Stable, high-efficiency, low-cost UV-C laser light source for HPLC

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Objective: To create a small footprint, stable, deep UV-C laser source

Introduction: The UV-C light source has been actively developed for its wide applications, i.e., in chromatography detectors[1]. Generating deep UV-C (200–220 nm) from a visible light fundamental wavelength (400–440 nm diode laser) using the second harmonic generation (SHG) principle has shown great promise. However, SHG light roughly co-propagates with the unconverted fundamental wavelength making extraction of SHG light challenging due to the extreme intensity difference and the absorption loss at UV-C wavelength.

Method: An 80 MW 443 nm laser diode (OSRAM) provided the fundamental wavelength. The SHG wavelength (221.5 nm) is in the 0.5-1μW range. A non-linear Barium borate (BBO, Inrad) crystal was used to generate the SHG light. A prism-based separation optic created for this study fit within a 40x40 mm² area (Figure 1).

Results: The limitation on the optical materials with good transparency and refractive index contrast at UV-C made it difficult to achieve a high rejection ratio above OD4 over large spectral range with traditional spectral filtering. Gratings also have difficulty rejecting light at wavelengths with multiple integer ratios. While the effect of prismatic refraction is usually small, the dispersion is favorably strong at UV-C wavelength. The index of refraction vs. wavelength plot clearly indicates the large difference of refraction effects between 220 nm and 440 nm (Figure 2). The spatial separation of the fundamental and SHG beam grows with propagation and is accelerated by multiple stages of refraction. With suitable amount of separation and additional spatial filtering the residual fundamental light can be reduced to <1% of the SHG light within a separation stage. Figure 3 shows that in the spectrum, as acquired at the detector port, the 440 nm "peak" is diminished to beneath the noise floor. A second major advantage is to exploit the cross-polarization nature of the fundamental and SHG. A solution of incident angle and polarization found via the Fresnel equation (see calculations) achieved SHG light extraction throughput above 99%, even through multiple refractions.

Calculations: The transmission efficiency of fundamental and SHG light at crossed polarization can be calculated by using the Fresnel equation. (See Figure 4 for diagram of prismatic refraction.)

The incident and refraction angle will follow the Snell's Law:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$

The reflectivity of the s-polarization can be found by the Fresnel's equation

$$R_p = \left|\frac{n_1 \cos(\theta_2) - n_2 \cos(\theta_1)}{n_1 \cos(\theta_2) + n_2 \cos(\theta_1)}\right|^2$$

and the reflectivity of the p-polarization is:

$$R_p = \left|\frac{n_1 \cos(\theta_2) - n_2 \cos(\theta_1)}{n_1 \cos(\theta_2) + n_2 \cos(\theta_1)}\right|^2$$

The geometry also dictates this relationship:

$$\theta_3 = \alpha - \theta_2$$

The transmittance can be computed with the preceding equations. Calculation results are shown in Figure 5.

While the fundamental light propagating at the s-polarization suffers Fresnel refraction loss at both interfaces (Tp1_442: air into prism and Tp2_442: prism back into air), the SHG light at p-polarization enjoys a high transmission efficiency between 53 to 63 degrees at both interfaces (Ts1_221 and Ts2_221). When a 69-degree prism is used, a peak transmission of the SHG up to 99.97% can be achieved at an incident angle of about 57.9 degree

In summary, when a single prism is considered alone such a transmission difference is insufficient to discriminate the fundamental light. However, the goal of this multiple prism design is to provide sufficient angular difference while maintaining extremely high transmission efficiency of SHG. As a result of this design, the goal of high transmission efficiency of SHG has been achieved. The pinhole after the prism stage provides a spatial filtering effect that can achieve attenuation of the fundamental light as high as ND6 (6 orders of magnitude reduction).

Conclusions: A high-efficiency and miniaturized UV-C light source at 220 nm has been demonstrated and is capable of replacing the traditional UV lamps in HPLC applications.

References: 1) Heinz, T. F., et al. (1982). "Spectroscopy of Molecular Monolayers by Resonant 2nd-Harmonic Generation". Physical Review Letters. 48 (7): 478-81.

