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Tunable UV source for UV fluorescence remote sensing

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Abstract

Efficient generation of ultraviolet radiation tunable over the 240-410 nm range has been achieved in a system suitable for ultraviolet (uv) fluorescence remote sensing. Light from an Optical Parametric Oscillator/Amplifier tuning in the 0.7-2.1 μm range is mixed with the second or third harmonic from a Nd:YAG laser, to obtain up to 30 mJ of broadly tunable output in the ultraviolet.

Introduction

Ultraviolet fluorescence remote sensing at kilometer distances requires a transmitter capable of generating at least 10 mJ/pulse of light that is tunable from 250 to 400 nm. Additional constraints are that the system be rugged, reliable and require little operator intervention and maintenance. We have developed an all-solid-state system suitable for uv fluorescence remote sensing. This paper discusses the design, performance and advantages of our Optical Parametric Oscillator approach over other possible systems.

Discussion

A typical all-solid-state system for generation of broadly tunable ultraviolet requires harmonic generation or sum-frequency generation of tunable, usually visible or near infrared photons, to generate the desired ultraviolet radiation. As shown schematically in Figure 1, several tunable photons are summed by nonlinear optical crystals to produce the desired ultraviolet output. This approach, while straightforward, suffers two serious drawbacks. First, continuous tuning over a wide range is difficult to achieve, because (as shown in Figure 1) the ranges defined by the various harmonics of the tunable laser (e.g., a titanium-doped sapphire or alexandrite laser) generally do not overlap. Second, the overall efficiency for conversion of pump laser photons to ultraviolet photons is poor, since the output is the product of roughly several sequential steps with conversion efficiencies in the range of 25-60% on each step.

Another method of generating broadly tunable ultraviolet radiation is to pump an Optical Parametric Oscillator (OPO) with the fourth[1] or fifth harmonic of the pump laser. While such sources are capable of tuning over the desired range, the poor beam quality available in the fourth and fifth harmonics of a pump laser such as Nd:YAG and the relatively low damage threshold of broadband uv coatings discourage the design of such a system.

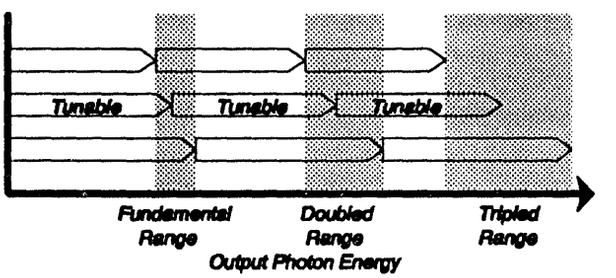

Figure 1. In the typical approach to UV generation, successive harmonics of a tunable laser are generated. Because the tuning ranges of the harmonics do not overlap, continuous tuning is not possible with this approach.

A better approach uses as many pump laser photons as possible to compose the output photon, since the two-step generation of tunable IR light from pump light is especially inefficient. By utilizing only one tunable photon in the production of the output, the overall

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system efficiency is optimized. As shown in Figure 2, it is possible to achieve continuous tunability by mixing the single tunable IR photon with various pump laser harmonics. It is clear from examination of Figure 1b that the tunable IR source employed for broadly tunable UV generation must be capable of an extremely wide tuning range; such a range is not possible using a conventional laser source. Fortunately, the required tuning range is possible using an OPO. In order to avoid gaps in wavelength coverage, the tunable component must have a tuning range equal to one pump-photon energy

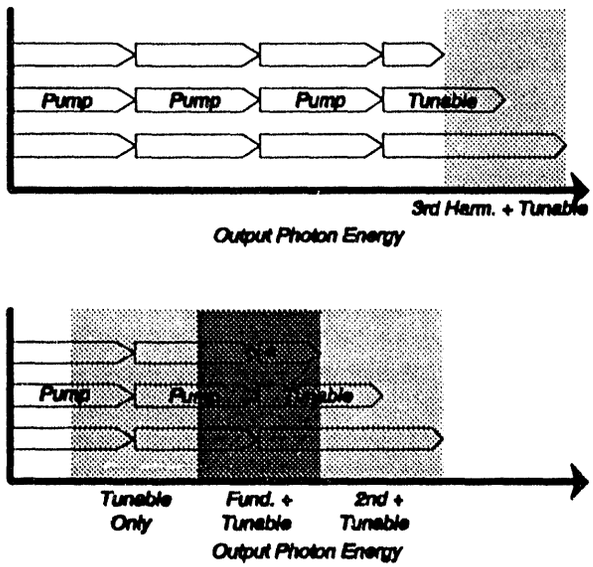


Figure 2 Top, showing the tuning range available for mixing the pump third harmonic with the output of a parametric converter; Bottom, showing other ranges available using the same converter.

