Wavelength-versatile, green –yellow – red laser

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Abstract: We report an all-solid-state Raman laser with intracavity frequency mixing, which can be easily configured (without exchanging optics) to provide selectable output at various wavelengths in the range 532nm – 606nm, with average powers of up to 2W.

Ocis Codes: (140.3550) Lasers, Raman; (140.3580) Lasers, Solid-State

1. Introduction

Solid-state Raman media have proven to be efficient frequency converters for Q-switched (ns) Nd lasers, creating a class of near-to-mid IR and yellow-to-red lasers with excellent potential for scaling to multiwatt powers[1]. For diode-pumped all-solid-state systems, single wavelength output powers of up to 3W have been reported at 1156nm[2] and up to 1.7W in the yellow [3]. However, in dermatology and other applications it is useful to have the wavelength selectable by the user.

Raman lasers have the ability to simultaneously oscillate on fundamental, first Stokes and higher-order Stokes wavelengths, and thereby comprise a convenient laser system for generating output on multiple visible wavelengths by intracavity second-harmonic generation (SHG) or sum frequency generation (SFG). Over 20 years ago Ammann [4,5] reported an intracavity Raman laser capable of providing different frequencies of visible laser output light based on an arclamp-pumped Nd:YALO laser and intracavity lithium iodate ($LiIO_3$) crystal (the latter has both χ_2 and χ_3 nonlinearity and acts both as a Raman medium and nonlinear frequency mixing medium). Up to 4 laser lines were generated in the yellow-to-red spectral range (in addition to the second harmonic of the fundamental at 540nm) by adjusting the $LiIO_3$ angle to phase match different combinations of the resonant fundamental and first two Stokes wavelengths. The highest output power of 0.6W was obtained at the second harmonic of the first Stokes wavelength.

In more recent developments of intracavity frequency-doubled Raman lasers, separate crystals for the Raman and nonlinear mixing media have been used to achieve high conversion efficiencies (up to 10% diode pump to visible power) by optimising the resonator mode size in each active element [3,6]. This also permits a wider choice of Raman materials (and output wavelengths) and of frequency mixing materials (and methods for phase-matching).Clearly, there are substantial opportunities to increase the efficiency and versatility of wavelength-switchable visible Raman lasers.

In this paper we report an intracavity Raman laser based on a diode end-pumped Nd:YAG crystal providing the 1064nm fundamental Raman pump, and which includes a separate nonlinear frequency-mixing medium. Lithium borate (LBO) is used as the nonlinear medium as this material provides efficient sum-frequency conversion and the output wavelength can be easily changed either by angle tuning or by temperature tuning. The Raman laser medium, potassium gadolinium tungstate (KGW), has a high damage threshold (~100 times that of $LiIO_3$) and high Raman gain on two Stokes lines at 768cm^{-1} and 902cm^{-1} (corresponding to the orientation of the N_m and N_g crystal axes along the pump polarization) [7]. Output is therefore possible on two wavelengths for each Stokes order depending on the crystal rotation about the laser axis, giving rise to a diversity of visible wavelengths. We describe here output performance of an intracavity frequency-mixed Raman laser with output selectable between four visible laser lines spanning the green-to-red spectral range which arise from frequency mixing of the fundamental (1064nm), first Stokes (1158nm) and second Stokes (1272nm) wavelengths which correspond to the Raman peak at 768cm^{-1}.

2 . Experiment

The layout of the intracavity Raman resonator is shown in Fig. 1. The pump source is a fibre-coupled, 808nm diode laser which produces 23 W output from a 400 μm diameter fibre (NA~0.22). The output from the end of the fibre is launched via 2 lenses into a laser crystal (5 mm diameter x 5 mm long, 1% doping) giving a pump spot size (beam radius) in the Nd:YAG laser crystal of approximately 300 microns. The pumped face of the Nd:YAG crystal is coated for high reflectivity at 1064 nm and 1155 nm and the rear surface is AR coated. The fundamental output was acousto-optically Q-switched, typically at repetition rates around 15 kHz. The $KGd(WO_4)_2$ crystal (5x5x50 mm) in our experiments was cut for propagation along the b axis (optical N_p axis). The laser resonator is typically 25 cm long and is defined by the coated plane face of the Nd:YAG laser crystal, the plane dichroic mirror at 45 degrees and an end mirror with radius of curvature 200 mm. The dichroic mirror has high reflectivity at 1064 nm and 1158 nm, and high transmission in the visible. The end mirror is a high reflector at the second harmonic as well as the infrared wavelengths.

