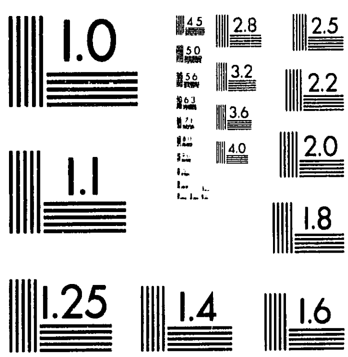
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Sum frequency generation using an optical parametric oscillator

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Abstract

We demonstrate high photon conversion (>50%) of a tunable near infrared OPO into the ultraviolet by sum frequency mixing with the harmonics of a Nd:YAG laser.

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Introduction

A number of applications would benefit from sources of tunable coherent ultraviolet (uv) radiation in the 250 to 400 nm range. Among these are uv fluorescence laser detection and ranging (LIDAR)[1]. Other applications such as photolithography could use a fixed-frequency solid-state equivalent to excimer lasers. Broad tunability in this wavelength region has generally been accessed by frequency doubling tunable visible or near infrared lasers or by frequency mixing these lasers with the harmonics of a Nd:YAG laser. Unfortunately, to cover the full wavelength range requires multiple dye changes and/or multiple nonlinear crystals because of the relatively narrow tuning range of any one laser medium. The use of optical parametric oscillators (OPO's) with their wide tuning range as a tunable source of near infrared light coupled with a single β-barium borate (BBO) crystal for sum frequency mixing with the Nd:YAG harmonics should yield a convenient alternative to cover this wavelength range.

In this paper we demonstrate that an OPO can be efficiently sum frequency mixed with the Nd:YAG harmonics to produce tunable uv radiation in the 250-400 nm range. This is significant because OPO's generally have poor beam quality which limits their nonlinear conversion in critically phase matched processes. Specifically, we have mixed the 780 nm signal beam from a potassium tytanyl phosphate (KTP) OPO with the second harmonic from a Nd:YAG laser in BBO converting up to 50% of the OPO photons into 316 nm photons. We have also demonstrated the generation of narrow bandwidth 248 nm by mixing 827 nm from the OPO with the third harmonic of the Nd:YAG.

Summary

Our experimental setup for the 316-nm generation experiment is shown in Figure 1. The pump laser consists of the oscillator of a Continuum NY61 flashlamp-pumped, Q-switched, injection-seeded Nd:YAG laser. Because the oscillator was found to produce much smoother beam profiles than the oscillator/amplifier configuration we chose to use only the oscillator output and to efficiently frequency double it in an external crystal. The 1.06 μm beam diameter from the graded-reflectivity output coupled oscillator was reduced with a telescope to yield a beam approximately 2 mm in diameter.

The 1.06 μm beam was frequency doubled in an uncoated 2 cm long, Type I lithium triborate (LBO) crystal using noncritical phase matching at approximately 150C. The 110 mJ of fundamental produced approximately 70 mJ of second harmonic. The spatial profile of the second harmonic had a relatively intense central region with a diameter of 0.77 mm full width at half maximum (FWHM) intensity points containing approximately 60% of the energy and a low intensity component with a 4 mm diameter. The pulse duration was approximately 7 ns FWHM. For the 316 nm generation experiment, the second harmonic was split into two beams of approximately equal intensity. One beam was directed to pump the OPO and the second was sent through a telescope to collimate the beam to a divergence less than 120 μRadians FWHM, delayed to match the OPO temporal peak and directed to the mixing crystal.

For the 248-nm generation experiments the second harmonic beam was mixed with the residual 1.06 μm in a 1 cm long, critically phase matched, Type I BBOcrystal to generate as much as 15 mJ of 355 nm. To accomplish this, the polarization of the residual 1.06 μm from the doubling was rotated in a wave plate designed to be $\lambda/2$ at 1.06 μm and $\lambda/1$ at 532 nm. The third harmonic beam under this configuration was found to have a much smaller beam diameter than the 532 nm beam. For the mixing experiments we found it desirable to increase the Q-switch delay of the Nd:YAG laser to improve the beam quality at the expense of 532 and 355 nm energy. The second and third harmonics were separated using a dichroic beam splitter. The third harmonic is directed through a telescope that collimated and matched the beam diameter to the OPO beam at the mixing crystal. The remainder of the second harmonic pumps the OPO.

