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# Discretely tunable, all-solid-state laser in the green, yellow, and red

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We report an all-solid-state intracavity Raman laser with intracavity nonlinear sum-frequency generation providing visible output wavelengths selected from second harmonics and sum frequencies of the fundamental and Stokes fields. The laser comprises a diode end-pumped Nd:YAG laser, an acousto-optic  $Q$  switch, a  $\text{KGd}(\text{WO}_4)_2$  Raman crystal, and a lithium borate nonlinear converter in a resonator designed to accommodate dynamic thermal lensing. For 20 W of pump power, output powers up to 1.8 W are demonstrated at wavelengths of 532, 555, 579, and 606 nm, selectable by angle and temperature tuning of the nonlinear medium. © 2005 Optical Society of America

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All-solid-state intracavity, frequency-doubled, Raman lasers are an important class of efficient and powerful sources in the yellow–orange spectral region with applications in biomedicine and defense. Output powers exceeding 1.5 W at 579 nm with optical diode-to-visible efficiencies approaching 10% have been reported for compact diode end-pumped systems.<sup>1</sup> Raman lasers are also highly amenable for generating several output wavelengths from a single device (or multiple output wavelengths simultaneously) as a result of cascading to higher-order Stokes lines and the capability to oscillate these in a single resonator.

Ammann<sup>2</sup> first reported a wavelength-selectable intracavity Raman laser that used arc-lamp-pumped Nd:YALO and the Raman material  $\text{LiIO}_3$ , which also acted as a sum-frequency-mixing and second-harmonic generation medium, to generate five wavelengths in the range of 540–655 nm at output powers up to 600 mW. Achieving higher average output powers in the multiwatt range requires consideration of the resonator spatial-mode dynamics in the presence of a second thermal lens formed in the Raman medium (as well as the thermal lens in the laser medium). Pask and Piper<sup>3</sup> demonstrated efficient generation of 578-nm output at 1.2 W from a  $\text{LiIO}_3$  Raman laser that used a separate nonlinear mixing crystal (lithium borate) and a Nd:YAG fundamental gain medium in a resonator designed to optimize the mode sizes in the Raman crystal and nonlinear frequency-mixing medium at maximum pump power. In recent years,  $\text{KGd}(\text{WO}_4)_2$  (KGW) has emerged as an excellent Raman (and self-Raman) material owing to its substantial Raman gain and good thermophysical properties.<sup>4,5</sup> Through improved resonator design and Raman crystal selection, more powerful and all-solid-state Raman lasers have been demonstrated.<sup>1</sup> Combining a cascaded Raman resonator with intracavity sum-frequency generation provides a novel and practical approach to realizing wavelength-selectable visible lasers of substantial output power.

In this Letter we report for the first time to our knowledge an intracavity frequency-mixed Raman laser from which output is easily selected between four visible laser lines spanning the green-to-red

spectral range. The output wavelengths correspond to frequency mixing of the fundamental (1064-nm), first Stokes (1159-nm), and second Stokes (1272-nm) wavelengths of Nd:YAG Raman shifted by the  $768\text{-cm}^{-1}$  Raman mode of KGW. We also report a novel approach to wavelength switching that involves two intracavity nonlinear mixing crystals and that offers some practical advantages.

The layout of the intracavity Raman resonator is shown in Fig. 1. The pump source is a fiber-coupled, 808-nm diode laser that produces 23 W of output from a 400- $\mu\text{m}$ -diameter fiber (N.A.  $\sim 0.22$ ). The output from the end of the fiber is collimated and focused into a Nd:YAG laser crystal (5 mm diameter  $\times$  5 mm long, 1% doping), yielding a pump spot size (beam radius) of approximately  $300\mu\text{m}$ . The pumped face of the Nd:YAG crystal is coated for high reflectivity at 1064 and 1159 nm, and the second surface is antireflection coated for the near infrared. The laser is acousto-optically  $Q$  switched at a 16-kHz repetition rate. The KGW crystal of dimensions 5 mm  $\times$  5 mm  $\times$  50 mm is broadband antireflection coated for 1064–1150 nm. The crystal is cut for propagation along the optical axis (i.e., the  $N_p$  axis) and oriented with the optical  $N_m$  axis vertical (which is parallel to the fundamental field) to select the  $768\text{-cm}^{-1}$  Raman mode. The laser resonator is typically 25 cm long and is defined by the coated face of the Nd:YAG laser crystal, a plane dichroic mirror at  $45^\circ$ , and an end mirror with a radius of curvature of 200 mm. The dichroic mirror has high reflectivity at

