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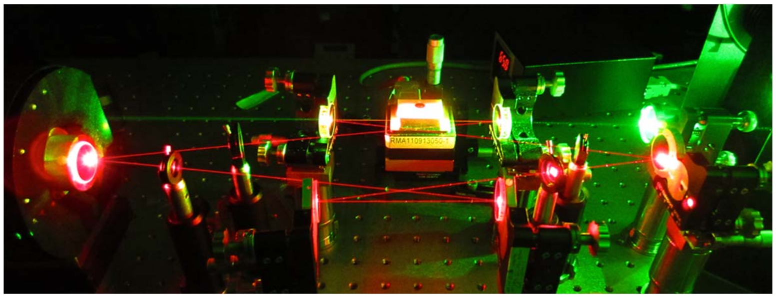

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Breakthroughs in Photonics 2012: Breakthroughs in Optical Parametric Oscillators

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(Invited Paper)

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Abstract: The latest breakthroughs in optical parametric oscillators (OPOs) for the generation of tunable coherent radiation from the continuous-wave to femtosecond time-scales are presented. Advancement of novel device concepts, development of phase-coherent and broadband frequency combs, and expansion of wavelength coverage of OPOs to new limits toward the visible and mid-IR are the main focus of the review.

Index Terms: Optical parametric oscillators (OPOs), nonlinear materials, frequency conversion, tunable lasers, visible lasers, mid-infrared lasers, mode-locked lasers, ultrafast sources, frequency combs.

This review describes breakthroughs in optical parametric oscillators (OPOs) during 2012. The review covers devices based on $\chi^{(2)}$ nonlinearity in bulk crystals, deploying resonant cavities and pumped by low-intensity laser oscillators. The discussion is focused mainly on continuous-wave (cw) and ultrafast OPOs, as the most important recent advances have been in this area. We begin with a discussion of cw OPOs, followed by femtosecond (fs) and picosecond (ps) OPOs. We will finally briefly describe the main developments in pulsed nanosecond (ns) OPOs.

The major breakthroughs in cw OPOs during 2012 have been the development of innovative device concepts for the generation of tunable coherent radiation with new properties. One such development has been the direct application of mode-locking, as used in conventional lasers, to cw OPOs [1], [2]. This has opened up the possibility of generating ps and fs pulses from cw OPOs without the need for mode-locked lasers and synchronous pumping, thus greatly alleviating the complexity and cost associated with ultrafast OPOs. By deploying active mode-locking using a phase modulator (PM) and an antiresonant ring (ARR) interferometer internal to a cw doubly resonant oscillator (DRO) based on MgO:sPPLT and pumped at 532 nm, see Fig. 1(a), a stable train of 800-ps pulses at 160 MHz was generated [1]. The concept was later successfully extended to a cw singly resonant oscillator (SRO), validating the universal viability of the technique [2]. In this case, mode-locking was achieved by direct use of a PM internal to the OPO cavity, producing stable 230-ps pulses at 80 MHz. The ultimate extension of the concept to passive techniques, such as

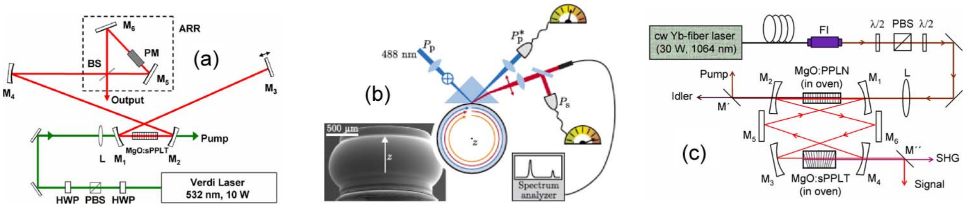

Fig. 1. (a) Hybridally mode-locked cw OPO [1], (b) WG cw OPO [3], and (c) Frequency-doubled cw OPO [5].