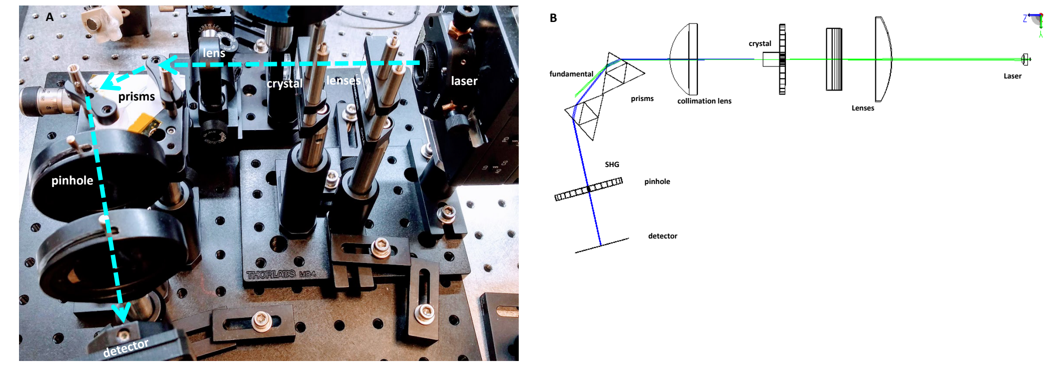

Figure 1

Panel A. A Photograph showing the experimental set-up for SHG generation.
Panel B. A schematic of the elements employed in the separation of the fundamental and frequency doubled wavelengths.

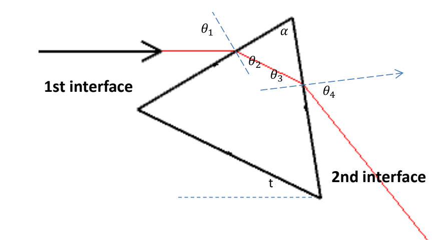

Figure 4

Illustration of the SHG refraction through the prism interfaces.
n1: refractive index of the input side medium (air).
n2: refractive index of the prism.
α: prism tip angle.
θ_1: incident angle from air.
θ_2: refraction angle into prism.
θ_3: incident angle inside prism.
θ_4: refraction angle out of prism.

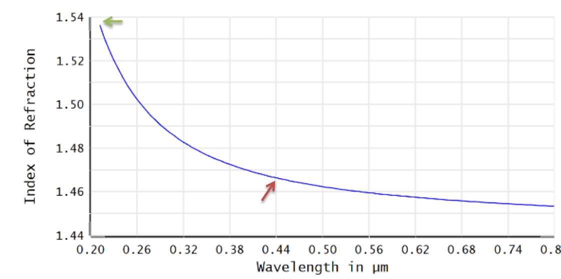

Figure 2

Index of refraction versus wavelength. The red arrow indicates the refractive index for 440 nm. The green arrow indicates the refractive index for 220 nm.

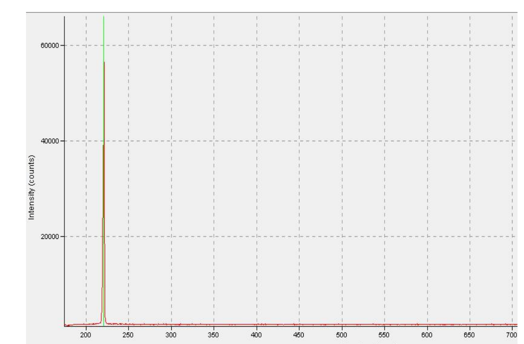

Figure 3

Spectrum acquired at the detector port. The green line is the cursor line marking the SHG wavelength.

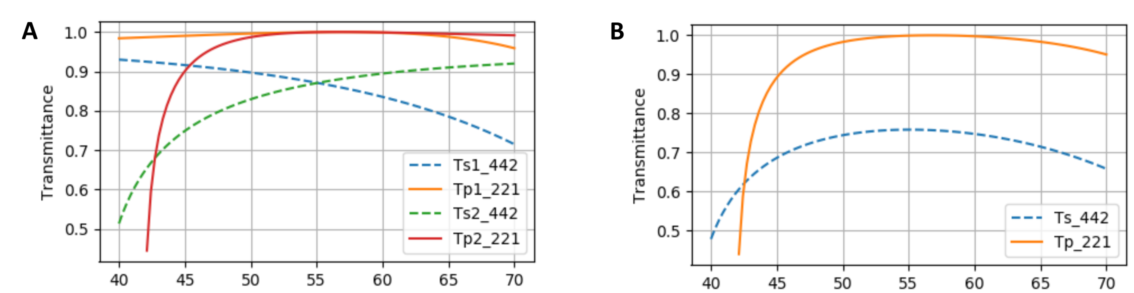

Figure 5

Transmittance of the SHG and the fundamental through prism interfaces versus incident angle. **Panel A** shows the transmittance of both fundamental (dashed lines) and SHG light (solid lines) at both the first and second interfaces. **Panel B** shows the total transmission after both interfaces. The SHG light (Tp_221) has efficiency above 99% with the incident angle within 53 to 63 degree while the fundamental light (Ts_442) has lower transmission at about 76%.

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