

# Ten deep-blue to cyan laser emission lines from 451 nm to 495 nm using Nd:YLF-KGW-LBO intracavity Raman laser

Dimitri Geskus,<sup>1</sup> Jonas Jakutis Neto,<sup>1</sup> Helen M. Pask,<sup>2</sup> Niklaus U. Wetter,<sup>1</sup>

<sup>1</sup>Centro de Lasers e Aplicações, IPEN/SP, Av. Prof. Lineu Prestes, 2242 São Paulo, SP, Brazil

<sup>2</sup>MQ Photonics, Department of Physics and Astronomy, Macquarie University, Sydney, NSW 2109, Australia

Author e-mail address: nuwetter@ipen.br

**Abstract:** A three-level neodymium, Raman and frequency converted laser is reported with a maximum extracted quasi-cw output power of 0.94 W, resulting in ten laser emission lines in the attractive deep-blue to cyan spectral region.

**OCIS codes:** (140.3530) Lasers, neodymium, (140.3550) Lasers, Raman, (190.2620) Harmonic generation and mixing.

## 1. Introduction

Many “hard to reach” wavelengths in the near-infrared and visible spectral regions can efficiently be obtained using wavelength agile, all solid-state intracavity frequency converted Raman lasers [1, 2]. By making use of a high-Q cavity, the highly enhanced intracavity fundamental field allows strong stimulated Raman scattering (SRS) allowing continuous wave (cw) SRS laser operation [3]. In addition intracavity sum frequency generation (SFG) and second harmonic generation (SHG) has been reported resulting in laser output in the yellow-orange-red spectral region [4-6]. The continuous improvements in crystal quality and coating technologies provide optical to optical (diode pump to visible) efficiencies in excess of 20% [4]. Recent achievements in intracavity Raman laser technology using the three level laser transition of Nd:YLF resulted in laser operation in the 9XX nm wavelength region [7] and enabled us to generate in this work ten emission lines in the deep-blue to cyan (451-495 nm) by intracavity SHG and SFG using a LBO crystal, providing a suitable replacement for Argon ion lasers.

## 2. Experimental setup and measured laser performance

In this experiment we use an approximately 11 cm long, linear cavity based on [7]. The cavity consists of two concave (ROC = 50 mm) mirrors with high, reflectivity from 900 nm to 1000 nm. A photograph of the cavity is given in Fig. 1a.

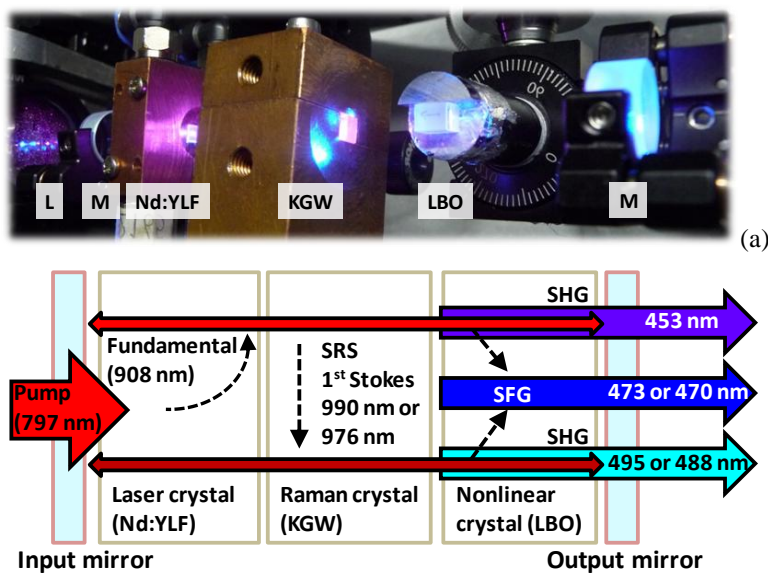


Fig. 1, a) Photograph of the setup generating laser emission at 473 nm. With “M” indicating the position of two concave (ROC = 50 mm) cavity mirrors and “L” indicating the pump focusing lens. b) Schematic representation of the setup used to generate the blue laser emission based on a 908 nm fundamental field. Both figures are aligned with respect to each other, to easily identify the components.

The quasi-cw (qcw) fundamental intracavity laser field at 903 nm ( $\pi$ ) or 908 nm ( $\sigma$ ) is generated by the transition to the ground-state of a 3 mm long Nd(0.6%):YLF crystal pumped at 797 nm with a duty cycle of 1.7%. A 10 mm long KGW crystal was placed in the center of the cavity to generate SRS using the 901  $\text{cm}^{-1}$  or 768  $\text{cm}^{-1}$  Stokes shift of the KGW crystal by reorienting (rotating around the optical axis) the KGW crystal accordingly, thereby creating six intracavity laser lines in the 9XX nm regime. A 10 mm long LBO crystal inside the cavity converts the infrared wavelengths to ten deep-blue to cyan emission lines via SHG and SFG. The involved optical conversion processes are drawn in the schematic of Fig. 1b for a fundamental field oscillating at 908 nm.