System Architecture

We have designed and built an ultraviolet coherent source tunable over the entire 240-420 nm range, using the approach of Figure 2. The system, shown in Figure 3, derives its broad tunability by mixing either the second or third harmonic of a Nd:YAG pump laser

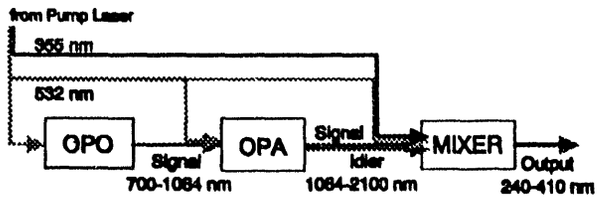


Figure 3 Configuration of the ultraviolet source using a widely tunable parametric source mixed with the second and third harmonics of Nd:YAG.

with the output of a very broadly tunable optical parametric oscillator/parametric amplifier (OPO/OPA) system. The OPO/OPA is pumped by the second harmonic of the pump laser. The full output range can be subdivided into four sub ranges, as described in Table I. The shortest wavelengths are produced by mixing the energetic third harmonic of the pump laser with the OPA signal output. The longest wavelengths required are generated by combining the pump second harmonic with the OPA idler output. Intermediate wavelengths are produced from other combinations of parametric output and pump harmonics.

Table I
Operating Wavelength Ranges

Nd:YAG Harmonic	OPO/OPA	Output (nm)
3rd (355 nm)	Signal (0.71-1.06 μm)	240-266
3rd (355 nm)	Signal (0.71-1.06 μm)	266-304
2nd (532 nm)	Idler (1.06-2.12 μm)	304-355
2nd (532 nm)	Idler (1.06-2.12 μm)	355-420

The requirement for 30 mJ ultraviolet output energy motivates the use of an oscillator/amplifier configuration for the tunable IR source as greater energies can be obtained in such a configuration for a given beam quality. The angular acceptances of suitable frequency-mixing materials for the final stage are small, so good beam quality, at least along the critical direction of the mixing crystals, is required from the parametric source. Good beam quality from high energy parametric oscillators has not been achieved, because high output energies call for large apertures, and efficient parametric oscillators must have short cavities; the resulting high Fresnel numbers of high-energy OPOs typically result in very low quality beams, with large diffraction angles. Instead, by using a low-energy oscillator followed by a high-energy amplifier, we were able to supply the mixer with a high energy beam of adequate beam quality.

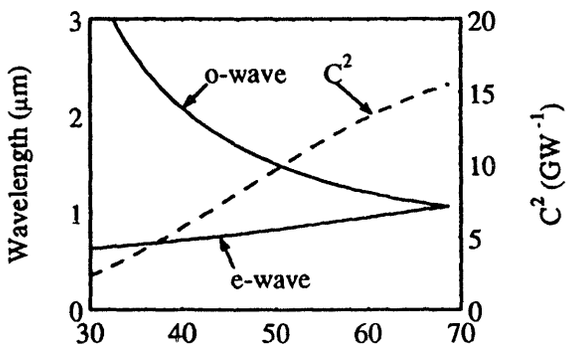
OPO Stage

The OPO is the most critical component of the ultraviolet laser source. One critical requirement is the ability to tune through degeneracy (signal wavelength equal to idler wavelength) with good performance. It is well known[1] that Type I OPOs, in contrast to Type II OPO's, exhibit very large spectral bandwidth near degeneracy. Type II phase matching was chosen, since no spectrally selective elements (other than the nonlinear crystals) would be required in the cavity to limit the spectral linewidth.

