Continuous-wave wavelength conversion for high-power applications using an external cavity diamond Raman laser

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Received April 23, 2012; revised May 29, 2012; accepted May 30, 2012; posted May 30, 2012 (Doc. ID 167242); published July 3, 2012

We demonstrate continuous-wave (cw) operation of a diamond Raman laser at 1240 nm in an external cavity configuration. The output power increased linearly with pump power with a 49.7% slope efficiency and reached 10.1 W at the maximum available pump power of 31 W. The combination of resonator design with diamond provides a novel approach to power-scalable cw wavelength and beam conversion. © 2012 Optical Society of America

OCIS codes: 140.3550, 140.3580, 160.4330, 190.5650.

High-power cw generation at wavelengths different from rare-earth ion (Nd, Yb, Er, Ho, Tm) lasers and their harmonics remains a challenge. Instead of using alternative laser media, nonlinear frequency conversion in optical parametric sources (OPOs) and Raman lasers is often used to extend the range of available wavelengths. The main advantages of OPOs are the continuous wavelength tuning and the broad spectral coverage from generally visible to the mid-infrared. However, the average power scaling is limited due to thermal loading of the \( \chi^2 \) nonlinear crystal arising from parasitic absorption leading to phase-mismatch and damage [1]. Raman lasers, on the other hand, offer a simple approach free from phase matching constraints, which can utilize a class of materials with improved thermal properties.

To date Raman fiber lasers, because of the thermal advantages of a distributed active media, offer the highest cw output power of 150 W with 85% efficiency in the infrared [2]. However, for subsequent harmonic conversion, narrow linewidth output needs to be carefully managed and stimulated Brillouin scattering avoided [3]. Bulk crystalline alternatives benefit from very low spectral broadening, which allows for efficient harmonic generation or frequency mixing. Raman crystals, such as metal nitrates and tungstates, have enabled generation of infrared output powers up to 11 W in pulse mode [4] and 3.4 W continuous wave [5]. In the visible, intracavity self-Raman lasers generating 4.3 W at 586 nm, the second-harmonic of the first Stokes, and 5.3 W at 559 nm, the sum frequency of the pump and the first Stokes, have been demonstrated [6]. However, poor thermal properties of these materials prevent straightforward power scaling in the case of external cavity Raman lasers. In the case of intracavity designs, the simultaneous thermal lensing in the laser media and Raman crystal make the power scaling even more challenging.

Recently, synthetic diamond has shown highly efficient visible [7] and infrared [8,9] Raman conversion. Compared to other Raman crystals, diamond’s 2 orders of magnitude higher thermal conductivity and low thermal expansion coefficient mitigates thermal problems, such as induced lensing, birefringence, and stress fracture. Already the highest average output powers for pulsed (24.5 W [10]), and cw intracavity Raman lasers (5.1 W [11]) have been demonstrated using diamond.

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The experimental arrangement is shown in Fig. 1. As a pump source we used a cw Nd:YVO₄ laser generating linearly polarized output at 1064 nm. At maximum output the $M^2$ was approximately 1.7. A half-wave plate and polarizer served as a pump power attenuator. After passing through an optical isolator a half-wave plate was used to align the polarization vector of the pump with the diamond’s (111) axis to access the highest gain [8]. In order to reach the threshold of the stimulated Raman scattering, a lens of focal length $f = 50$ mm was used to focus the pump in the diamond. The measured focal spot radius (at $1/e^2$) at the crystal midpoint was 30 μm resulting in an incident intensity of $\approx 0.8$ MW/cm² at the threshold of 11.3 W. The pump, residual pump, and Stokes powers were measured by PIN photodiodes A, B, and C calibrated using a power meter.

A 105 mm long quasi-concentric resonator comprised of two concave mirrors with 50 mm radius of curvature was used to mode-match the Raman oscillator and pump waist sizes. The input coupler was highly transmissive at the first Stokes wavelength of 1240 nm. The output coupler was highly reflective at 1064 nm and had 0.4% transmission at the first Stokes wavelength. To prevent generation of the unwanted second Stokes component the mirror reflectivity at 1485 nm was minimized.

Above threshold the Stokes output power increased linearly with input power, as shown in Fig. 2. The maximum output power reached 10.1 W with 31 W of incident pump power. Over the operating range, the residual pump power remained approximately constant at around 10 W. The conversion efficiency at maximum power was 31.7%. The $M^2$ parameter improved from 1.7 of the pump to 1.16 of the Stokes (refer to Fig. 1 for far-field images). No optical damage was observed and we expect that much higher output powers can be generated by increasing the pump power.