As shown in Fig. 1, the OPO is similar to that described by Hamilton[2]. It consists of a ring cavity having three flat mirrors and a Type II, 0.9 cm long KTP crystal ($\theta=51°$, $\varphi=0°$). The cavity resonates the signal wave in the near infrared (780 or 827 nm) and has an output coupling of 50%. The signal wave propagates as an extraordinary wave with polarization in the plane of the ring. One of the high reflectors is mounted on a piezoelectric transducer (PZT) to permit fine adjustment of the cavity length for injection seeding with either a continuous wave, single frequency wave titanium doped sapphire laser or diode laser. When injection seeded with 15 mW of power from the titanium-doped sapphire laser, the OPO linewidth is nearly transform limited. The intense portion of the pump beam is approximately 0.77 mm FWHM and the cavity length is approximately 7 cm in length yielding a Fresnel number of approximately 11 at 780 nm.

The OPO signal beam profile is nearly diffraction limited (.59 mRadian divergence FWHM) in the plane of the ring though the out of plane divergence is about twice diffraction limited. A 1 meter focal length lens positioned half a meter from the OPO produced a slightly focussing beam (-170 μ Radians FWHM) in the plane of the ring. The spatially integrated intensity has a smooth temporal profile approximately 5 ns FWHM although the intensity near the center of the beam shows strong back conversion when the OPO is driven much above threshold. A half wave plate rotates the polarization 90° for proper phase matching in the mixing crystal. Two dichroic mirrors are used to separate the signal beam from the pump and idler and to combine the signal beam with the Nd:YAG harmonics for the sum frequency stage.

The crystals used for the sum frequency stage are both BBO cut for Type I phase matching. The acceptance angle for this process is approximately 200 μRadian because of the large birefringence of BBO. For the 316 nm generation the crystal length was 10 mm and the crystal was cut at 31°. The crystal for the 248 nm generation was 6.6 mm long cut at an angle of 46°. Note that two crystals were used in these experiments because of the small (5 mm) apertures of the crystals, but a single crystal should, in principle, be sufficient to cover the entire wavelength interval from 248 to 400 nm (47° to 26° internal angle, respectively). The OPO beam was approximately 0.71 mm FWHM in the critical direction and 0.94 mm FWHM in the orthogonal direction. The pump beam was larger having dimensions of 1.3 and 1.5 mm FWHM, respectively and about 60% of the total energy was contained in this spot.

Figure 2 shows the generated 316 nm energy versus the 532 nm energy with a 780 nm beam energy of 3.6 mJ. The uv output energy monotonically increases to a value of approximately 4.6 mJ representing a conversion of over 50% of the 780 nm photons. Note that the overall mixing efficiency (uv energy out/ total energy in) peaks at about 24% with a 532 nm energy of 10 mJ. The beam profile of the uv varies with 532 nm energy from a single lobe at a few mJ of drive energy to more structured profiles at energies in excess of 15 mJ. It is believed that this is due to back conversion of the uv into 532 nm (355) and 780 nm (827).

The results for the 248 nm generation were less impressive because of poor beam quality on the 355 nm beam and poor temporal and spatial overlap in the mixing crystal. For input energies of 1.4 mJ and 5 mJ at 827 and 355 nm, respectively, about 1.2 mJ of 248 nm light was generated representing a conversion of 25% of the 827 nm photons. Improvements in our 355 nm beam should lead to increased conversion efficiencies. Spectral analysis of the tunable uv showed that it had a linewidth less than 2 GHz.

In conclusion, we have demonstrated that OPO's can be efficiently converted to the uv by sum frequency mixing with the harmonics of a Nd:YAG laser in a BBO crystal. We have shown 50% conversion of the photons in the signal beam of a 532 nm pumped KTP OPO. We have also shown 25%

photon conversion efficiency for converting 827 nm OPO light to 248 nm light by mixing with 355 nm. This bandwidth of this light was measured to be less than 2 GHz.