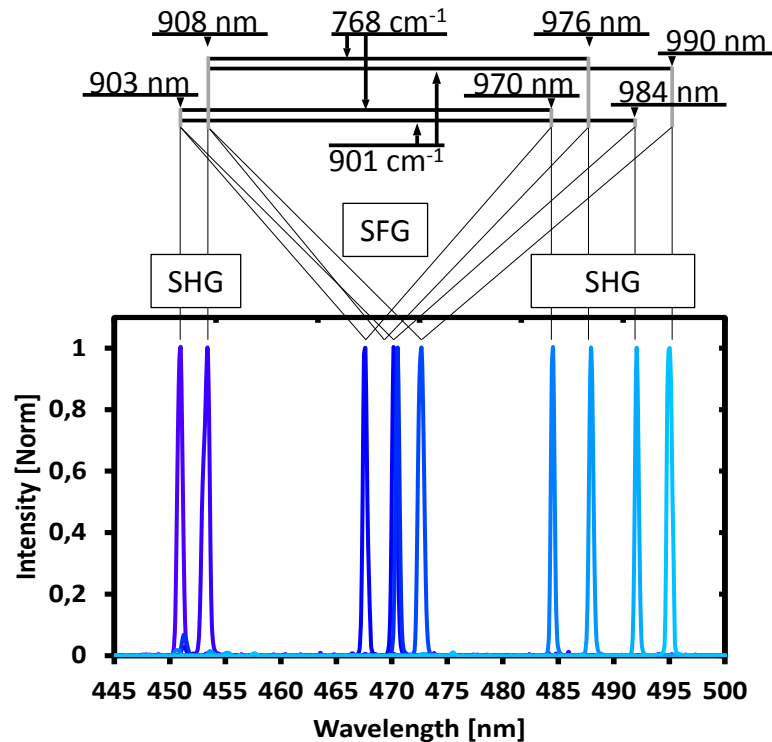


Fig. 2. Schematic of the intracavity laser processes, starting off with the fundamental laser lines at 903 nm and 908 nm from the Nd:YLF crystal, followed by their Stokes shifted intracavity fields ranging from 970 nm to 990 nm. Using SHG and SFG the infrared laser lines are converted by a LBO crystal, placed inside the cavity, resulting in ten measured blue spectral emission lines shown in the lower part of the graph.

Using this laser device ten individual spectral laser emission lines in the deep blue to cyan spectral regime were generated. The recorded output spectra are provided in Fig. 2, where the upper part of the figure schematically indicates the origin of each recorded laser line. In this study output power of the frequency doubled fundamental field was not characterized, as it does not require the Stokes shifted laser field. The best blue laser performance was found based on the 908 nm fundamental laser line in combination with the 901  $\text{cm}^{-1}$  and 768  $\text{cm}^{-1}$  Stokes shifts, generating intracavity fields at 990 nm and 976 nm respectively. These transitions provided maximum single-sided output powers up to 0.47 W in the blue to cyan spectral regime as shown in Fig. 2. Note that a similar blue beam is generated in the counter propagating direction adding up to a total extracted blue power of 0.94 W. The blue emission lines based on the 903 nm fundamental laser line are obtained using the birefringence of the LBO crystal and aligning the cavity such that only the corresponding  $\pi$ -polarization is supported by the cavity. The reduced gain at 903 nm was not sufficient to generate significant output power in the blue. Beam analysis reveals a small walk-off, typical for SFG and SHG, for the blue output beam as shown in the inset of Fig. 3. A  $M^2$  value of about 1.1 (average of both directions) is found for the blue laser beam.

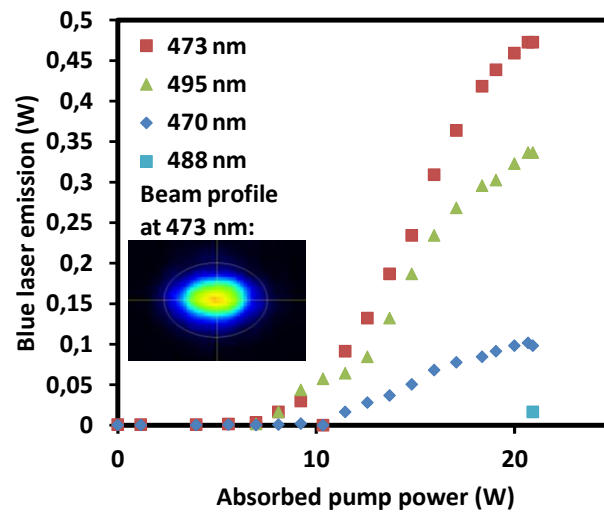


Fig. 3, Single-sided extracted blue laser power for the blue laser emission lines based at a fundamental field at 908 nm. A measured beam profile of the blue output beam at 473 nm is given in the inset.

Continuous wave laser operation is currently under investigation, and cw Raman laser oscillation has already been achieved, having an output power of 27 mW at 990 nm.

### 3. Conclusions and discussion

The emission of ten deep-blue to cyan laser lines is reported, obtained from a Nd:YLF-KGW-LBO intracavity frequency converted Raman laser. A single sided measured peak output power of 0.47 W, corresponding to a total extracted q-cw output power of 0.94 W, is demonstrated for the first time from such a laser. Earlier reported results, using a similar laser cavity based on the four level transition of the Nd-ion, demonstrated laser emission in the in the yellow lime-green region [6]. These results highlight the wavelength agile character of intracavity frequency converted Raman lasers, and demonstrate that the currently available quality of crystals and coatings allows the development of these wavelength versatile lasers in the visible. Selection of smaller Stokes shifts, such as for example the small  $89\text{ cm}^{-1}$  Stokes shift of KGW, would create a more closely spaced wavelength comb, allowing for tuning over a small wavelength range [8] and competing with optically pumped solid state (OPSL) Raman lasers [9], whereas the large Stokes shift of  $1332\text{ cm}^{-1}$  in diamond [10] would create a more widely spaced wavelength comb from blue to yellow.

*Acknowledgement: This research project is financially supported by CNPq: 401580/2012 and FAPESP: 11437-8.*

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