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# Tuneable powerful UV laser system with UV noise eater

Sergey Kobtsev[a,b], Daba Radnatarov[a,b], Sergey Khripunov[a,b], Yurii Zarudnev[a,b]
[a]Novosibirsk State University, Pirogova str., 2, Novosibirsk 630090, Russia
[b]Tekhnoscan-Lab LLC, Inzhenernaia str., 26, Novosibirsk 630090, Russia

## ABSTRACT

The present work for the first time presents the study of a laser system delivering into the fibre up to 250 mW of CW radiation tuneable across the 275–310-nm range with the output line width less than 5 GHz and stability of UV output power within 1%. This system can automatically set the output radiation wavelength within the range of 275–310 nm to the precision of 2 pm. UV output power stabilisation is provided by a newly proposed by the authors noise eating technology. This paper discusses details of the developed technology and the results of its application.

**Keywords:** UV laser system, UV noise eater, tuneable laser system, intracavity frequency doubling

## 1. INTRODUCTION

Narrow-line CW radiation tuneable within the UV range is traditionally generated through nonlinear conversion of visible/IR radiation (harmonic generation [1–4] and parametric conversion [5–7]) or in lasers using active media with gain in UV range [8]. Among the methods of non-linear conversion of continuous tuneable radiation prevail those based on second harmonic generation. They may be implemented through intracavity radiation frequency conversion [9–11] (in which case the radiation may contain multiple frequencies), as well as in an external [12–14], coupled [15], or in a nested [16] resonant cavity. When using an external cavity, the input radiation spectrum should only contain a single frequency and the external cavity must be in resonance with the input radiation [17]. Although radiation conversion in a coupled or nested cavity is also possible for multi-frequency radiation, such conversion has up to date only been demonstrated in fibre lasers, which are relatively weakly sensitive to intracavity radiation losses. Parametric conversion into UV range is chosen less often because of its lower conversion efficiency and considerably higher cost of periodically poled non-linear crystals [18] or waveguides [19].

Therefore, the problem of generation of CW tuneable narrowline UV radiation is usually solved primarily via second harmonic generation. In order to produce radiation wavelength-tuneable over the 275–310 nm, it is necessary to have fundamental radiation for the 550–620-nm range. Currently, this requirement may only be fulfilled by a dye-jet laser, and there is essentially no alternative. Solutions relying on other laser types in this range either suffer from a narrow wavelength tuning range or only offer isolated discrete wavelengths. The dye laser technology has been continuously perfected during recent years and today, the best implementations of dye-jet lasers are very close in convenience to solid-state Ti:Sapphire laser [20].

The present work reports for the first time on development and experimental study of a laser system based on a CW dye-jet laser with intracavity radiation frequency doubling, which provides output radiation power of up to 250 mW at the fibre delivery exit over the 275–310-nm range, while featuring the output radiation line width of less than 5 GHz and UV radiation power instability within 1%.

## 2. EXPERIMENT

A schematic diagram of the studied laser system is given in Figure 1. The output radiation wavelength was controlled with a wavelength meter to a precision of 1 pm within the 400–1100-nm range. A small fraction of the fundamental radiation passing through highly reflective mirror M5 was branched off into the wavelength meter input fibre. The wavelength meter digital output was connected to the laser system's electronic control unit. The electronic unit operated the electro-mechanical actuators of the spectrally selective elements (birefringent filter and etalon), as well as the nonlinear crystal motor. AutoWaveSet© technology was used for automatic wavelength setting down to the precision of

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the radiation line width in generation of both the fundamental and second harmonics, as well as for 'stitching' of continuous wavelength tuning ranges of the laser system (each of these ranges was 206-GHz wide). This technology is capable of precisely tuning the laser system to a dialled wavelength using only a wavelength meter and no other sensors or detectors.

The following elements were used in the laser cavity: 3-component birefringent filter [22], 0.5-mm thick solid Fabry-Perot etalon, 15-mm long nonlinear crystal, spherical dichroic mirror M4d with curvature radius of 50 mm and transmission of 85% at 290 nm, spherical mirrors M1 and M2 with curvature radii of 75 mm.

