Generation of combs of wavelengths in the infrared and visible using cascaded stimulated Raman scattering in potassium titanyl phosphate

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Abstract: We report the generation of a comb of emission wavelengths in the near-infrared, and wavelength-tunable emission at up to five discrete wavelengths in the visible between 534 nm and 572 nm by making use of cascaded stimulated Raman scattering in potassium titnyl phosphate in combination with Nd:GdVO$_4$ and Nd:YLF laser crystals.

1. Introduction

Stimulated Raman scattering (SRS) in crystalline materials is an established method of wavelength converting laser systems and it has been demonstrated with great efficiency in vanadates, tungstates and molybdates in both pulsed and continuous-wave modalities [1,2,3]. Potassium Titanyl Phosphate (KTP) is a well known crystal which features high second and third-order nonlinearities and it is often used for frequency-doubling, parametric generation and electro-optic modulation [4]. The application of KTP as a Raman-shifting medium has however, received relatively little attention, with the only published work (to the best of our knowledge) being that of *Chen* [5], where he demonstrated operation of a Q-switched laser using Nd:YAG as the laser medium and an *x*-cut KTP crystal as the Raman medium. In contrast with other Raman-active crystals such as vanadates, tungstates and molybdates, KTP has a strong Raman-shift at a low wavenumber, 270 cm^{-1} with secondary shifts at 214 cm^{-1} and 694 cm^{-1}. By cascading this strong Raman shift it is therefore possible to generate a comb of closely spaced wavelengths in the infrared. Then, by using intracavity sum-frequency and second-harmonic generation (SFG and SHG), it is also possible to generate a comb of wavelengths in the visible.

In this work, we examine the performance of KTP as an intracavity SRS medium in a continuous-wave (CW) laser. We examine its use with two different laser crystals, Nd:GdVO$_4$ and Nd:YLF. Nd:GdVO$_4$ was chosen for its polarised emission and its high emission cross-section. Nd:YLF was investigated as an alternative to Nd:GdVO$_4$ due to its weak thermal lens, and because it is not Raman-active.

2. Experimental Setup

For both combinations of crystals, Nd:GdVO$_4$/KTP and Nd:YLF/KTP, we investigated power scaling performance using two resonators, one to generate cascaded Stokes emission, and the other to generate visible emission. The general resonator layout is shown in Figure 1, and the resonator elements are summarised in Table 1.

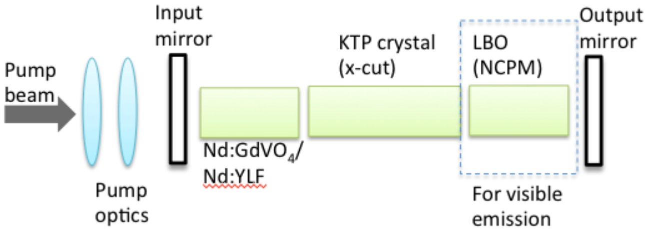

Fig 1: General resonator layout used in this work.

Table 1: Summary of resonator elements

Pump Source (fibre-coupled)	*Nd:GdVO$_4$ systems*: 879 nm, 25 W, 200 µm core diameter. Pump spot diameter~ 460 µm. *Nd:YLF systems*: 881 nm, 50 W, 100 µm core diameter. Pump spot diameter ~ 500 µm.
Nd:GdVO$_4$	0.3 at. % Nd-doped, 4×4×10 mm, AR/AR coated, R<0.1 %@ 1063-1190 nm.
Nd:YLF	1 at. % Nd-doped, 4×4×15 mm, AR/AR coated, R<0.45 %@ 1054-1190 nm.
KTP	x-cut, 4×4×20 mm, AR/AR coated, R<0.48 % @1054-1190 nm.
Lithium Triborate (LBO)	Non-critically phase-matched (NCPM), $\Theta=90^o$, $\Phi=0^o$, 4×4×10 mm, AR/AR coated, R<0.09 % @ 1054-1180 nm. **Note: This was inserted into the resonator to generating visible emission.**
Input Mirror	*Nd:GdVO$_4$ system*: flat, R>99.97 %@ 1063 nm/ R >99.993 %@1173-1308 nm. *Nd:YLF system*: 400 mm radius of curvature (ROC), R>99.992 %@ 1054 nm-1173 nm.
Output Mirror	*Nd:GdVO$_4$ and Nd:YLF, Stokes systems*: 250 mm ROC, R=99.91 %@ 1054 nm/1064 nm; R=99.4 % @1173 nm. *Nd:GdVO$_4$ visible systems*: 100 cm ROC, R>99.997 %@ 1063 nm/ R >99.993 %@1173-1308 nm. *Nd:YLF visible system*: 200 mm ROC, R>99.992 %@1054 nm-1173 nm.

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The resonators used with the Nd:$GdVO_4$/KTP combination were plano-convex, and were kept as short as possible to help offset the strong positive thermal lens generated in the Nd:$GdVO_4$ laser crystal. In contrast, due to the weaker thermal lens generated in the Nd:YLF crystal, the resonators formed using the Nd:YLF/KTP combination were concave-concave and featured spacing of 4 mm between the input mirror and the Nd:YLF crystal, and 10 mm between the Nd:YLF and KTP crystals in order to maintain good pump overlap and mode-match within the KTP crystal. Visible emission was obtained by temperature-tuning the LBO crystal (NCPM).

The Stokes output was separated from the residual fundamental emission using a long-pass filter and similarly, a short-pass filter was used to isolate the visible emission from the infrared. A fibre-coupled spectrometer (Ocean Optics HR 4000/USB2000) was used to monitor the emission from each resonator as the incident pump power was increased, this was also used to help determine the thresholds for emission at each wavelength.