The Stokes output exhibited substantial amplitude fluctuations when operated near the Raman laser threshold but became more stable at higher pump powers when a significant portion of the pump was depleted. The temporal behavior near maximum power (Fig. 2) shows some fluctuations remaining (about 10% of the average power) correlated with changes in pump depletion. These changes may be caused by mode instabilities observed in the pump laser and mechanical vibrations, which we expect can be reduced by standard techniques.

Simultaneous measurement of the pump power, back-reflected residual pump power, and generated Stokes output power enables the total resonator losses to be deduced. From the pump depletion, representing the change in the residual pump power upon alignment of the Raman laser cavity (from 31 to 9.2 W at maximum pump power), we obtain the power coupled into the Stokes and phonon fields (21.8 W). Of this depleted pump power, 14.2% is lost to the excitation of optical phonons (3.1 W), and the remainder is attributed to the generation of the intracavity Stokes field (18.7 W). Since the measured Stokes output (10.1 W) was 54% of the total Stokes generated, we deduce that the difference (8.6 W) represents the combined parasitic absorption and scatter loss in the diamond.

Well above threshold, the 46% loss fraction of the generated Stokes power was constant as a function of pump power, suggesting linear absorption and scatter loss processes. Using the known output coupler transmission ($T = 0.4 \pm 0.1$%), we deduce the Stokes power circulating in the Raman cavity and the combined absorption and scatter coefficient in the diamond at 1240 nm. As shown in Fig. 4, the loss coefficient distributed over the crystal length was $0.17 \pm 0.05\%$/cm for the investigated range. We believe this to be an upper bound as there may be some off-axes reflections of the diamond facets. Since the loss coefficient is close to the absorption coefficient value ($=0.1\%$/cm at 1064 nm) for the diamond supplier's low-nitrogen (20 ppb) material [13], we suspect diamond bulk absorption to be the main loss mechanism. Although slightly higher efficiency may be obtained by optimizing the output coupling, the results of this study show that...
the major limitation for this configuration is diamond loss. Improvements in diamond quality are thus expected to enable slope and conversion efficiencies much closer to the quantum limit (86% for pumping at 1064 nm).

Because of the heating in the crystal arising from inelastic (Stokes) scattering and parasitic absorption (deduced to be approaching 11.7 W in this case), the efficient operation of the device relies on excellent thermal handling properties of the Raman crystal. The superior thermal conductivity and low thermal expansion coefficient of diamond, combined with the concentric resonator design, act to diminish the impact of thermally induced lensing and birefringence as the laser power increases. In addition, the high thermal shock parameter for diamond holds promise for further power scaling without catastrophic damage [14,15].

We have demonstrated efficient conversion of a cw 1064 nm Nd laser to 1240 nm using an external cavity diamond Raman laser with substantial beam quality improvement. The maximum output power of 10.1 W was limited by pump power available, and we expect linear scaling to much higher levels with increased pump power.

The key design attributes of an external Raman resonator and a high gain Raman crystal with excellent thermal properties comprise a power-scalable wavelength conversion approach with intrinsically low spectral broadening (cf., fibers or parametric oscillators). This approach provides a simple add-on device that is applicable to a range of high-power cw laser technologies (including line-narrowed fiber lasers) and with further potential for extending wavelength range via Stokes cascading and subsequent harmonic conversion.

The authors would like to acknowledge the support of an Australian Research Council Future Fellowship (project number FT0990622) and Air Force Research Laboratory (under agreement number AOARD-10-4078).

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Optics Letters

ISSN: 0146-9592
Title: Optics Letters
Publishing Body: Optical Society of America
Country: United States
Status: Active
Start Year: 1977
Frequency: Semi-monthly
Volume Ends: Jan - Dec
Document Type: Journal; Academic/Scholarly
Refereed: Yes
Abstracted/Indexed: Yes
Media: Print
Alternate Edition ISSN: 1539-4794
Size: Standard
Language: Text in English
Price: USD 2,650 combined subscription per year domestic to institutions (Print & Online Eds.), USD 2,735 combined subscription per year in Canada to institutions (Print & Online Eds.), USD 2,840 combined subscription per year elsewhere to institutions (Print & Online Eds.) (effective 2010)
Subject: PHYSICS - OPTICS
Dewey #: 535
LC#: QC350
CODEN: OPLEDP
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Article Index: Index Available
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Editor(s): Alan E Willner (Editor-in-Chief)
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ADDITIONAL TITLE INFORMATION

Alternate Title: Medline Abbreviated title: Opt Lett; Abbreviated title: O L

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