

Optical Parametric Oscillators for the Visible and Ultraviolet

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(Invited Paper)

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Abstract

New strategies for the generation of tunable coherent radiation in the visible and ultraviolet using optical parametric oscillators are outlined. Spectral regions from 250 to 740 nm are accessed in the cw and femtosecond time-scales.

Summary

The development of coherent solid-state light sources for new spectral regions has long been a major goal of research in laser science and technology, since Maiman demonstrated the first experimental laser in 1960. Many approaches to deliver coherent light in difficult spectral regions have been explored using conventional laser techniques, but access to extended regions in the ultraviolet (UV), visible and infrared (IR) have remained difficult because of the absence of suitable solid-state gain materials. This has presented a persistent barrier to the realization of practical laser sources in many desired wavelength regions from the UV to the IR.

Optical parametric oscillators (OPOs) offer an attractive alternative for the generation of coherent radiation in spectral regions inaccessible to conventional solid-state lasers. While the first experimental demonstration of an OPO was reported in 1965, for nearly two decades thereafter there was little or no progress in the practical development of OPO devices, owing to the absence of suitable nonlinear materials and solid-state laser sources. With the advent of a new generation of birefringent nonlinear crystals such as β -BaB₂O₄ (BBO), LiB₃O₅ (LBO) and KTiOPO₄ (KTP) in the mid-1980s and quasi-phase-matched (QPM) materials, particularly periodically-poled LiNbO₃ (PPLN), but also PPKTP, in the mid-1990s, there began a renewed interest in OPOs as practical alternatives to conventional lasers for the generation of coherent radiation in new spectral regions. In the intervening period, OPOs have been transformed into truly viable, state-of-the-art light sources capable of accessing difficult spectral regions and addressing real application areas beyond the reach of conventional lasers. With exceptional spectral coverage, tuning versatility, temporal flexibility from the continuous-wave (cw) to femtosecond time-scales, practical performance capabilities, and compact all-solid-state design, OPOs are now firmly established as viable alternatives to conventional lasers and other technologies for the generation of coherent light in difficult spectral and temporal domains.

Advances in OPO device technology and applications have been particularly rapid in the 1-5 μ m spectral range, driven by the availability of practical near-IR solid-state pump sources and

suitable nonlinear materials. As a down-conversion process, optical parametric generation extends the pump to longer wavelengths. As such, the widespread use of solid-state Nd-doped crystalline and fiber lasers near 1 μm or the Ti:sapphire laser near 800 nm as the pump source has permitted OPO access to wavelengths above 1 μm . The main exception has been in the nanosecond regime, where the use of Q-switched frequency-doubled and tripled Nd-based solid-state lasers at 532 nm and 355 nm has enabled wavelength extension of pulsed OPOs into the visible and near-UV. In other operating regimes, advancement of OPO devices to wavelengths below 1 μm has been challenging because of a lack of laser pump sources of sufficient intensity and high beam quality at shorter wavelengths in the visible and UV, and so new techniques have to be devised to overcome this obstacle.

Here, we describe practical approaches to spectral extension of cw and ultrafast femtosecond OPOs into the visible and UV by using novel nonlinear materials and additional frequency upconversion steps in combination with the OPO. By deploying frequency-doubled cw Nd-based solid-state lasers at 532 nm or the second harmonic of the Kerr-lens-mode-locked (KLM) femtosecond Ti:sapphire laser as the pump source, and by using internal frequency doubling of the OPO signal, we have achieved wavelength generation from 250 nm in the UV to 740 nm in the red in the femtosecond regime and down to 425 nm in the blue in cw operation.

A schematic of the experimental configuration for the generation of femtosecond pulses in the UV is shown in Fig. 1. The OPO is synchronously pumped by the second harmonic of a KLM Ti:sapphire laser at 415 nm. Single-pass frequency-doubling in a 1-mm BiB₃O₆ (BIBO) crystal provides 1.15 W of average power in the blue at $\sim 55\%$ conversion efficiency. The blue pump pulses at 415 nm have durations of ~ 180 fs. The nonlinear crystal for the OPO is 400- μm BIBO, providing signal pulses in the 500-700 nm range.¹ Internal frequency doubling is then performed in a 500- μm β -BaB₂O₄ (BBO) crystal,² providing UV coverage across 250-355 nm with up to 225 mW of average power in pulses with durations of 132 fs (Fig. 2).

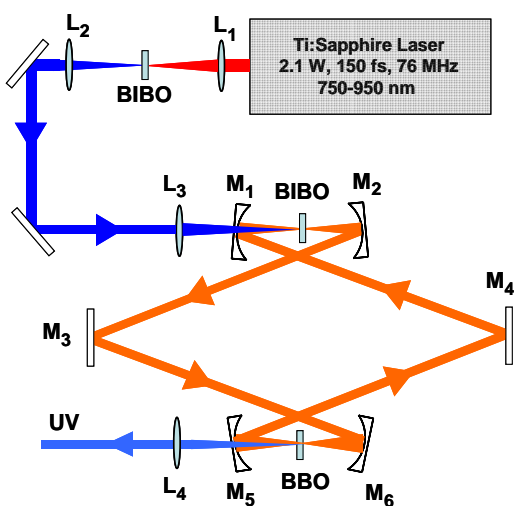


Fig. 1. Configuration of the intracavity frequency-doubled BIBO femtosecond OPO pumped by the second harmonic of KLM Ti:sapphire laser in the blue for the generation of tunable femtosecond pulses in the UV.

