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Tailored UV-laser source for fluorescence spectroscopy of biomolecules

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Abstract

A dual-wavelength UV-laser source was developed for biosensing. First, a passively Q-switched diode-pumped Nd:YAG laser was constructed. The astigmatic diode output beam was converted into a homogenous beam profile by utilizing a mode converter. As a result, a frequency-doubling conversion efficiency of 50% was achieved in a periodically poled $KTiOPO_4$. With a repetition rate of 100 Hz, the pulse energies and lengths were 650 μJ and 1.8 ns, respectively, at 532 nm with a M^2 of 1.3. The UV-generation is based on cascaded parametric processes using an intra-cavity sum-frequency mixing scheme in a periodically poled $KTiOPO_4$ parametric oscillator pumped at 532 nm. Here, the wavelengths 293 and 343 nm were generated, with conversion efficiencies of 7% and 6.5%, respectively, in respect to 532 nm. With pulse length 1 ns and an average power above 2.7 mW, the wavelengths were used for fluorescence measurements of non-pathogenic bacteria.

Keywords: Diode pump solid-state laser; Beam transformation; Beam shaping; Optical parametric oscillator; Parametric devices; Ultraviolet generation

Pulsed ultraviolet (UV) lasers are very attractive for many applications both in science and industry, such as photo-lithography, micromaching of electronic devices and laser-induced fluorescence (LIF) spectroscopy. In order to meet the increasing demands for national security, the latter field is of great interest for detection and characterization of biological agents. The UV-excitation is targeted at the proteins or more explicitly at the aromatic amino acids, particularly tryptophan (Trp) and tyrosine (Tyr) [1], and also nucleotides such as NADH, which are involved in the cell metabolism [2]. These biomolecules have strong absorption bands in the spectral region ranging from 280 to 340 nm and emitting in the 300–600 nm region. Two or more absorption wavelengths with corresponding emission spectra are ideally used to discriminate one biomolecule from another. Preferably, when exciting an agent, the excitation wavelengths should be chosen so that the absorption spectra of the present biomolecules within the agent do not overlap. This will enable a good selectivity and classification of the agent in a rapid way.

Commonly used UV-light sources for fluorescence spectroscopy, such as xenon and tungsten–halogen arc-lamps, suffer from poor spectral quality and require sophisticated optics to constrict the bandwidth to a narrow linewidth. More recently AlGaN-based LEDs, which emit below 300 nm, have been developed [3]. Unfortunately, they have low output powers and limited lifetime, due to high aluminum concentration, and has a continuous spectrum far down in the visible region which can interfere with the fluorescence spectrum. Furthermore, solid-state lasers are also widely used, for e.g., Ti:sapphire (mulitphoton) [1] and quadrupled or tripled Nd:YAG lasers [4,5]. However, both of these are out of the desired wavelength range. In contrast, novel solid-state lasers such as Ce:LiSAF [6] and Ce:LiCAF [7], which have continuous tuning from 280 to 315 nm, utilize a complicated pumping arrangement. A common problem is that the crystals suffer from growth defects that degrade the efficiency of the laser and thus only research samples are available at the moment. In summary, there are no compact UV-laser sources enabling emission of two or more separate wavelengths in the specified spectral region with good spectral resolution, short pulse length and good spatial beam quality. The UV laser does not need to be continuously tuneable, since the absorption bands of biomolecules are inherently broad [2]; it should rather be step-wise tuneable over the specified spectral region. An

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efficient way to obtain dual or multi-wavelength UV sources in a compact and simple design is to begin with a high-energy pulsed IR laser and then frequency convert it to UV. An attractive approach to generate tailored wavelengths is to use quasi-phased matched (QPM) materials in an optical parametric oscillator (OPO) pumped by a solid-state laser. The advantages of nanosecond OPOs over, for e.g., optical parametric generators (OPGs), under the same pump conditions are that they are more efficient, have lower thresholds and high intra-cavity intensity. In addition, it is easy to deploy wavelength tuning by changing the temperature [8], rotating the crystal [9,10], or pumping a crystal containing multiple QPM gratings [11]. The inherent high intra-cavity intensity of the OPO can be used for intra-cavity sum-frequency mixing (SFM) [12]. Utilizing the generated signal from the OPO together with the pump, it is possible to reach the desired UV range specified above.

In this work, we deployed a periodically poled $KTiOPO_4$ (PPKTP) parametric oscillator with intra-cavity SFM in a BBO crystal. By tailoring the QPM period in the PPKTP, the spectral range from 285 to 340 nm is accessible through SFM between the generated OPO signal and the pump. The developed dual-wavelength UV laser was used for fluorescence sensing of *Bacillus thuringiensis* (BT) stabilized in aqueous NaCl solutions. The technology opens up the possibility to assemble compact and robust instruments for rapid detection in field trails.