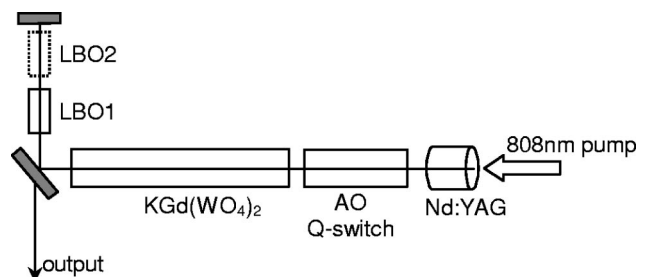


Fig. 1. Experimental arrangement of the intracavity Raman laser. AO, acousto-optic.

**Table 1. Angle Selection of Output Wavelength with a LBO Temperature of 54 °C**

LBO1 Angle <sup>a</sup>	Wavelength (mm)	Output Power (W)
0°	579	1.8
11°	555	0.95
17°	532	1.7

<sup>a</sup>The LBO1 angle is the LBO1 rotation angle (i.e., external angle).

1064 and 1159 nm and high transmission in the visible. The end mirror is a high reflector at the visible and infrared wavelengths.

The selectability of output wavelengths stems from the dynamic interactions between the fundamental (1064-nm) and Stokes (1159- and 1272-nm) optical fields. In the absence of sum-frequency generation to the visible, the growth in the fundamental field and subsequent conversion into Stokes orders occurs rapidly in the high-*Q* resonator. In the present case, high resonator losses for wavelengths >1250 nm (owing to increased losses at antireflection-coated surfaces and through the end mirrors) limits the second-order Stokes field and precludes higher-order (>2) Stokes generation. As a result, most efficient conversion is demonstrated for the sum frequencies and second harmonics of the fundamental and the first two Stokes orders.

Nonlinear crystals that are often used for second-harmonic generation (SHG) or sum-frequency generation (SFG) in this wavelength range include lithium triborate (LBO),  $\beta$ -barium borate, KTP, and quasi-phase-matched crystals. In this work we selected LBO because it can be easily configured by either angle or temperature tuning in addition to its well-known efficient conversion by SHG or SFG. LBO also allows excellent alignment stability in the case of a temperature-tuned laser as noncritical phase matching occurs near room temperature.

For angle tuning, a single 4 mm × 4 mm × 10 mm piece of LBO (LBO1) cut for type I noncritical phase matching (i.e.,  $\theta=90^\circ$ ,  $\phi=0^\circ$ ) and antireflection coated for the 1064-nm fundamental is placed in the resonator cavity on a rotatable temperature-controlled mounting. Table 1 summarizes the laser performance for LBO1 at 54 °C (corresponding to noncritical phase matching at 579 nm at normal incidence). For 23 W of incident diode pump power (which corresponds to ~20 W of absorbed pump power), 1.8 W is obtained at 579 nm corresponding to 8% diode-to-yellow optical conversion efficiency. With the diode pump laser operating and the crystal tilted by approximately 10° (external angle), 0.95 W of output power is generated at 555 nm (SFG of the fundamental and first Stokes). Increasing the angle to 17° generates 1.7 W at 532 nm (second harmonic of the fundamental). Note that changing the angle of the LBO crystal results in some minor beam displacement that often makes it necessary to readjust the laser end mirror in the horizontal plane. (However, mechanical arrangements providing automatic walk-off compensation could eliminate the need to realign the

cavity end mirror when wavelength switching by angle tuning.) As discussed in more detail below, generation of longer wavelengths corresponding to frequency mixtures of higher-order Stokes fields (606 nm, 636 nm, etc.) can be achieved by decreasing the LBO temperature or selecting other nonlinear materials.