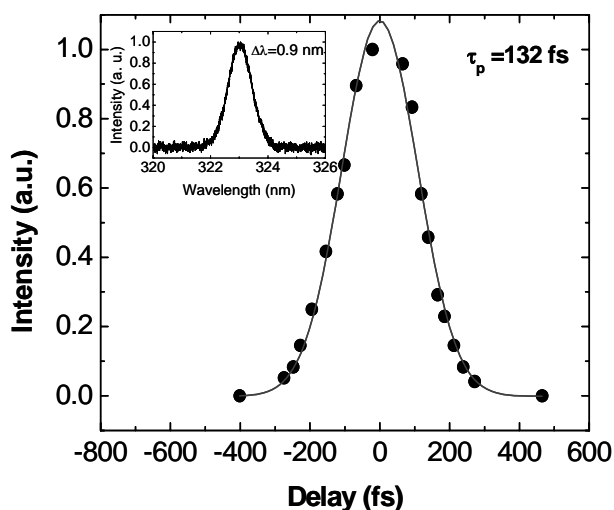


Fig. 2. Cross-correlation trace, and (inset) spectrum of the generated UV pulses at 323 nm. The time duration of $\Delta\tau \sim 132$ fs and the spectral bandwidth $\Delta\nu \sim 0.9$ nm result in near-transform-limit pulses with a time-bandwidth product of $\Delta\nu \cdot \Delta\tau \sim 0.34$.

The development of QPM materials such as MgO:sPPLT has also provided new opportunities for spectral extension of cw OPOs into the visible and towards the UV by similarly deploying internal frequency conversion steps. Using this approach, we have been able to generate practical powers and extended tuning in the blue by internal doubling of high-power cw singly-resonant OPOs based on MgO:sPPLT.³ The device, based on a 30-mm MgO:sPPLT crystal and configured in a ring cavity, is pumped by a 10-W, frequency-doubled cw Nd:YVO₄ laser at 532 nm. Using highly reflecting mirrors maximizes circulating signal power to tens of watts, allowing practical single-pass doubling into the blue in a 5-mm BIBO crystal internal to the OPO cavity. Continuous tuning in the blue is obtained by adjustment of MgO:sPPLT crystal temperature and rotation of the BIBO crystal. The ring cavity ensures emission of the blue beam in a single direction (Fig. 3). With this approach, we have generated nearly 450 mW of cw blue power with a tunable range across 425–490 nm (Fig. 4). The output beam is single-frequency with a Gaussian spatial profile.⁴ Using alternative gratings for the MgO:sPPLT crystal, the tuning range can be further extended to cover 300–530 nm.

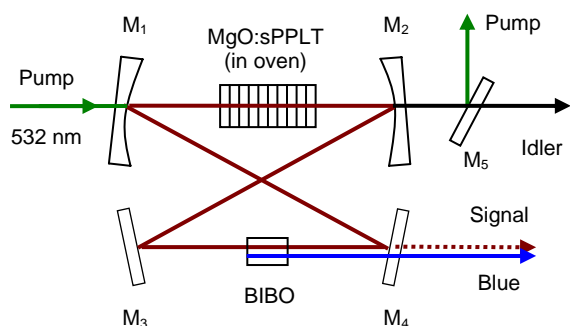


Fig. 3. Schematic of the intracavity frequency-doubled cw OPO based on MgO:sPPLT for blue generation.

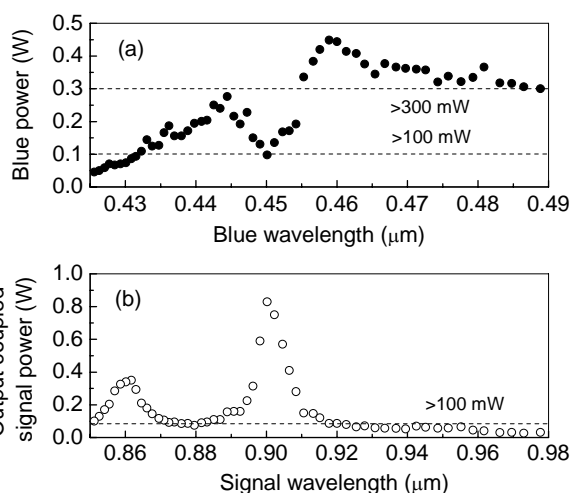


Fig. 4. (a) Second harmonic blue power versus wavelength, and (b) Out-coupled signal power across the tuning range.

The application of the OPO approach in combination with additional frequency upconversion steps thus offers promise for the realization of a new generation coherent solid-state light sources capable of providing wide tunability and practical powers in arbitrary wavelength regions across the visible and into the UV, where there is a scarcity of solid-state laser sources and where many applications in spectroscopy, biophotonics, microscopy, medical diagnostics, and nanotechnology can benefit.

References

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