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Optical Parametric Oscillators: A New Generation

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Abstract: Progress in continuous-wave and ultrafast femtosecond optical parametric oscillators, covering spectral regions from 250 nm in the ultraviolet to 5 μm in the infrared, using novel design concepts and advanced laser pump sources is reviewed.

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Optical parametric oscillators (OPOs) were recognized as potentially viable sources of tunable coherent light more than four decades ago, after the demonstration of the first experimental device in 1965. Following the initial rapid progress, research in OPO devices was hampered by several obstacles, mainly a lack of suitable nonlinear materials. This led to a conspicuous decline in OPO research and a long period of quiescence for nearly 20 years, until in the 1980s, the advent of novel nonlinear materials once again prompted a revival of interest in the field. The emergence of a new generation of birefringent crystals such as β-BaB_2O_4 (BBO), LiB_3O_5 (LBO) and $KTiOPO_4$ (KTP) provided renewed impetus for research in OPO devices. Combined with the widespread availability of pulsed laser sources of sufficient intensity and high output beam quality, rapid progress in OPO technology was witnessed in the pulsed regime, transforming nanosecond OPOs from proof-of-principle laboratory prototypes to practical sources of widely tunable radiation from the ultraviolet (UV) to mid-infrared (mid-IR), with many devices finding their way to the commercial market and addressing different applications. On the other hand, advancement in OPO technology in other operating regimes, particularly the continuous-wave (cw) and ultrafast femtosecond time-scales has been more difficult, due to the low nonlinear gains available under low-intensity pumping. Combined with the increasingly stringent material requirements be met in the low-intensity regime, progress in cw and femtosecond OPOs has taken place at a substantially slower pace than in pulsed nanosecond oscillators.

In the cw regime, the advent of quasi-phase-matched (QPM) ferroelectric materials has led the way to the realization of novel devices by providing a new class of engineered nonlinear crystals fulfilling the simultaneous requirements of high optical nonlinearity (d_{eff}~10-20 pm/V), long interaction length (20-80 mm), noncritical propagation, and arbitrary phase-matching throughout the material transparency range. Among the QPM materials, periodically-poled $LiNbO_3$ (PPLN) has had an unparalleled impact on cw OPOs, but because of photorefractive susceptibility the wavelength coverage of devices based on PPLN has remained confined to ~1.5-5 μm in the IR. In the femtosecond time-scales, the advent of PPLN and other QPM materials such as PPKTP and PPRTA has had a similarly important impact on ultrafast OPOs based on the Kerr-lens-mode-locked (KLM) Ti:sapphire laser as the pump source, providing wavelength coverage across ~1-5 μm, but spectral extension below ~1 μm has again remained difficult.

Against this backdrop, an important goal in further advancement of OPO technology is spectral extension of cw and femtosecond oscillators to previously inaccessible regions in the visible and UV by exploiting new nonlinear materials and devising new strategies to overcome the fundamental limitation of the parametric down-conversion process, namely spectral generation at wavelengths longer than the pump. Here we review how the deployment of novel design concepts based on multistep frequency up- and down-conversion in combination with new QPM and birefringent nonlinear materials can provide a viable solution to the generation of widely tunable radiation in the visible and UV, in both cw and femtosecond time-scales, using OPOs.

Progress in material science during the past few years has led to the emergence of alternative QPM materials to PPLN with reduced photorefractive susceptibility, while offering similarly attractive nonlinear optical properties. Among these, MgO:sPPLT offers great potential due to its high photorefractive damage threshold, a near-UV transmission cutoff, high thermal conductivity, absence of residual absorption, and the ability to be reliably fabricated with short grating periods (<10 μm) over long interaction lengths (>30 mm), providing a promising route to wavelength generation at shorter wavelengths into the visible. The development of new birefringent crystals such as the biaxial BiB_3O_6 (bismuth triborate, BIBO), with increased optical nonlinearity (d_{eff}~3-4 pm/V) over BBO and LBO, flexible phase-matching properties, reduced spatial walkoff, and a transparency window extending into the UV, has similarly provided new avenues for wavelength generation into the visible and near-UV. By taking advantage of these developments and through the application of external and internal frequency up-conversion techniques, we have been able to extend the spectral coverage of cw OPOs down to ~400 nm in the blue, while in femtosecond OPOs we have achieved wavelength generation down to ~250 nm in the UV.

