Pulsed Blue and Ultraviolet Laser System for Fluorescence Diagnostics based on Nonlinear Frequency Conversion

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Objectives

The goal of this project is to contribute to the development of light sources used in fluorescence diagnostics in biomedical imaging; in particular, in the blue (~405 nm) and near ultraviolet (~340 nm) regions, to excite fluorescence in exogenous markers and autofluorescence respectively.

The proposed project involves an investigation into novel configurations of producing pulsed blue or ultraviolet (UV) laser action through the use of external cavity diode lasers and non-linear optics interaction, while keeping a heavy emphasis on real-life applications, practicality, and clinical adaptability. Thus, the project will involve the following areas:

1. Solid-state lasers and external cavity diode lasers
2. Non-linear optics (e.g. sum-frequency generation and frequency doubling)
3. Developing breadboard prototype(s) that can be used in field trials and/or support experiments based on findings in points 1 and 2 above.

As part of the diode group's on-going collaborations with Lund University Hospital, one desired outcome of the project is to have a prototype light source for fluorescence imaging field tests at the hospital. The constraint on the proposed project outcome is that it contains a functional, clinically-feasible prototype for real-life application(s).

Motivation

Fluorescence imaging provides a powerful diagnostic tool in monitoring treatment progress in photodynamic therapy (PDT) of cancerous cells and in identifying malignant cells during surgical operations. This is because the technique is non-invasive, and makes real-time information available to surgeons. As an example, tumour boundaries could be identified during the treatment of skin cancer in Moh's surgery. Traditionally, this is done by pathology. Fluorescence imaging may provide an economical alternative with real-time diagnosis capability.

While fluorescence imaging has proved a promising tool in cancer diagnosis, suitable light sources with sufficiently high repetition rate, high peak power and good beam quality is somewhat limited. In order to increase the signal-to-noise ratio, it is desirable to use a pulsed blue/UV laser with high repetition rate and high peak power in combination with gated detection, while a good beam quality is required for efficient coupling and delivery through optical fibres. Currently, no pulsed 405 nm or 340 nm laser systems are available commercially. In a previous PhD project carried out at Risø DTU, 318mW of continuous-wave (cw) power was achieved at 404 nm [1.] In comparison, Toptica Photonics AG manufactures commercial frequency-doubled diode lasers at 100 mW in the 330 nm and 400 nm regions [2.]

Research Activities

The difficulty in obtaining a high repetition rate, high peak power, good beam quality pulse train lies in the fact that there are no suitable laser materials at ~680 nm and ~808 nm that can be easily pulsed and frequency-doubled into the aforementioned wavelengths, with the exception of diode lasers. The use of a combination of fixed wavelength solid-state lasers and tunable external cavity diode lasers will allow the generation of light with the desired wavelengths. Novel techniques involving cavity scanning, single-pass sum-frequency generation (SFG), linear cavity dumping, and non-linear cavity dumping have been discussed within the group. Improvements and formulation of other schemes will be part of the project's research activities.

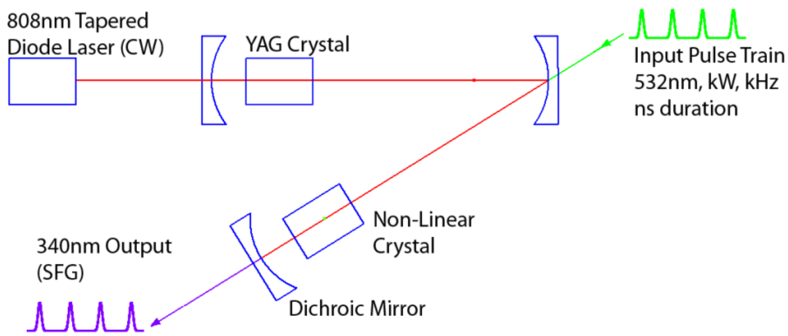

Figure 1 - Schematic diagram of non-linear cavity dumping

One technique that has proved quite successful in obtaining relatively high average power in the blue and UV was demonstrated at Risø. It involves using a scanning piezo-mirror in a high-finesse cavity to build up the electric field for second-harmonic generation (SHG) [1]. While the repetition rate is limited by the inertia of moving mechanics and mechanical stability is crucial in this setup, a high peak power was achieved. In fact, the results were the highest SHG powers obtained at this wavelength with a PPKPT crystal [1]. Another technique, nonlinear cavity dumping, has also been demonstrated at 593 nm at DTU [3]. While the peak power of such system may be limited by the amount of energy allowed to be built up inside the cavity, recent development in spectral and spatial stabilization of high power diode lasers [4] makes it an interesting experiment in the blue and UV region.

Figure 1 illustrates the non-linear cavity dumping technique described above. Energy of a 946 nm CW laser is allowed to build up inside a cavity, and is released by some type of non-linear interaction such as SFG with a pulsed beam from a second laser. It was demonstrated that a 10kW peak power pulse is sufficient in dumping all of the built up energy in a 5kHz pulse train [3]. If this is successfully applied in the blue or UV wavelengths, it could provide a light source that is more compact and efficient for applications such as fluorescence imaging.