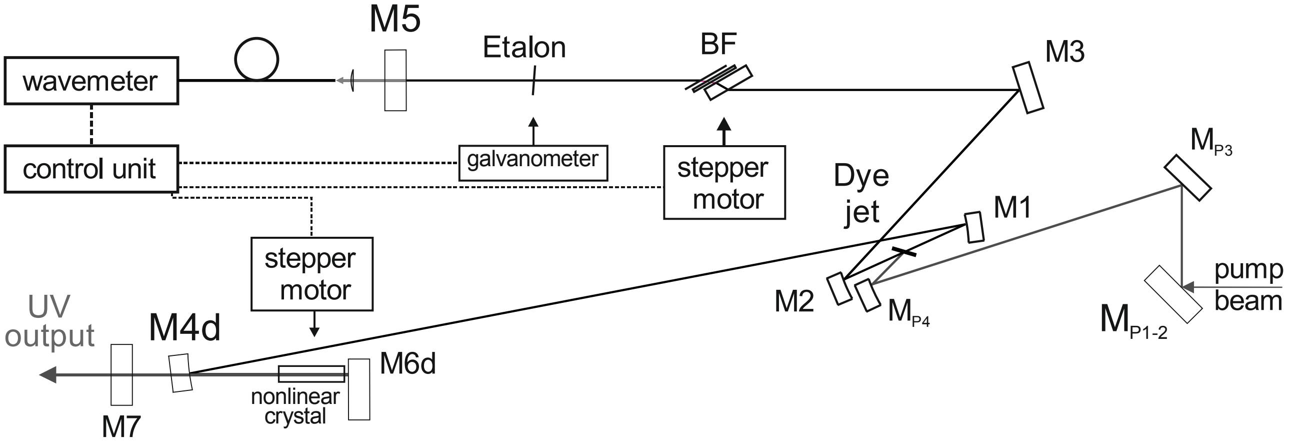

Figure 1. Diagram of the studied tuneable UV laser system: BF – birefringent filter, Mp – mirrors guiding the pump radiation into the laser, M1–M6 – cavity mirrors, M7 – dichroic spectral filter.

## 3. UV NOISE EATER

In recent years became broadly used so-called 'noise eaters', external devices for stabilisation of the laser output power. These devices regulate attenuation of the passing radiation with a feed-back system controlled by a signal from a photodetector measuring the intensity of the exiting radiation. In order to provide a certain dynamic range for the feed-back system, the chosen stabilised power level is usually below the achievable maximum, for example, around 80–90%. Therefore, the external stabiliser 'eats' a certain amount of the power of the radiation passing through it and maintains the output power at a certain level below maximum. For intensity attenuation of the radiation passing through the stabiliser, various media are used, such as liquid crystals, acousto-optical modulators, and others. Commercial products are available for the visible and IR ranges, but the corresponding solutions for the UV light are still at the stage of development.

In the present work, we report, for the first time, the development of a UV noise eater based on a different principle as compared to the available noise eater designs for the visible and IR ranges. The attenuation element adjusting transmission of the input UV radiation consists of a waveguide and a tilted quartz plate for guiding the radiation into the waveguide. A schematic diagram of the developed noise eater is demonstrated in Figure 2. Adjustment of the tilt angle of the quartz plate leads to the corresponding displacement of the input beam relative to the waveguide core. Thus, the waveguide and the quartz plate form an element for adjustment of the fraction of the input radiation fed into the waveguide. The input aperture of the waveguide plays, in this case, the role of an aperture stop.

When using a relatively fast galvo drive (*e.g.* 62xxH Series Galvanometer made by Cambridge Technology) and a small quartz plate, the system has a response time of approximately 0.1 s and may be used for long-term stabilisation of radiation power exiting the waveguide. The working spectral range of the developed UV noise eater may extend into the short-wave domain down to ~200 nm, limited by the transmission drop in quartz, the material used both in the waveguide and the tilted plate. In the long-wave domain, the proposed noise eater is useable up to ~2.5 μm with the waveguide and plate made of quartz. Other materials (e.g. waveguides made of chalcogenide glass, etc.) allow extension of the working range of the developed noise eater into the long-wave range up to 10 µm and farther.