Figure 1 depicts three different OPO devices capable of delivering tunable radiation across the visible using two-step external and internal frequency conversion techniques. In Fig. 1(a), external second harmonic generation (SHG) of a KLM Ti:sapphire laser into the blue in BIBO, followed by parametric down-conversion in an OPO, also based on BIBO, permits femtosecond pulse generation across the entire visible spectrum over 480-720 nm [1], whereas in Fig. 1(b) the direct use of the KLM Ti:sapphire laser to pump an OPO based on PPLN, followed by internal SHG of the circulating signal in BIBO allows wavelength generation in the visible [2]. On the other hand, the deployment of similar strategies in the cw regime, but through the use of a Nd:YVO_4 green laser to pump an OPO based on MgO:sPPLT [3], followed by internal SHG of the circulating signal in BIBO, enables wavelength generation in the visible and down to the blue, at watt-level output power [4].

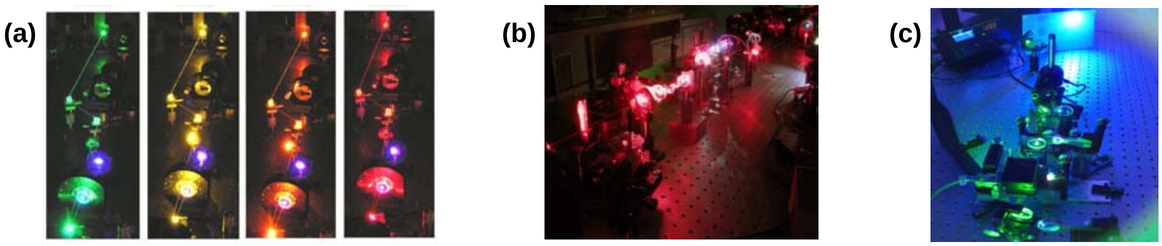

Fig. 1. Optical parametric oscillators for the visble. (a) Blue-pumped BIBO femtosecond OPO, (b) Internally-doubled PPLN femtosecond OPO, (c) Internally-doubled cw OPO based on MgO:sPPLT.

At the same time, with the rapid advances in pump laser technology, particularly fiber and optically-pumped semiconductor lasers (OPSLs), offering unprecedented optical powers and high spectral and spatial beam quality, another important direction in the advancement of OPO technology will the development of more simplified, compact, portable and cost-effective device formats to replace the more bulky, complex and high-cost architectures based on solid-state pump lasers deployed thus far. To this end, we have been able to extend the operation of cw and ultrafast OPOs to fiber lasers as well as OPSLs as the pump source, providing a new class of practical light sources, tunable in the visible and infrared, and capable of delivering cw and average powers of several watts. Figure 2 shows two device architectures based fiber and OPSL pumps, which we have recently demonstrated. Fig. 2 (a) depicts a cw OPO pumped by a frequency-doubled cw Yb fiber laser at 532 nm in the green [5], while Fig. 2(b) shows a high-power cw OPO using an OPSL in the green as the pump source.

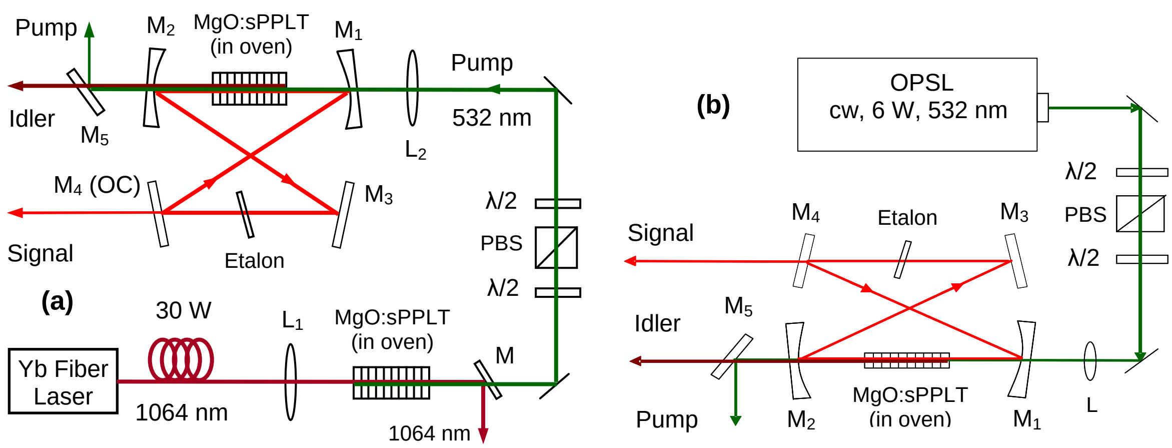

Fig. 2. Continuous-wave optical parametric oscillators pumped by: (a) Frequency-doubled fiber laser at 532 nm; (b) Optically-pumped semiconductor laser (OPSL).

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