3. Results/Discussion

Nd:$GdVO_4$/KTP System

Results obtained from the Stokes and visible resonators are summarised in Table 2.

Table 2: Summary of output powers achieved from the Stokes and visible resonators using Nd:$GdVO_4$/KTP

Wavelength (nm)	**Threshold Pump Power (W)- Absorbed**	**Max Output Power (mW)**
1063.0 nm (Fundamental)	0.397	676
1065.0 nm (Fundamental-orthogonal pol)	8.72	694
1094.3 nm (1st-Stokes 270 cm^{-1})	2.09	468
1127.4 nm (2nd-Stokes 270 cm^{-1})	3.08	587
1147.8 nm (1st-Stokes 690 cm^{-1})	4.49	115
1165.6 nm (3rd-Stokes 270 cm^{-1})	9.57	< 20 mW
1173 nm (self-Raman 1063 nm line)	5.34	< 20 mW
1175.8 nm (self-Raman 1065 nm line)	9.71	< 20 mW
539.3 nm (SFM fund+1st-Stokes)	1.95	183
547 nm (SHG 1st Stokes)	2.37	542
555.4 nm (SFM 1st+2nd-Stokes)	4.07	78
563.7 nm (SHG 2nd-Stokes)	3.78	62
572.35 nm (SFM 2nd+3rd Stokes)	4.34	35

The Stokes resonator exhibited a low fundamental (1063 nm) emission threshold of 0.397 W and progressively higher thresholds of 2.1 W, 3.1 W and 9.6 W for first, second and third-Stokes respectively. Maximum emission of 468 mW at the first-Stokes (1094 nm) and 587 mW at the second-Stokes (1127.4 nm) was achieved. In addition to the fundamental and cascaded-Stokes emission lines, other lines at 1065 nm (fundamental emission wavelength for the orthogonal polarisation of Nd:$GdVO_4$), 1147.8 nm (first-Stokes generated by the 694 cm^{-1} line), 1173 nm (self-Raman of the 1063 nm fundamental) and 1175.8 nm (self-Raman of the 1065 nm fundamental) were observed. These additional lines occurred at pump powers above the threshold for first-Stokes and were found to oscillate in competition with the cascaded Stokes orders. This competition is a subject of our ongoing research.

The maximum power emitted in the visible was 542 mW, achieved at 547 nm (the SHG of the first-Stokes). As the number of Stokes orders increased with the incident pump power (due to cascaded SRS), it became increasingly difficult to achieve emission at a single visible wavelength, and the resonator became increasingly unstable, as evidenced by a rapid decrease in output power. The resonator also operated highly multi-mode. We were unable to generate emission at the second-harmonic of the third-Stokes order because the temperature which the LBO had to be tuned to was very close to that required for second-harmonic generation of the Nd:$GdVO_4$ self-Raman line (first-Stokes).

Nd:YLF/KTP System

In light of the significant competition effects we observed when using Nd:$GdVO_4$ with the KTP crystal, we investigated the application of Nd:YLF as the active laser medium because it is not Raman-active. Results obtained from the Stokes and visible resonators are summarised in Table 3.

Table 3: Summary of output powers achieved from the Stokes and visible resonators using Nd:YLF/KTP

Wavelength (nm)	Threshold Pump Power (W)- Absorbed	Max Output Power (mW)
1053 nm (Fundamental)	0.55	831
1084 nm (1st-Stokes 270 cm^{-1})	5.91	173
1117 nm (2nd-Stokes 270 cm^{-1})	10.98	16
534.5 nm (SFG Fund and 1st-Stokes)	1.945	200
542 nm (SHG 1st-Stokes)	2.64	130
558 nm (SHG 2nd-Stokes)	12.37	5

The lasing thresholds using Nd:YLF were higher, and the overall emitted powers lower, in comparison to the Nd:GdVO$_4$/KTP system. This was due to the fact that the round-trip resonator losses at the fundamental (1053 nm), first (1084 nm) and second (1117 nm) Stokes wavelengths were approximately 2.5 times higher than that in the Nd:GdVO$_4$-based system. The maximum incident pump power used was also lower in comparison to that used in the Nd:GdVO$_4$/KTP system, due to potential damage to the crystal. Despite the lower overall output power from both the Stokes and visible resonators, the emission spectra were significantly cleaner than that obtained from the Nd:GdVO$_4$/KTP system, with the absence of orthogonally polarised fundamental emission and self-Raman lines. Our ongoing work is focussed on reducing the round-trip losses within the Nd:YLF/KTP based resonator, and increasing the overall output power at each visible wavelength.

3. Conclusion

We have demonstrated the generation of a span of emission wavelengths in the near-IR and the visible by making use of cascaded SRS in KTP. When used with Nd:GdVO$_4$ as the laser medium, it was possible to generate emission at the third Stokes-order, and wavelength selectable visible emission at five discrete wavelengths in the visible between 539 and 573 nm. Maximum output power was limited by the onset of additional fundamental emission lines and self-Raman generation in the Nd:GdVO$_4$ crystal. When KTP was combined with Nd:YLF as the laser medium, we were able to generate cascaded Stokes emission to the second Stokes-order, and visible emission at three discrete lines between 534 and 558 nm. While the maximum output power at each wavelength was limited, the spectral purity was excellent with no undesired lines being observed. We anticipate that improved performance will be obtained when the system is optimised for lower loss.

4. References

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