A diode-pumped passively Q-switched Nd:YAG laser was constructed to be used as the pump source for the parametric processes. The Nd:YAG pump module consists of a fast-axis collimated quasi-CW single broad-strip diode-laser (emitting area $1\,\mu m \times 10\,mm$), two cylindrical lenses at right angles with focal lengths $f_{fast\ axis} = 50\,mm$ and $f_{slow\ axis} = 30\,mm$, a 16.6 mm-thick biconvex cylindrical lens with radius of curvature of 5 mm (also called beam twister), and a spherical lens, $f_1 = 10\,mm$, depicted in Fig. 1. The two cylindrical lenses and the beam twister were used to transform the highly astigmatic diode beam into a homogeneous irradiance profile. In optical beam analysis of laser resonators the Hermite–Gaussian mode functions are commonly used to describe propagation through the optical system, since in real lasers the beam is usually distorted by optical elements in the cavity, and a rectangular coordinate system is preferred because of its ability to describe both astigmatic and stigmatic beams [13]. It has been proven, both theoretically and experimentally, that astigmatic beams mathematically described by Hermite–Gaussian mode functions, such as the output from a broad-strip diode-laser, can be transformed into Laguerre–Gaussian beams by using two cylindrical lenses with the same focal length [14,15]. This, however, can only be achieved when predefined conditions are met. First, the transverse beam waists should coincide between the cylindrical lenses, which are rotated at an angle of $\pm 45^\circ$ around the propagation axis. Secondly, the focal length of the lenses should be related to the Rayleigh lengths, z_{Rx} and z_{Ry}, as $1/f = d/(z_{Rx}^2 + d^2) - d/(z_{Ry}^2 + d^2)$ [14], where $2d$ is the distance between the cylindrical lenses. Third, the lenses should be positioned where the two transverse radii of the astigmatic beam are equal. However, all of these conditions are difficult to meet when beam-shaping a broad-strip diode-laser, since the beam quality parameters (M^2) are highly different for the slow and fast axis. Nevertheless, it is still possible to equalize the beam quality parameters in the x- and y-axes (slow axis (SA) and fast axis (FA)) so that a homogenous beam profile is obtained. In our set-up, instead of using two cylindrical lenses a thick cylindrical lens is used as a mode converter. The extension between the two cylindrical surfaces (called the center plate) is determined by [16]

$$t = \frac{2r}{n-1}\left(1 + n\frac{1-\sqrt{2}}{\sqrt{2}}\right), \qquad (1)$$

where n is the refractive index (SF4 glass, $n = 1.755$) and r is the radius of curvature. Thus the total length, L, is then $L = t + 2r = 16.6\,mm$. With the two cylindrical lenses 5 mm apart, f_{FA} and f_{SA} focused the FA and SA, respectively, to a coinciding focus within the beam twister, which was rotated at an angle of $\alpha = 45^\circ$. The measured beam waists were $\omega_{FA} \approx 200\,\mu m$ and $\omega_{SA} \approx 270\,\mu m$, respectively, whereas the Rayleigh length for the FA was much longer than for the SA, $z_{R,FA} \gg z_{R,SA}$. The imperfect mode matching resulted in a diamond-shaped output beam with equally diverging transverse components, a so-called

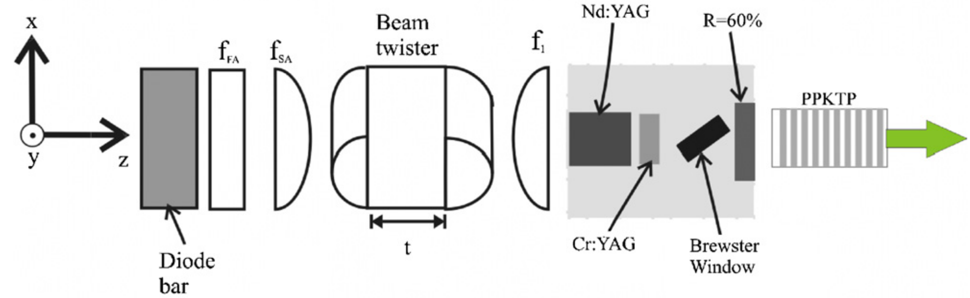

Fig. 1. The diode pumped passively Q-switched Nd:YAG laser, with beam twisting optics. The total length of the laser is 25 cm.