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Low-threshold Highly Efficient Backward Wave OPO

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Abstract: Cavity-free, precision-tunable source of a nanosecond, mJ-level, pulses consisting of backward optical parametric oscillator pumped by diode-seeded laser amplifier shows a record threshold of 19 MW/cm² and an optical-to-optical efficiency exceeding 70%.

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Introduction

Differential absorption LIDAR instruments for concentration mapping of greenhouse gases require fast tuning to access on-line and off-line wavelengths in the mid-infrared rotational-vibrational spectrum of the relevant molecules. These instruments, delivering mJ-level nanosecond pulses, will see future deployment on airborne and space-borne platforms and need certain mechanical robustness and compact design solutions. These requirements emphasize the energy efficiency of the coherent source technology used in such applications. Here we demonstrate that backward wave optical parametric oscillator (BWPO) pumped by a tunable fiber-laser Yb-doped power amplifier (MOPA) has the potential for satisfying the requirements mentioned above in terms of precise and fast tuning of a narrowband output, high conversion efficiency, and cavity-less robust design.

BWPO is based on counterpropagating $\chi^{(2)}$ interactions, where one of the parametric waves is generated in the direction opposite to that of the pump [1, 2]. The phase-matching of such interaction requires substantial photon momentum compensation owing to the significant phase mismatch naturally present due to the anti-parallel walk-off between the waves. Thus, quasi-phase-matching (QPM) needs to be employed. The three-wave mixing enforces the parametric wavelengths by conservation of the photon energies ($\omega_p = \omega_f + \omega_b$) and phase-matching of the waves ($\Delta\mathbf{k} = \mathbf{k}_p - \mathbf{k}_f + \mathbf{k}_b - \mathbf{K}_\Lambda = \mathbf{0}$), respectively. Subscripts p, b, and f indicate the pump, backward and forward wave, respectively, while $\mathbf{K}_\Lambda = 2\pi/\Lambda$ is the (first-order) wavevector of the QPM grating. For near-infrared pumped parametric process generating in the mid-infrared, the QPM grating periodicity is well-below one micron, which was successfully realized in periodically poled KTiOPO₄ (PPKTP) over crystal volumes suitable for mJ-level pulse generation [3-5]. BWPO does not require an optical cavity and self-established oscillation has a threshold comparable to that of a singly-resonant OPO realized with the same nonlinear material of the same length [6]. The counterpropagating geometry gives rise to the unique spectral property of the device, namely, that the forward wave content is a spectrally-shifted phase-locked replica of the pump, while the backward wave is inherently narrowband and transform-limited [7]. Thus, for a pump frequency tuning $\Delta\omega_p$, the parametric frequencies are shifted by $\Delta\omega_f = (1 + \varepsilon) \Delta\omega_p$ (forward) and $\Delta\omega_b = -\varepsilon \Delta\omega_p$ (backward) ($\varepsilon \sim 10^{-3}$). For a narrowband, continuously tunable pump, the BWPO forward wave will follow the changes in the pump frequency without mode-hops due to the absence of a cavity. Moreover, the symmetric intensity distribution of the forward and backward waves with maxima at the opposite ends of the crystal drastically reduces back-conversion, therefore enabling high conversion efficiency. The output of the BWPO is eventually limited by optical damage of the host crystal by the pump, of which the threshold at 1 μm for KTP is 12 J/cm² [8].

Experimental results and conclusions

The Yb-based nanosecond (11 ns FWHM) MOPA pump source operating at 1.03 μm can be continuously tuned over a range of 10 GHz ($\Delta\omega_p$) [9]. The pump emits narrow bandwidth (100 MHz) mJ pulses at a repetition rate of 5 kHz. In combination with BWPO, the system is essentially free from mechanical optical cavities, which is vital for airborne and space applications. The pump was focused on a 140 μm radius ($1/e^2$) in two ($\Lambda=580$ nm) BWPO crystals of lengths 7 and 17 mm. The BWPO created a signal at 1981.1 nm and a backward traveling idler of 2145.6 nm, monitored synchronously as the pump was detuned to measure $\Delta\omega_f$ and $\Delta\omega_b$. We also measured all involved waves' output power, bandwidth, and temporal traces. In the center of Fig.1, a sketch for counterpropagating interaction is shown to emphasize the directions of the different waves. In Fig.1 (a), we display the experimentally measured pump frequency modulation together with the forward (b) and backward wave tuning (c). It is clear from the figure that the forward wave tuning follows that of the pump, while the backward idler is stable, both being free from cavity modal jumps. The tuning is consistent with theory; the backward wave tuning is in the range of tens of MHz under the noise floor of the wavemeter, while the forward wave tunes on the order of tens of GHz. In principle, the pump pulses should be able to tune pulse-to-pulse, but in this measurement, it was limited by the integration time of the MIR wavemeter.