We used the proposed noise eater in the wavelength range of 275–290 nm. The second-harmonic radiation from a T&D-scan laser system was collimated by lens L1 having a focal length of 200 mm. Then, two adjustable mirrors M1, M2 and focusing lens L2 (f=50 mm) were used to guide the radiation into a waveguide with a 200-µm core (LWL Kabel UV200/220-1200-SMA-SMA-SP30 by Art Photonics). A 3-mm thick tiltable quartz plate with both faces antireflection coated for the 275–310-nm range was placed between the input end of the waveguide and the focusing lens. The neutral position of the plate corresponded to the normal incidence and the lowest input losses of the UV radiation entering the waveguide. Tilting the plate with the galvo drive led to a lower fraction of the input radiation entering the waveguide and, respectively, to a lower output power. The output radiation power was controlled with a photodetector. In operation, the photo-detector signal was used as input for a feed-back system controlling the galvo drive of the tilted plate for dynamic adjustment of the radiation power entering the waveguide.

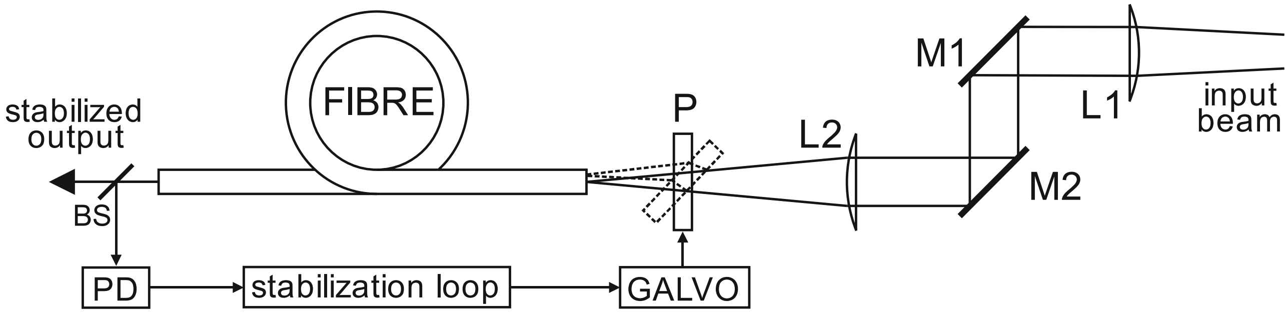

Figure 2. Diagram of the proposed fibre-based UV noise eater: BS – beam splitter, PD – photodetector, P – quartz plate with AR coatings, L1, L2 – lenses, M1, M2 – totally reflective mirrors.

It should be borne in mind that the operation principle of the proposed noise eater does not depend on the input polarisation and may be used in optical ranges beyond UV. An additional advantage of the proposed approach to stabilisation of the laser radiation power is that in many applications, laser radiation must be delivered through an optical fibre and therefore, the proposed method may be adopted to use the already existing optical waveguide.

In essence, the operation of the proposed noise eater is based on an electrically controllable element able to displace or deform the input beam placed in front of the optical fibre receiving the stabilised radiation. Both these effects lead to variation of the amount of radiation entering the fibre and, consequently, to variation of the optical power at the exit of the fibre. Without departing from the basic principle, it is possible to have stationary position and shape of the input beam, but a displaceable or tiltable input fibre end. This also allows automatic adjustment of the optical power at the exit of the fibre.

Fig. 3 shows a 9-hour long temporal trace of second-harmonic radiation power at 290 nm after passing through the proposed fibre-based noise eater. Long-term instability of the second-harmonic radiation does not exceed 1% at 150 mW exiting the fibre. The highest recorded second-harmonic power at 290 nm was over 200 mW when pumped with 12 W at 532 nm. In the reported experiment, we used a T&D-scan system configured with a dye-jet laser running on a solution of R110 dye with admixture of cyclooctatetraene [21]. When using R6G dye and 12 W of pump power, the second-harmonic radiation power within the 295–300-nm range exceeds 250 mW. Second harmonic generation was performed with BBO non-linear crystals whose temperature was actively stabilised around 60 °C.