Initial Results

The three-level DPSS laser at 946 nm to be used for sum-frequency generation in the 340 nm light source has achieved proof-of-concept results. Both numerical calculations and experimental results show that the tapered-diode laser pumped Nd:YAG laser show significant improvement over traditional broad-area diode laser (BAL) pumps. From the numerical calculations plotted in figure 2 below, it is clear that the smaller focus spot size and lower divergence from tapered diode lasers allow the gain in the laser crystal to stay dominant over reabsorption losses for longer crystal lengths. This results in significantly improved conversion efficiency and lower lasing threshold.

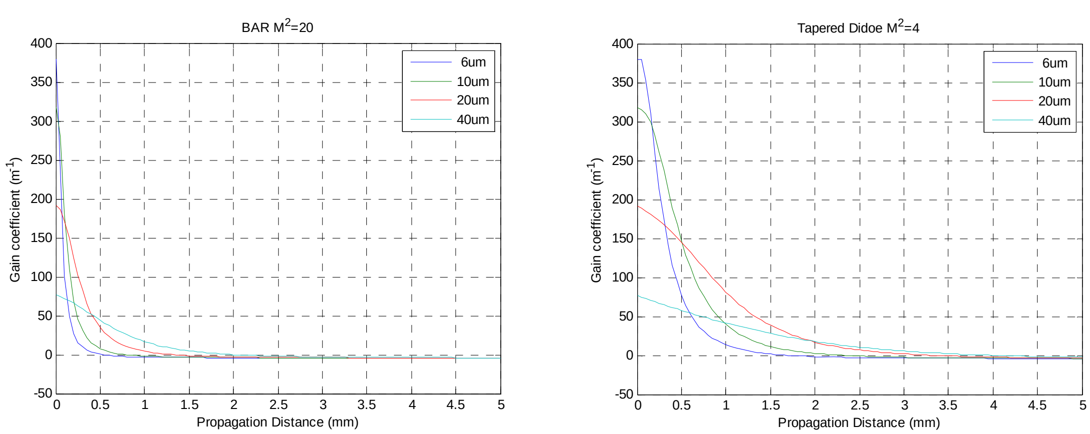

Figure 2 - Numeric calculation of the small-signal gain of the three-level laser line at 946 nm of Nd:YAG pumped by traditional a broad area diode laser (left) and a tapered diode laser (right).

The aforementioned observations were confirmed experimentally when both a BAL and tapered diode laser were used to pump Nd:YAG crystals of length 1.5 mm and 3 mm in length. Figure 3 below illustrates the experimental setup and output performance achieved with the respective pump lasers. The folded cavity consists of an Nd:YAG crystal with high reflection coating at 946 nm, a curved mirror to control the beam waist, and a 3% output coupler at 946 nm. Lasing at 1064 nm is suppressed by anti-reflection coatings on the mirrors and laser crystal. We failed to achieve lasing in the 3 mm crystal with the BAL pump. This may be due to the lower gain available to overcome reabsorption losses in the latter part of the crystal.

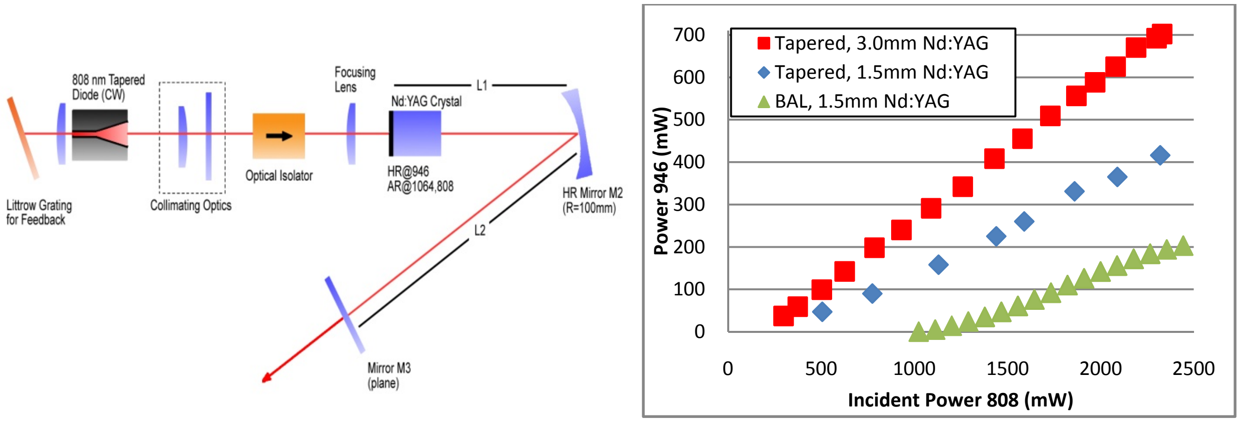

Figure 3 - Experimental setup (left) and output results (right) of 946 nm Nd:YAG laser pumped by BAL and tapered diode laser

Due to the better beam quality from the tapered diode, 84% of the pump beam power was absorbed in the laser crystal, and a conversion efficiency of 33% was achieved in terms of incident pump power. 700 mW of CW output power at 946 nm was achieved, and is the highest achieved to the best of our knowledge at this wavelength with a single emitter diode pump source. It can be clearly seen that the threshold of a tapered diode laser pumped Nd:YAG light source can reduce the threshold by a factor of three and increase the conversion efficiency by a factor of two. These encouraging results suggest that higher peak power and repetition rates are possible for 340 nm pulsed light generation.

References

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