In surveying the candidate Type II materials, BBO and KTP were found to offer the most promise for the

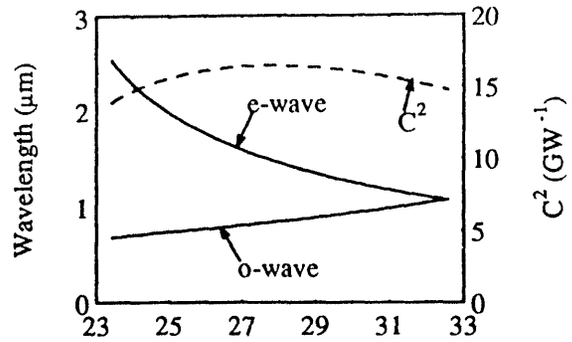
widely-tunable OPO. The phase matching curves for the two materials are shown in Figures 4 and 5. We realized that using KTP in the OPO could lead to difficulties in tuning over the required range. As is obvious from Figure 5, KTP exhibits a wide variation in its nonlinear drive, C^2, and would require rotation through large angles. In contrast, BBO has nearly constant C^2 and can tune over a wide wavelength range with acceptable crystal angles.

A walkoff compensated crystal pair was used in this and subsequent stages, preventing beam displacement during tuning as well as enhancing conversion. The cavity consists of a three-mirror ring similar to that used with KTP[3,4]. The 532 nm pump light enters the crystal pair via one of the two high reflectivity mirrors. The output coupling is approximately 50% from 700 to 1064 nm. The tuning curve for the OPO (and the OPA as well) is shown in Figure 6. The spectral bandwidth of the OPO was found to be 2-4 cm^{-1} over its operating range. The pulse duration of the OPO was measured to be about 5 ns FWHM; while that of the pump laser was 8 ns FWHM. The OPO can produce output energies in excess of 6 mJ of signal and idler for an incident pump energy of about 25 mJ.



Phasematching Angle (degrees)

Figure 4: Phase matching curve for KTP, showing the need for wide tuning angle, and the large variation in nonlinearity, to achieve tuning over the required range for the ultraviolet laser source.



Phasematching Angle (degrees)

Figure 5: Phase matching curve for Type II BBO, demonstrating nearly constant nonlinearity and convenient angular range.

OPA Stage

BBO in a Type I configuration is used for the OPA. Like the OPO, the OPA is pumped by 532 nm radiation. Use of Type I BBO is advantageous for several reasons. The input signal and idler beams are polarized parallel to one another making it easy to reject the orthogonally polarized idler emerging from the OPO. The Type I BBO requires a very small angular rotation of the crystals to phase match over the required wavelength range and has a relatively large wavelength bandwidth. Finally because the signal and idler emerge with the same polarization, coupling to the next stage (Type I) is quite convenient. The OPA stage is operated in a saturated manner, with an effective energy gain of about 10, although small-signal measurements show gain of more than 20. Note that between 25% and 40% of the pump light incident upon the OPA is converted into tunable radiation.

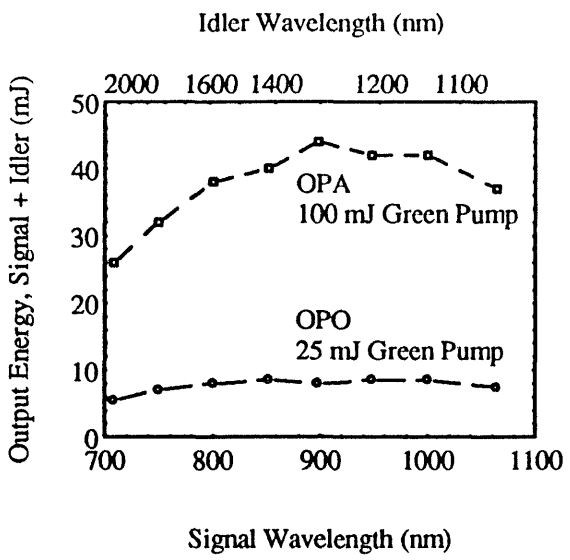


Figure 6: Wavelength tuning curves for the OPO and OPA.