## 4. CONCLUSION

The developed tuneable laser system with a noise eater (Fig. 4) based on an original design ensures continuous UV radiation output at the level of several hundred mW within the 275–310-nm range with the output line width narrower than 5 GHz. The proposed technology of fibre-based noise eater is universal and makes this noise eater applicable also in visible and IR spectral ranges, while ensuring better than 1% long-term stability of the second-harmonic radiation power. The studied laser system was designed for calibration of hyperspectrometers.

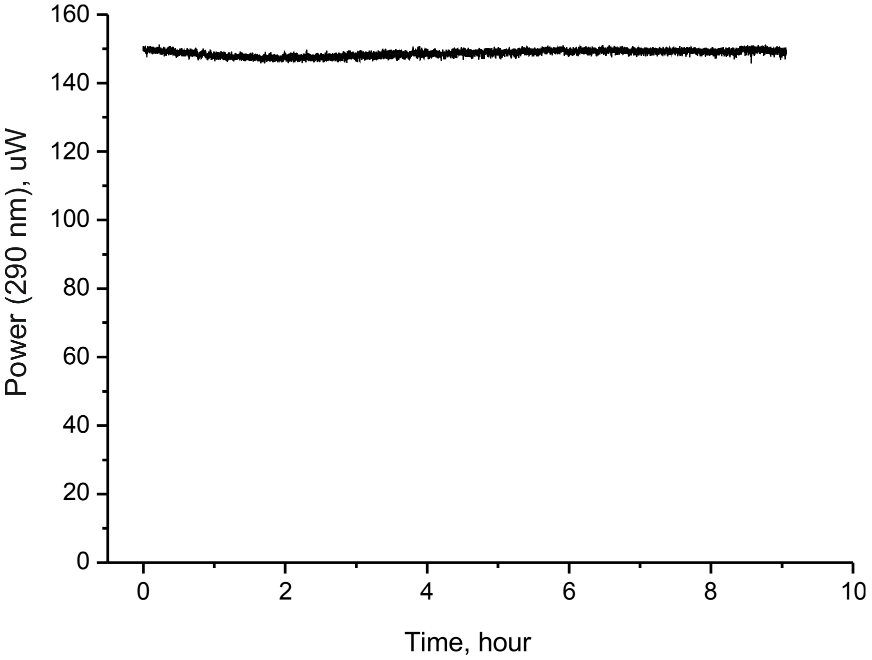

Figure 3. Time trace of the second-harmonic radiation from a T&D-scan laser system at 290 nm.

Figure 4. External view of the proposed tuneable powerful UV laser system with UV noise eater.

It is necessary to point out that powerful narrow-band radiation of the blue-UV range may be equally generated *via* intra-cavity second harmonic generation in an external cavity [23–25] relying on single-frequency lasers and resonant radiation frequency doublers. However, these systems are considerably more complicated, more difficult to maintain and to automate, therefore resulting in substantially more expensive solutions. The output radiation line width produced by this technology is often much narrower than required by the applications (*e.g.* spectrometer calibration), but this very narrow line width and the associated complexity of the technical implementation are inherent aspects of single-frequency resonant approach. The intra-cavity second harmonic generation inside the laser resonator offers a significantly simpler solution better corresponding to the problem of spectrometer calibration.

Pulsed lasers with relatively long output pulse duration (~1 ns) may also be used for generation of UV radiation with line width of 1–2 pm. However, second harmonic generation from such long pulses is relatively inefficient in the single-pass mode [4] (when the fundamental radiation passes through a non-linear crystal outside the laser cavity), while intra-cavity second harmonic generation in this case is similarly complicated and delivers similar efficiency compared to CW second harmonic generation.

# ACKNOWLEDGMENTS

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