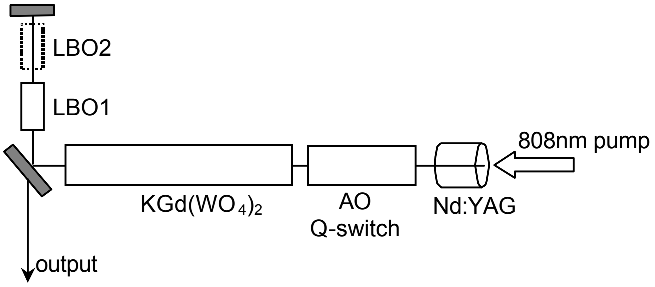

Fig. 1. Experimental arrangement of the intracavity Raman laser

LBO can be configured by angle tuning or temperature tuning to achieve phase-matching over the wavelength range of interest. For wavelength selection by angle tuning, a single 4x4x10 mm piece of LBO cut for type 1 critical phase-matching at 579nm was positioned in the short arm of the resonator near a beam waist and rotated by up to 17degrees. For temperature tuning, the strong dependence of wavelength on phase-matching temperature provided by LBO enables the output wavelength to be changed between 555 nm, 579 nm and 606 nm simply by varying the nonlinear crystal temperature over a fairly modest temperature range (<100°C) at fixed angle. Though in principal phase matching can also be achieved in LBO1 for 532 nm (by increasing its temperature to 150°C), this would require a multi-stage TEC to be used. Therefore we used two intracavity LBO crystals to achieve wavelength selection across the 4 wavelengths (532 nm, 555 nm, 579 nm and 606 nm). When the KGd(WO$_4$)$_2$ crystal is oriented such that the fundamental is polarised along the optical N$_m$-axis, the peak Raman gain occurs at 901 cm^{-1} whereas for the fundamental polarised along the optical N$_g$-axis, the 768 cm^{-1} mode is dominant. Different visible wavelengths can therefore be selected by rotating the crystal about its optical N$_p$-axis, but are not reported here.

3. Results

Wavelength selection by angle tuning

Table 1 summarises laser performance for a single intracavity LBO crystal (LBO1) cut for type I phase matching for SHG of 1158nm at normal incidence and inserted in the resonator cavity on an angle-tunable temperature-controlled mount . For 23W of incident diode pump power, 1.8W was obtained at 579 nm corresponding to 8% diode-to-yellow optical conversion efficiency. With the diode pump laser operating, the crystal was tilted by approximately 10° (external angle) in order to generate 0.95W output at 555nm (sum frequency of fundamental and first Stokes), while increasing the angle further to 17° generated 1.7W at 532 nm (second harmonic of the fundamental). Note that when changing the angle of the LBO crystal, the resulting beam walk-off made it necessary to readjust the laser end-mirror in the walk-off plane. Generation of higher order wavelengths (606 nm, 636 nm etc.) was prevented by the limited aperture size of our LBO crystal.

Table 1. Angle selection of output wavelength

LBO1 Angle	532 nm (Green) Output (W)	555 nm ("Lime") Output (W)	579 nm (Yellow) Output (W)
0°	0	0	1.8
11°	0	0.95	0
17°	1.7	0	0

Switching output wavelength by temperature tuning

Output was obtained at the four wavelengths 532 nm, 555 nm, 579 nm and 606 nm (SFG of the fundamental and second Stokes) using two LBO crystals at temperatures and output powers shown Table 2. With the LBO1 temperature set for phase matching at 579 nm, we obtained 0.6W on this single laser line at 3% diode-to-yellow conversion efficiency. The notably lower efficiency of yellow generation compared to the single LBO crystal case is attributed to the increased insertion loss of the second LBO crystal and the effect of the additional resonator length on the pump-resonator mode overlap in the Nd:YAG rod. In order to minimize the generation of the fundamental second harmonic, and thus allow the build-up of the first Stokes field in the resonator, the temperature of the LBO2 crystal was increased 25° above the phase match temperature. Switching to 555nm was achieved by adjusting the temperature of LBO1 to 95°C. The maximum output at 555nm was 0.52W. Switching to 532nm was achieved at by adjusting the temperature of LBO2 to 25°C. The maximum output of 1.5W is not sensitive to the temperature of LBO1 as expected since LBO1 only influences the dynamics of the Stokes fields. Output power ~0.25W was obtained for 606 nm when the LBO1 temperature was 19°C and LBO2 at 52°C. Note that the output power is notably lower for the red generation since the intrinsic efficiency for second Stokes line is comparatively low and the reflectance characteristics of the resonator mirrors were far from optimum for operation at 1272nm.

Table 2. Temperature selection of output wavelength

Temp LBO 1	Temp LBO 2	Green (532 nm) Output Power	"Lime" (555 nm) Output Power	Yellow (579 nm) Output Power	Red (606 nm) Output (W)
19°C	52°C	0	0	0	~0.25
48°C	52°C	0	0	0.57	-
95°C	52°C	0	0.52	0	-
-	25°C	1.5	0	0	-

3. Conclusion

We have demonstrated an effective a method for providing easily switchable visible laser output from an all-solid-state intracavity Raman laser with intracavity frequency mixing. Best output powers (indeed the highest reported to date for an intracavity frequency-doubled Raman laser) are obtained for angle tuning of a single LBO crystal. Mechanical arrangements providing automatic walk-off compensation can be used to eliminate the need to realign the cavity end-mirror when wavelength switching by angle tuning.

An alternative approach to wavelength switching has been demonstrated wherein two intracavity LBO crystals are temperature-tuned across modest temperature ranges to achieve four wavelengths spanning green to red. This approach has the advantage that cavity mirror re-alignment is not required and wavelength selection is easily controlled electronically, though overall conversion efficiencies are reduced due to increased insertion losses. Higher powers are anticipated with improved mirror coatings (allowing for higher reflectance at the second Stokes wavelength) and further optimisation of resonator design to improve mode matching in the laser material at high powers.

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