For temperature tuning, the strong dependence of wavelength on phase-matching temperature provided by LBO allows the output wavelength to be simply switched among 555, 579, and 606 nm by varying the nonlinear crystal temperature over a fairly modest temperature range (<100 °C) at a fixed angle. As discussed in more detail below, phase matching can also be achieved for 532 nm by increasing the temperature to ~150 °C; however, the extended temperature range is not practical for the Peltier thermoelectric heating and cooling needed in these experiments. Instead, we use two closely spaced intracavity LBO crystals to overcome this limitation and to provide rapid (<1-min) wavelength switching across the four wavelengths (532, 555, 579, and 606 nm) with only modest temperature changes (<50 °C). The second LBO crystal (LBO2) was the same as LBO1 but cut for SHG from 1064 nm at 25 °C ( $\phi\sim 11.5^\circ$ ). The temperature settings and output powers obtained are shown Table 2.

We achieve output power of 1.5 W at 532 nm by adjusting the temperature of LBO2 to 25 °C. Note that the temperature setting of LBO1 is not important under these conditions because efficient frequency doubling depletes the fundamental, effectively forestalling conversion to the first Stokes. We switch to 555 nm by adjusting the temperature of LBO1 to 95 °C, the phase-matching temperature for SFG of 1064 and 1159 nm, and by detuning the temperature of the LBO2 crystal (by heating to 52 °C). The strong fundamental field now drives the first Stokes field in the resonator. SFG of 1064 and 1159 nm in LBO1 provides maximum 555-nm output of 0.52 W. Similarly, with the LBO1 temperature set for phase matching at 579 nm (i.e., ~48 °C) we obtain 0.6 W at 3% diode-to-yellow conversion efficiency, and with the LBO1 temperature set for SFG of the first and second Stokes (1159 nm+1272 nm, 19 °C) we obtain ~0.25 W output power at 606 nm.

In comparison with the results obtained with a single LBO crystal arrangement, the lower output powers are attributed to the additional insertion loss of the second LBO crystal and the effect of the addi-

**Table 2. Temperature Selection of Output Wavelength**

LBO1 Temperature (°C)	LBO2 Temperature (°C)	Wavelength (nm)	Output Power (W)
19	52	606	0.25
48	52	579	0.57
95	52	555	0.52
—	25	532	1.5

tional resonator length on the pump-resonator mode overlap in the Nd:YAG rod. At 606 nm the output power is low compared with the shorter wavelengths owing to the aforementioned coating losses at 1272 nm. With improved mirror and antireflection coatings, substantial powers are anticipated at 606 nm and for wavelengths based on SHG and SFG of high Stokes orders.

A number of options are available that provide tuning over a large number of wavelengths. For angle tuning it is desirable to use small rotation angles because large angles introduce large reflection losses and also require larger-aperture (and thus larger-volume and more expensive) crystals. Although angle tuning has been demonstrated for three wavelengths for the LBO at 54 °C, using a lower LBO temperature would allow four or more wavelengths to be scanned for a similar range of angles. As shown in Fig. 2(a), for LBO at 20 °C, for which noncritical phase matching (NCPM) for SFG of the first and second Stokes at 606 nm is achieved, four wavelengths can be scanned for less than a 12° rotation of the