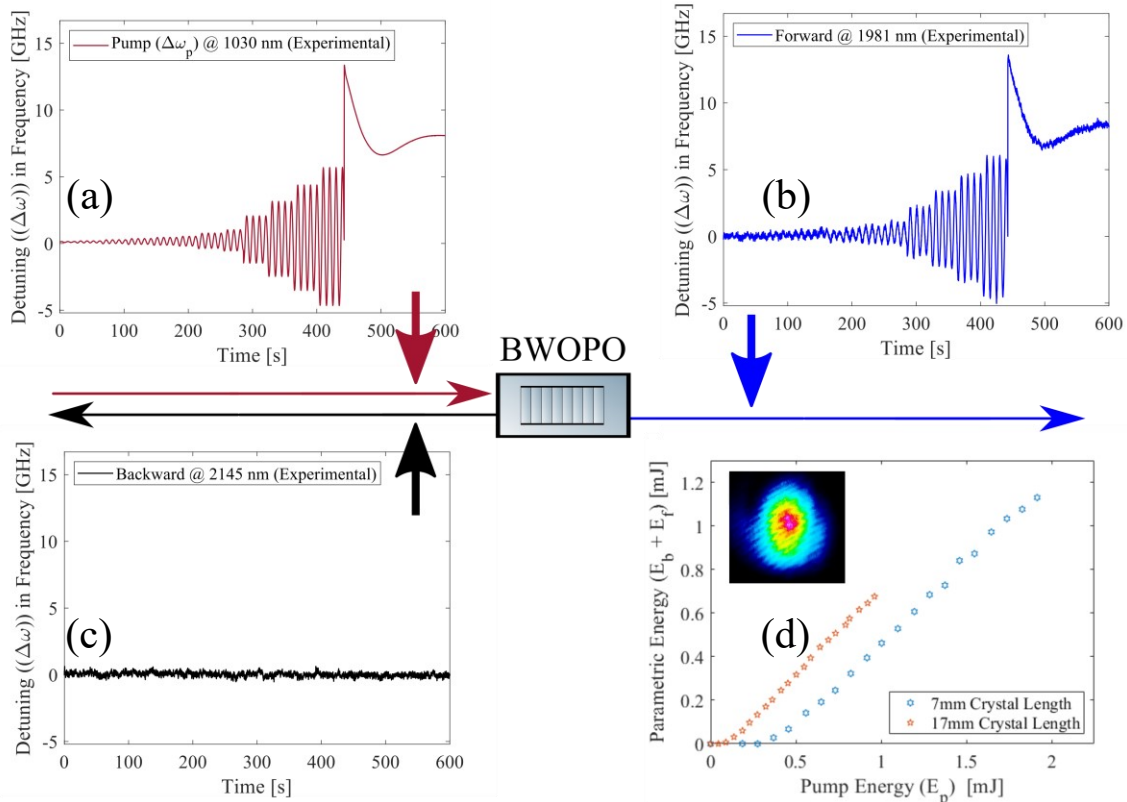


Figure 1. Center is a simplified schematic of the setup and the geometry of the output parametric waves. Tuning of the pump (a) with the tuning of (b) Forward and (c) Backward wave pump show distinct different dependence on the pump detuning. In the last part (d), the total parametric output energy is shown as a function of pump energy for two crystal lengths together with the forward traveling 1981 nm beam profile as an inset.

As seen in Fig.1 (d), the BWOPO is an efficient device, with conversions reaching 70% and 50% for the long and short crystal, respectively. The beam profile of the forward wave is also depicted as an inset. The significant efficiency allows for parametric pulses of over half an mJ to be produced at a modest pump of 1.92 mJ for the short crystal. The longer crystal reached conversion of 70% already at 0.96 mJ of pump, producing combined parametric energy of 0.68 mJ. The BWOPO oscillation threshold was 103 MW/cm² (370 μ J) and 19 MW/cm² (70 μ J) in the short and long crystal, respectively. Assuming Gaussian pulses, analytical expressions for the BWOPO threshold [6] were used to find the effective nonlinear coefficient d_{eff} of 7.2 pm/V and 7 pm/V for the short and long crystal, respectively. Pulse durations of the parametric waves were roughly 12 ns with 300-400 MHz bandwidth as measured with a MIR scanning 10 GHz Fabry-Perot ($F > 150$). The tuning speed, output power, and bandwidth make this system feasible for tuning on and off resonances of greenhouse gases. The cavity-free arrangement makes it feasible for a system that could withstand vibrational environments, as found in space and air flight.

In short, this demonstrates a narrowband MIR mJ-level source that can be continuously tuned over several GHz with efficiencies exceeding 70% in an arrangement that is resistant to mechanically challenging areas, as found in space- and airborne environments. This work has been done under the framework of the LEMON project, EC grant agreement No. 821868.

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