Mixer Stage

Measurements conducted previous to this work showed that the mixing of infrared wavelengths with Nd:YAG harmonics could be very efficient, and stimulated the effort to design this tunable ultraviolet system. In fact, when excess pump-derived photons are provided, greater than 50% of tunable infrared photons can be converted into the ultraviolet. Figure 7 shows the ultraviolet output as a function of input second-harmonic energy, for two values of infrared input.

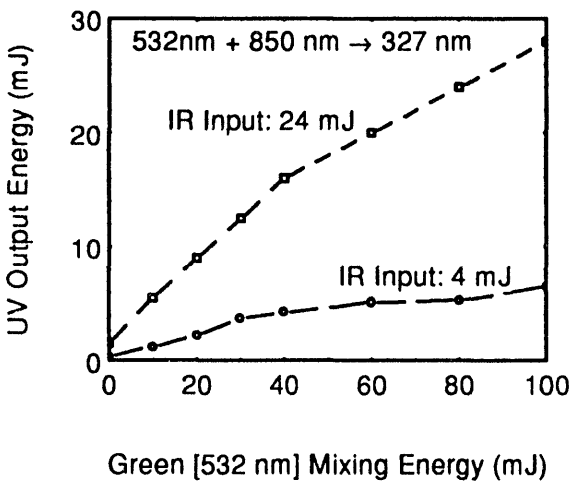


Figure 7 Ultraviolet output from the mixing stage, as a function of Nd:YAG second-harmonic input energy for two values of infrared input.

System Performance

Preliminary measurements of the total system performance have been carried out, and it is expected that overall performance will continue to improve as the system is optimized. The output energy at various wavelengths is depicted in Figure 8. We have clearly exceeded the 10 mJ/pulse requirement for uv fluorescence LIDAR. The minimum in the uv output is caused by the reduced OPO and OPA performance at the extremes of their tuning ranges (i.e., signal wavelengths near 700 nm and idler wavelengths near 2100 nm).

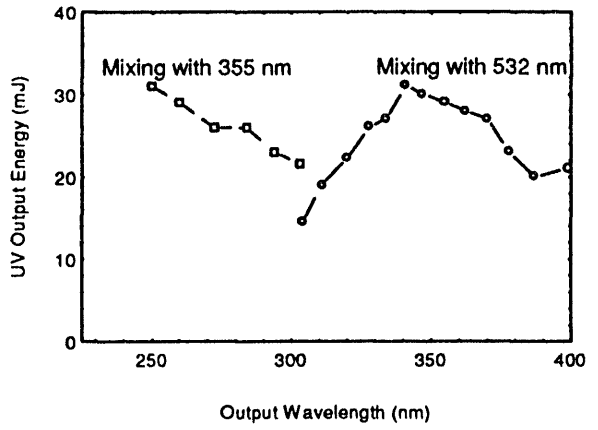


Figure 8 System output as a function of ultraviolet wavelength.

Scaling to higher energy should also be possible and will be investigated as we obtain more intense pump sources. Average output power from this type of system at higher repetition rates will ultimately be limited by the output power capability of the last (mixing) stage; deep in the ultraviolet, heating of the nonlinear crystals may limit average powers to a few watts. Based upon our previous measurements, we expect that this approach to ultraviolet generation will also work well when scaled down by as much as an order of magnitude. This may be useful for developing systems that are very compact and portable.

Narrowband output could be obtained by line narrowing the OPO source, perhaps by injection seeding or the use of intracavity dispersive elements. Expansion of the tuning range beyond that accessible by mixing only with the second and third harmonics would be straightforward, only requiring a change of some dichroic optics.

Summary

We have developed an all-solid-state system suitable for uv fluorescence remote sensing. This system is pumped by the second and third harmonics of a flashlamp-pumped Nd:YAG laser. The broad tunability arises from the use of a broadly tunable OPO that is frequency summed with the second or third harmonics from the pump laser. Over 10 mJ/pulse of light was obtained over the 250-400 nm tuning range of the system and as much as 30 mJ/pulse has been obtained in some regions.

Acknowledgments

The work performed at Aculight Corporation was supported by Sandia National Laboratories under contract AH-5454. The authors thank S.C. Tidwell for his contributions to the optical system design and Ron Allman for his technical contributions. The work at Sandia National Laboratories was supported by the Department of Energy under contract DE-AC04-94AL85000.

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