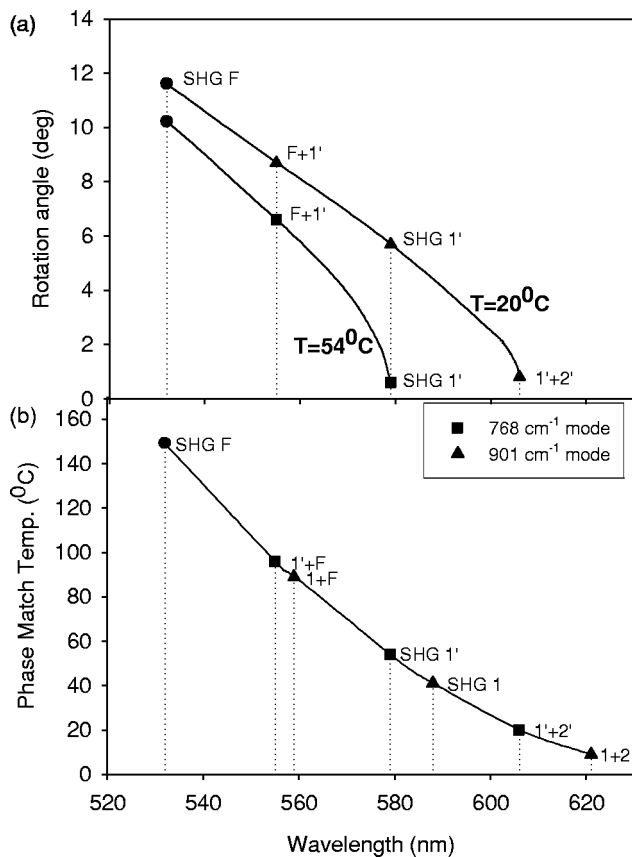


Fig. 2. Phase-matching angles (internal angles) and temperatures (calculated using SNLO) for SHG and SFG of fundamental and Stokes fields in LBO (a) as a function of angle and (b) as a function of temperature for NCPM. F, fundamental 1064 nm; 1'; 2'; first and second Stokes for the 768-cm<sup>-1</sup> Raman mode of KGW; 1, 2, first and second Stokes of the 901-cm<sup>-1</sup> Raman mode. The curve fits are included for aesthetic purposes.

beam axis in the crystal (~18° external angle). By use of  $\beta$ -barium borate as the nonlinear medium, the four wavelengths can be accessed within a 3.5° rotation. The smaller angle would allow switchability between a large number of wavelengths for a narrow-aperture crystal and avoids the high losses incurred for high incident angles.

Temperature tuning of a NCPM crystal offers an approach with the key practical advantages of excellent alignment stability, no mechanical movement of optics (which is desirable from the viewpoint of commercial systems), and the ability to fix the crystal normal to the resonator axis where the insertion losses are minimized. Using a larger temperature range than investigated here (using a multistage Peltier cooler or a wire-wound heater, for example), it is possible to scan more than four wavelengths with a single LBO crystal. As shown by the phase-matching curves for SHG and SFG in Fig. 2(b), tuning across 532, 555, 579, and 606 nm can be achieved within the temperature range of 17 °C–145 °C.

It is also important to note that Raman materials such as KGW provide an increased number of wavelength options owing to their second high-gain Raman mode, which is selectable by reorienting the Raman crystal. For example, rotating the crystal through 90° relative to the fundamental polarization provides a set of alternative wavelengths corresponding to the second Raman mode KGW at 901 cm<sup>-1</sup>. The available wavelengths (559, 588, 621 nm,...) along with the corresponding NCPM temperatures are shown in Fig. 2(b). Moreover, it is possible to generate high-order Stokes wavelengths that comprise a mixture of the two Raman modes, as demonstrated recently for an external-cavity KGW Raman laser.<sup>6</sup>

In conclusion, we have demonstrated a discretely tunable laser in the green-to-red spectral region at output powers in the watt range at diode-to-visible output efficiencies up to 8%. The combination of intracavity SHG or SFG with intracavity Raman frequency conversion provides for selectable visible output over a substantial spectral range from compact, efficient, and practical devices.

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