Solid-State Raman Lasers

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Abstract: Crystalline solid-state Raman lasers offer practical and efficient frequency conversion from existing (pulsed) solid-state laser sources which, in combination with SFG, provides for wavelength selection from near-ir to visible and uv at multiwatt average powers.

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1. Introduction

Although Stimulated Raman Scattering (SRS) has been known almost since the beginning of the laser, and was first used (by Ammann [1]) to achieve efficient frequency conversion for Nd^{3+} lasers more than 25 years ago, crystalline solid-state Raman lasers have only recently become established as practical sources generating high peak and average powers in the near-ir and, in combination with SFG, the visible. Compact, all-solid-state devices employing intracavity SRS and SFG of diode-pumped Q-switched Nd:YAG and Nd:YVO_4 lasers and delivering average powers up to 1.8 W in the yellow at optical conversion efficiencies (from the diode pump) up to 10% have been reported [2]; Raman conversion from a 532nm visible pump to the yellow/orange /red in an external Raman resonator has been achieved with efficiencies ~30% at similar power levels [3].

Realisation of high conversion efficiencies at high average powers in solid-state Raman lasers requires detailed considerations of the characteristics of the pump laser, the Raman material, the design of the Raman resonator (in particular the effects of dynamic thermal lensing in the Raman medium), and the output coupling scheme (which may include extraction at high order Stokes wavelengths and/or shorter wavelengths via intracavity SHG/SFG). Building on two excellent recent reviews of solid-state Raman lasers [4,5], this tutorial paper will cover the fundamentals and recent progress in solid-state Raman lasers, focusing on practical issues of device development.

2. Pump lasers

The comparatively low gain coefficients (~10 cm/GW) of practical Raman materials (eg $Ba(NO_3)_2$, YVO_4, $KGd(WO_4)_2$, $LiIO_3$) generally require that the laser pump source be pulsed to ensure adequate Raman conversion efficiency. In the case of ultrashort pulse lasers, conversion efficiencies of >50 and up to 85% have been reported for double-pass Raman generators; for nanosecond pump lasers (eg Q-switched Nd:YAG) Raman resonators are generally required to increase the intracavity optical fields and so lower Raman threshold and achieve high conversion efficiencies (~60%). A very recent and exciting development is demonstration of cw oscillation in crystalline Raman media in high-Q resonators pumped by cw diode-pumped Nd lasers.

3. Crystalline Raman materials.

A range crystalline Raman materials of high quality and reasonable price is now available. $LiIO_3$, which was used in the earlier Ammann work, and was the subject of our own extensive study of thermal effects in SRS, has good gain (4.8 cm/GW) but suffers from comparatively low damage threshold (~100 $MWcm^{-2}$) and therefore is restricted to use at lower powers. $Ba(NO_3)_2$ has high gain (11cm/GW) and higher damage threshold (~400 $MWcm^{-2}$) and is suitable for high peak power SRS, but is restricted by relatively poor thermal characteristics at high average powers. $KGd(WO_4)_2$ has moderate gain (~4 cm/GW) very high damage threshold, excellent thermal characteristics and two Raman modes (768 and 901 cm^{-1}) which are accessible at different pump polarization with respect to crystal axes, and which makes it extremely versatile in high average power generation over a range of wavelengths. A variety of other tungstates have also been shown to have excellent SRS properties, though KGW is generally preferred for all-round performance.

4. Raman resonators

Raman resonators take various forms: external Raman resonators, for which an external pump beam is coupled into a resonator containing the Raman crystal and from which is coupled the Raman output (first or higher Stokes orders depending on mirror coatings), or which may also contain a nonlinear element for SFG/SHG; intracavity Raman lasers, where the Raman crystal is contained in the same resonator as the laser material which generates the pump wavelength, and which has mirror coatings to couple out the first or higher order Stokes wavelengths, or the SFG/SHG wavelengths from an intracavity nonlinear element; or coupled-cavity Raman lasers in which the laser crystal and the Raman crystal are contained in separate arms of coupled resonators.

In all examples of Raman resonators, the thermal energy deposited in the Raman crystal by SRS itself is a significant factor in resonator design, which must take account of the resultant thermal lensing at high average powers. Both resonator stability and spatial mode overlap are important issues, even for the simplest external resonator. In the case of intracavity Raman lasers, considerations of spatial mode overlap extend to the laser material, and the nonlinear SFG/SHG element if included: mode sizes must be optimized at each element to ensure high overall conversion efficiency at the input/output power design operating point.

5. SFG/SFG in Raman resonators

The inclusion of intracavity SFG or SHG in Raman lasers provides a highly desirable option for extracting the optical output by way of the second harmonic of the first, second, or higher Stokes order, or sum-frequency combinations of the fundamental and the various Stokes orders. In this way the Raman laser can be engineered to allow the Raman orders to cascade, the optical power being extracted at a given SFG or SHG wavelength, which can be chosen simply by controlling the phase matching of the nonlinear frequency converter. This enables the output wavelength to be switchable amongst a range of visible wavelengths relatively simply and quickly while maintaining good overall conversion efficiencies from the pump.

6. Conclusion

SRS in crystalline materials provides a practical and efficient means for frequency conversion of the output of standard pulsed solid-state lasers, and in combination with intracavity SFG/SHG, permits efficient extraction at a range of visible wavelengths. Multiwatt powers have been demonstrated for ir Stokes wavelengths and 1-2W for visible Stokes and SHG wavelengths, with good prospects for power scaling towards 10W.

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