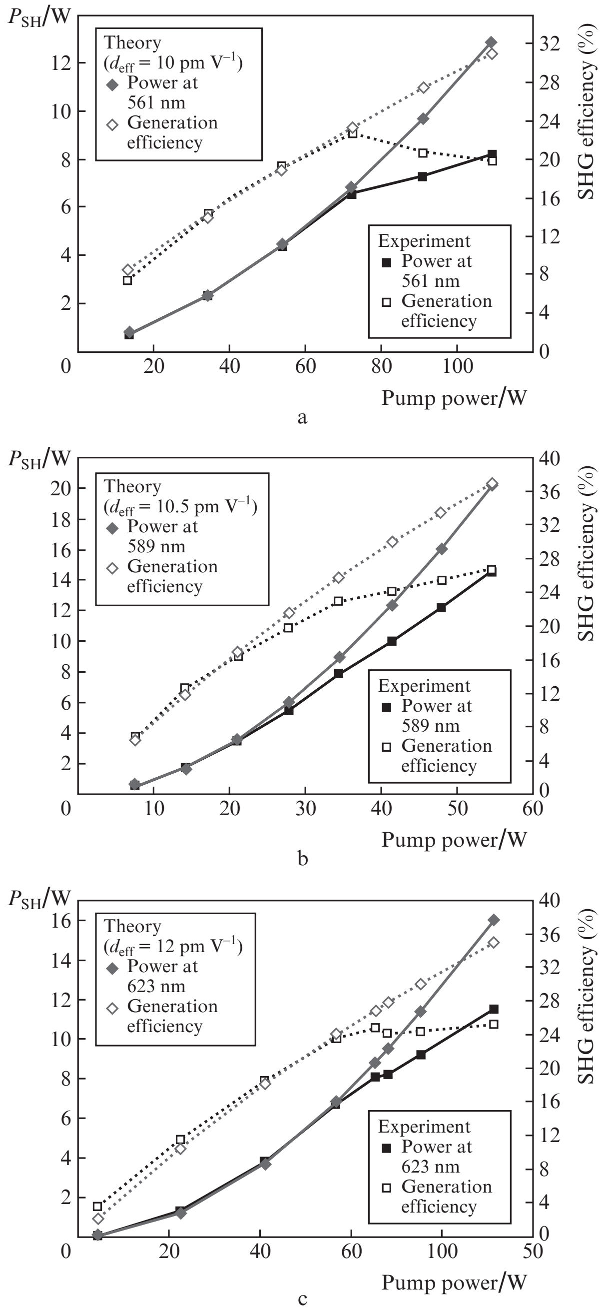

Figure 6. Measured and calculated second harmonic power P_{SH} and SHG efficiency as functions of Raman laser pump power at wavelengths of (a) 1122, (b) 1178 and (c) 1246 nm.

calculated using reduced equations of SHG. In all cases, there was good agreement between experimental data and calculation results at low pump powers (under ~25 W). Note that in our calculations the effective nonlinear susceptibility coefficient d_{eff} was varied in order to match theoretical and experimental data, because the nonlinear susceptibility coefficient of PPcLT crystals is available in the literature mainly only for the SHG of light with λ = 1064 nm (9 pm V^{-1}) and there are no complete data on the spectral dependence of d_{eff} [30, 31]. The other parameters influencing SHG efficiency in experiments had optimal values and were known with good accuracy. The following values of d_{eff} were taken for the above λ_{SH} wavelengths: d_{eff} = 10 pm V^{-1} at 561 nm, 10.5 pm V^{-1} at 589 nm and 12 pm V^{-1} at 623 nm.

At pump powers above 25 W, we observed discrepancies between the experimental data and calculation results. This is related, first, to specific spectral features of the Raman laser output: at high powers, Raman linewidths become comparable to the phase matching bandwidth of the crystal (10-dB SRS linewidth exceeds 0.2 nm). Another cause is the nonuniform heating of the crystal due to the pump and second harmonic absorption. The use of narrower band FBGs to form the cavity of Raman lasers will allow even narrower band Raman fibre lasers to be made, and a narrower Raman pump laser linewidth will offer the possibility of using longer crystals for SHG and focus the pump beam to a larger diameter waist. Increasing the crystal length will help to increase the SHG efficiency and second harmonic power, which is currently limited by both spectral and thermal effects, and weaker pump light focusing will help to extend the operating life of the crystal.

All this opens up new possibilities for application of such lasers in hologram recording and adaptive optics and for producing high-power laser projectors.

The optical scheme used in this study makes it possible to extend the range of obtainable visible wavelengths to 660 nm (a wavelength attractive for manufacturing laser projectors). A 1320-nm Raman pump laser can be made in a four-cascade configuration based on a germanate-core silica fibre or in a two-cascade configuration based on a phosphosilicate fibre, simultaneously using both the phosphate and silicate SRS gain peaks [11]. Second harmonic generation (λ_{SH} = 660 nm) for light with λ = 1320 nm in a MgO : PPcLT crystal is expected to be no less efficient: the phase matching bandwidth of the crystal at these wavelengths will be larger and limiting thermal effects will be weaker because the optical absorption coefficient decreases with increasing wavelength in the visible range [32]. The 660-nm boundary is somewhat arbitrary: nothing prevents one from obtaining visible lasing in a longer wavelength range (limitations on SHG are less stringent, as above). A key issue is then the feasibility of making a high-power (above 30 W), narrow-band cw Raman laser having a linearly polarised output and operating at a desired wavelength. Here, possible difficulties in producing a high-power Raman fibre laser may be related to the well-known absorption peak of water in optical fibre at λ = 1385 nm.

If such narrow-band pump lasers for wavelengths in the IR range will be created, another interesting possibility will emerge: third harmonic generation in periodically poled crystals. At the present stage, the sum power of the fundamental and second harmonics is already sufficient for third harmonic generation with a power above 5 W at wavelengths of 374, 392 and 415 nm for light at λ = 1122, 1178 and 1246 nm, respectively. A separate issue is the optical damage resistance of crystals at these wavelengths, which lie in the UV spectral region.

Using the described optical scheme, we developed a laser module design suitable for the three output wavelengths: 561, 589 and 623 nm. We demonstrated pilot samples and performed qualification tests. The characteristics of VLM series devices are presented below, and Fig. 7 shows the appearance of a VLM laser.

Linewidth/nm	0.1
Output power/W at λ_{SH}	
561 nm	8
589 nm	15
623 nm	15

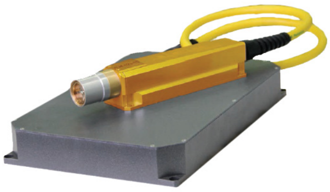

Figure 7. Appearance of a VLM series laser.

Long-term stability (%)	±2
Wall-plug efficiency (%)	> 4
Dimensions of the Raman laser package/mm	325×43×217
Dimensions of the converter package/mm	233×50×45.6
Weight/kg	4.5

4. Conclusions

An approach has been proposed for preventing spectral line broadening in Raman fibre lasers, by using thermostated narrow-band fibre Bragg gratings for the signal wavelength, and its viability has been demonstrated for one-, two- and three-cascade Raman lasers. We have achieved for the first time efficient (above 25%) SHG at a power above 10 W and wavelengths of 561, 589 and 623 nm in periodically poled lithium tantalate crystals for narrow-band cw Raman fibre laser light.

A series of visible lasers has been made using narrow-band Raman fibre lasers as pump sources. We have obtained cw light with an output power above 10 W at wavelengths of 561, 589 and 623 nm.

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