Kerr-lens-mode-locking (KLM), together with suitable dispersion control, offers the intriguing possibility of generating fs pulses from the UV to mid-IR using cw OPOs pumped by widely available cw solid-state lasers, potentially transforming existing ultrafast technology. In another interesting advance, the whispering gallery (WG) resonator concept in $\chi^{(3)}$-based microcavity parametric oscillators has been extended to $\chi^{(2)}$ cw OPOs employing monolithic cavities of millimeter size [3], [4]. In such OPOs, the optical cavity is formed by the spheroidally shaped nonlinear crystal, with all interacting waves (pump, signal, idler) resonating in a triply resonant oscillator scheme without the need for external mirrors. The pump is coupled into the cavity using an external prism, and the resonant waves are guided by total internal reflection, oscillating circularly as WG modes around the monolithic cavity, with the output waves coupled out by the same prism. Attractive features of such WG cw OPOs are the small mode volume, high finesse, and low loss over a broad spectral range, resulting in a strong enhancement of nonlinear interaction, low threshold (μW range), and broadband tuning, potentially across the full transparency range of the crystal. Other features include compact size, intrinsic frequency stability, narrow linewidth, and high internal efficiency. On the other hand, high input coupling loss and low extraction efficiency and output power (mW range) are inherent properties of such OPOs. By employing a millimeter-size spheroidal WG cw OPO based on MgO:PPN pumped at 488 nm in blue, see Fig. 1(b), tunable signal (idler) wavelengths across 707–865 nm (1.120–1.575 μm) were generated with $\sim$10 μW of signal output power for 1 mW of input pump at an external efficiency of $\sim$1% [3]. The OPO exhibited a pump coupling loss of $\sim$60% and had an external pump threshold of 160 μW. Later, the effect of pump coupling strength on threshold and efficiency of such WG cw OPOs was studied using a similar crystal pumped at 1.037 μm [4]. By varying the coupling strength over three orders of magnitude, a threshold variation by a factor of 20 was measured, with the OPO yielding a minimum threshold of 200 μW, maximum efficiency of $\sim$30%, and output power of 1.3 mW for 4.32 mW of input pump power. The small-size, low-threshold, and mW-level output power makes such WG cw OPOs suitable for diode laser pumping and attractive for applications requiring low photon numbers, such as quantum optics. Another significant advance has been the development of compact watt-level fiber-pumped cw SROs for difficult spectral regions below 1 μm using intracavity signal up-conversion. By deploying an OPO cavity comprising MgO:PPLN as gain medium and MgO:sPPLT as doubling crystal, see Fig. 1(c), as much as 3.7 W of cw power across 775–807 nm, together with 4 W of idler over 3.125–3.396 μm, was generated in single-mode spectrum ($<$ 10 MHz) with high beam quality ($M^2 < 1.4$) [5]. The technique could be used to cover the full Ti:sapphire (TiS) range of 700–1100 nm using suitable grating periods, with the potential for power scaling using higher fiber pump powers and optimized output coupling (OC). In this context, some recent research has focused on performance enhancement of cw OPOs with regard to threshold, output power, and efficiency through OC optimization [6], [7]. In one study, the novel use of an ARR interferometer for variable signal OC in a fiber-pumped MgO:PPLN cw SRO was demonstrated [6]. A maximum signal power of 2.8 W under optimum OC ($\sim$4.6%) and 4.2 W of idler under minimal OC ($\sim$0.8%) were obtained for 28.6 W of pump at $\sim$24% total extraction efficiency, with a minimum threshold of 12.3 W for OC $\sim$0.8%. Similar studies were performed in intracavity cw SROs using a conventional discrete OC mirror [7]. Using a signal mirror transmission of 9.6% in a PPLN cw SRO pumped internal to a diode-pumped Nd:YVO$_4$ laser, 5.03 W of signal and 1.43 W of idler were generated at an overall extraction efficiency of 30.2%. The SRO had a threshold of 2.46 W.