References

1. Phil's UV LIDAR
2. C.E. Hamilton and W.R. Bosenberg, in *1992 Conference on Lasers and Electro-Optics*, 1992 OSA Technical Digest Series Vol. 12 (Optical Society of America, Washington, D.C., 1992), p 370.

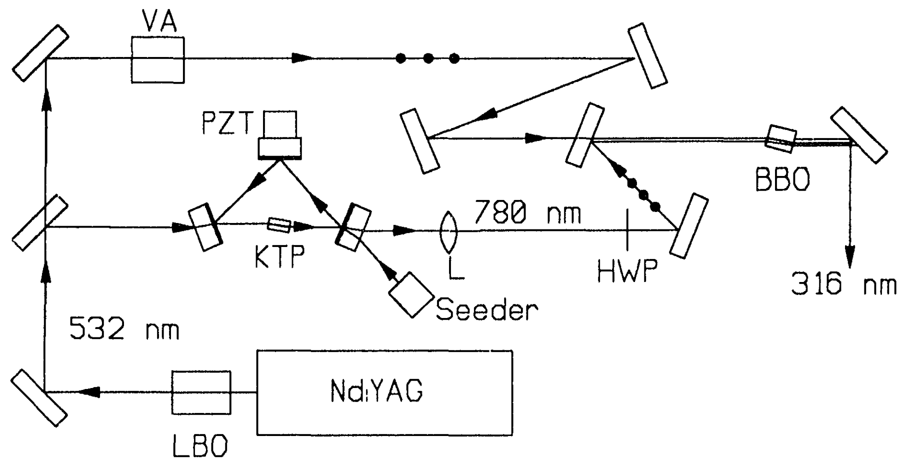

Figure 1. The experimental layout is shown above. Not shown are telescope optics for the 1.06 μm and 532 nm beams. A variable attenuator (VA) is used to vary the 532 nm energy at the mixing crystal. A 1 meter lens is used to reduce the OPO beam divergence and a half-wave plate (HWP) rotates its polarization.

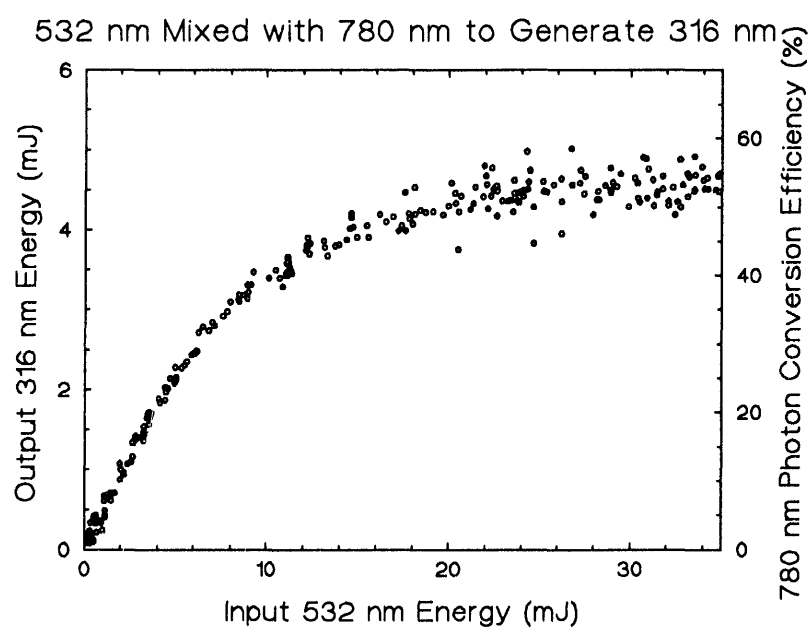

Figure 2. The energy and OPO photon conversion efficiency are plotted versus the incident 532 nm energy. An imput energy of 3.6 mJ at 780 was used.

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