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Cascaded intracavity frequency down-conversion of 1 μm laser radiation to the mid-IR

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Cascaded or tandem optical parametric oscillators (OPOs) for down conversion of laser radiation into the mid-IR spectral range using non-oxide nonlinear crystals in the second stage have rarely been realized with intracavity pumping [1]. In addition to the more compact and robust design such schemes profit from the higher (intracavity) pump power for the OPO second stage provided by the signal or idler wave of an oxide crystal based OPO first stage, in turn pumped as a rule at 1.064 μm by a Nd:YAG laser system. Compared to pumping inside the cavity of a ns laser, demonstrated in the past with CdSe, $ZnGeP_2$ (ZGP) and orientation-patterned GaAs (OPGaAs) in gain-switched or Q-switched lasers, the cascaded OPO approach offers the flexibility of selecting the most suitable pump wavelength for broadband tunability of the second stage based on a specific non-oxide nonlinear crystal [1]. Previous demonstrations of intracavity pumped (or coupled) tandem OPOs were characterized by limited tunability, maximum up to about 8 μm [2] determined by the doubly-resonant OPO (DRO) scheme and the crystal choice in the second stage. We investigated a singly-resonant OPO (SRO) based on a $AgGaSe_2$ (AGSe) crystal intracavity pumped at ~1.85 μm by the signal pulses of a Rb:PPKTP DRO. Both the choice of a SRO design and the transparency of the AGSe crystal enabled coverage of much broader portions of the mid-IR spectral range. With two AGSe samples cut for type-I and II phase-matching, an extremely broad tuning range for the non-resonated idler was achieved, extending from 5.8 to ~18 μm [3].

Depending on the interaction type in the two nonlinear crystals, by suitable adjustment of the polarizations, the coupled cavity set-up of such a cascaded intracavity pumped OPO can be easily transformed into a self-seeded mid-IR OPO where the two nonlinear crystals share exactly the same doubly-resonant cavity. We studied also such a scheme, equivalent to intracavity difference-frequency generation (DFG) due to the high seed level, employing a similar set-up with the same nonlinear crystals and a dichroic half-wave plate [4]. It is simpler, the overall insertion loss due to the AGSe crystal is reduced and the extraction of the mid-IR radiation can be more efficient. This novel scheme relies on the Rb:PPKTP based DRO as a first stage aiming at high depletion of its signal wave in the second (DFG) stage based on type-I AGSe. Consequently DFG radiation is created in both directions. Notwithstanding expected complications related to relative phases of undepleted waves, we employed a double pump pass. With this scheme, we achieved an average power of 67 mW (100 Hz) at 7 μm equivalent to an overall conversion efficiency from the 1.064 μm pump of 1.2%. The output energy of the mid-IR ns pulse (0.67 mJ) is comparable with the best results achieved by extracavity DFG at 5 Hz [5] but the overall conversion efficiency is two times higher.

[1] V. Petrov, "Frequency down-conversion of solid-state laser sources to the mid-infrared spectral range using non-oxide nonlinear crystals," Progress Quantum Electron. **42**, 1-106 (2015).
[2] P. B. Phua, K. S. Lai, R. F. Wu, and T. C. Chong, "Coupled tandem optical parametric oscillator (OPO): an OPO within an OPO," Opt. Lett. **23**, 1262-1264 (1998).
[3] A. A. Boyko, G. M. Marchev, V. Petrov, V. Pasiskevicius, D. B. Kolker, A. Zukauskas, and N. Y. Kostyukova, "Intracavity-pumped, cascaded $AgGaSe_2$ optical parametric oscillator tunable from 5.8 to 18 μm," Opt. Express **23**, 33460-33465 (2015).
[4] A. A. Boyko, N. Y. Kostyukova, G. M. Marchev, V. Pasiskevicius, D. B. Kolker, A. Zukauskas, and V. Petrov, "Rb:PPKTP optical parametric oscillator with intracavity difference-frequency generation in $AgGaSe_2$," Opt. Lett. **41**, 2791-2794 (2016).
[5] R. Utano and R. J. Ferry, "8-12 μm generation using difference frequency generation in $AgGaSe_2$ of a Nd:YAG pumped KTP OPO," Advanced Solid-State Lasers, 1997, Vol. 10 of OSA TOPS, paper PC11, pp. 267-269.