In the ultrafast regime, much of the recent advances in fs OPOs have been driven by their potential to generate frequency combs in the mid-IR for precision spectroscopy and other applications [8]. Using stabilized fs TiS and fiber pump lasers, such OPOs are uniquely versatile sources of optical frequency combs from $\sim$400 nm to $\sim$ 6 μm. In degenerate DRO operation under type-I phase-matching, fs OPOs have been shown to exhibit self-phase-locked behavior, providing coherent broadband output centered at degeneracy. In a recent study, coherence properties of such OPOs were explored by interfering the outputs of two identical but independent oscillators based on 500-μm MgO:PPLN and pumped by a 70-fs Er-fiber laser at 1.560 μm [9]. It was shown that the two outputs centered at 3.120 μm are mutually coherent, and locked in frequency and phase to the pump laser, suggesting that when pumped by a carrier-enveloped-phase (CEP)-stabilized frequency comb, such OPOs inherit all the coherence properties of the pump. This makes them attractive for mid-IR frequency comb generation for molecular spectroscopy. By deploying a $\sim$90-fs Tm-fiber laser at 2.050 μm to synchronously pump a 500-μm crystal of orientation-patterned GaAs (OP-GaAs), a degenerate fs OPO was demonstrated, providing an output spectrum extending across 2.6–6.1 μm [10]. With a threshold of 17 mW, the OPO delivered 37 mW of average power at 75 MHz. The octave-spanning output spectrum in a wavelength range containing several molecular fingerprints (OH, CH, CO, and NH) suggests the potential of the OPO for precision frequency comb spectroscopy after CEP stabilization. Later, operation of a degenerate fs OPO based on a 1-mm MgO:PPLN crystal pumped by a 30-fs KLM TiS laser at 1 GHz was reported, generating $\sim$85-nm-wide spectrum centered at 1.6 μm with $>$ 100-mW average power [11]. Stable phase-locked comb generation was evidenced by measurements of RF spectrum, confirming a single indistinguishable signal–idler output comb at exact degeneracy with a mode spacing of 1 GHz. Subsequently, operation of a fs OPO based on a 1-mm Brewster-cut MgO:PPLN pumped by a $\sim$200-fs Yb-fiber laser at 1.035 μm and $\sim$36.7 MHz was reported [12]. Using an 8.16-m ten-mirror cavity for synchronous pumping, the OPO generated a $\sim$137-nm-wide spectrum centered at 2.070 μm in 48-fs pulses, with a pump threshold $<$ 10 mW and $\sim$10 mW of average output power. By using two lasers providing pulse trains of slightly different repetition rates to pump a fs OPO based on a 20-mm MgO:PPLN with high intracavity dispersion, two asynchronous broadband idler pulse trains with a stabilized repetition-rate difference of up to 5 kHz centered at 3.3 μm were generated with nearly identical spectra ($\sim$200-nm-wide) and output power ($\sim$100 mW) [13]. With additional CEP stabilization, such a system could be potentially useful for coherent dual-comb spectroscopy. In later study, using a fs OPO based on a 500-μm PPKTP pumped by a sub-20 fs TiS laser (800 nm, 35-nm bandwidth, 100 MHz), locking of CEP frequencies of the pump, signal, idler, and the non-phase-matched frequency-mixing pulses to 0 Hz was achieved, providing broadband phase coherence over a combined bandwidth of 400–3200 nm [14]. Other advances in fs OPOs include their performance enhancement and spectral extension to the visible and mid-IR, and novel techniques for arbitrary wavelength pair generation. By deploying a frequency-doubled thin-disk fs Yb:KLu(WO_4) laser at 515 nm, delivering 13 W of average power at $\sim$34 MHz, a non-collinear OPO based on a 2-mm $\beta-\mathrm{BaB}_2\mathrm{O}_4$ crystal was demonstrated, providing signal tuning across 650–850 nm with $>$ 3-W maximum average output power [15]. The use of double chirped mirrors combined with positive intracavity dispersion resulted in signal pulses of $\sim$90 fs after external compression. In another report, a flexible technique for performance enhancement of ultrafast OPOs based on synchronized retroreflection of the pump was demonstrated, where in a fs OPO based on a 1.5-mm $\mathrm{BiB}_3\mathrm{O}_6$ crystal pumped by a KLM TiS laser, a threshold reduction of 22% and power enhancement of 70% compared to single-pass pumping were obtained [16]. Another topic of research interest in fs OPOs has been dual-wavelength generation. Applying a novel technique using an ARR interferometer to connect two cavities, dual-wavelength operation of fs OPOs was demonstrated, providing independent, arbitrary, and uninterrupted tuning of signal (idler) pairs, even through degeneracy [17]. By deploying two fs OPOs based on 500-μm MgO:PPLN pumped by a single KLM TiS laser, signal pair generation across 1.5–1.58 μm with frequency separation from $\sim$10 THz to exact degeneracy, in pulses of $\sim$200-fs duration, was achieved using cavity length tuning. Operating a fs OPO based on 2-mm MgO:PPLN pumped by a KLM TiS laser in a signal range where phase-matching and group velocity mismatch are balanced, dual-wave generation was observed across 1–2 μm [18], with the signal (idler) wavelengths coupled by phase-matching and energy conservation. Using a similar approach but operating a fs OPO in the zero dispersion region, dual-wave generation in a fs OPO based on a 1-mm MgO:PPLN pumped by a 530-fs Yb:KGW oscillator at 1040 nm was reported, providing coupled signal wavelengths across 1.563–1.621 μm and 1.795–1.859 μm [19]. External difference-frequency mixing of two signal waves in GaSe/$AgGaSe_2$ provided tunable mid-IR radiation across 10.5–16.5 μm with up to 4.3 mW of average power at 42 MHz. In the ps timescale, the advent of high-power fiber lasers has enabled the development of multiwatt ps OPOs for new spectral regions in the visible and near-IR. By intracavity doubling of the resonant signal in a ps OPO based on 50-mm MgO:PPLN pumped by a Yb-fiber laser at 1.064 μm, tunable $\sim$15-ps pulses over 752–860 nm with as much as 3.5 W of average power at 81 MHz were generated [20]. The use of a 5-mm $\beta-BaB_2O_4$ doubling crystal with large spectral acceptance under type-I phase-matching enabled full wavelength coverage with minimal angle tuning. With further optimization, the tuning range of the OPO could be potentially extended to cover the full TiS wavelength range.

In the ns regime, the most significant developments have been the extension of tuning range of pulsed OPOs beyond $\sim$5 μm by exploiting new nonlinear materials and pump sources. These include cascaded pumping of a ns $ZnGeP_2$ SRO at 2.128 μm by a degenerate Rb:PPKTP OPO/OPA, itself pumped at 1.064 μm by a Q-switched Nd:YAG laser [21]. The OPO provided tuning over 6.27–8.12 μm in 5-ns pulses with peak power of 193 kW at 100 Hz at the important wavelength of 6.45 μm for minimally invasive surgery. Direct pumping of $BaGa_4S_7$ at 1.064 μm has also been shown to provide idler pulses from a ns SRO tunable across $\sim$5.5$-$7.3 μm, with $\sim$0.5-mJ pulse energy and 50-mW average power at 6.217 μm in $\sim$6-ns pulses at 100 Hz [22]. In another report, the power instability of ns SROs was theoretically studied and experimentally verified, confirming that the maximum instability occurs at input pump power $\sim$1.5 time threshold [23].

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