Octave-wide Gallium Phosphide OPO Centered at 3 µm and Pumped by an Er-fiber Laser

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Abstract: We achieved 2.35-4.75 µm continuous spectrum from an Er-fiber pumped subharmonic OPO based on orientation-patterned GaP that is suitable for ultra-broad bandwidth comb generation. Less than 67-fs pulse duration and 29-mW output power were measured.

OCIS codes: (190.4975) Parametric processes; (190.4410) Nonlinear optics, parametric processes

1. Introduction

A new technique was introduced recently, suitable for generating broadband phase- and frequency-locked frequency combs in the mid-infrared, based on a degenerate optical parametric oscillator (OPO), which rigorously both down-converts and augments the spectrum of a pump frequency comb provided by a commercial mode-locked C-band fiber laser [1]. For example, an instantaneous mid-IR spectrum of 2.5-3.8 µm was achieved in a 0.5-mm-long periodically poled lithium niobate (PPLN) crystal [1]. Quasi-phase-matched (QPM) semiconductors, on the other hand, such as all-epitaxially-grown GaAs and GaP, have (i) much deeper mid-IR transparency and (ii) smaller group dispersion - a prerequisite for generating broadband frequency combs. While orientation-patterned (OP) GaAs has already shown great promise for wavelength conversion – both in mid-IR and THz ranges, and from CW to fs formats [2], its primary limitation is that it cannot be pumped at wavelengths below 1.7 µm due to the onset of two-photon absorption. Orientation-patterned gallium phosphide (OP-GaP) – a new QPM material with larger (and indirect) band gap of 2.26 eV at 300K overcomes this limitation. Recently femtosecond OP-GaP OPOs with the pump at 1 µm [3], 1.5 µm [4] and 2 µm [5] were successfully demonstrated. Here we report the first octave-wide GaP OPO that is pumped at a telecom wavelength and is suitable for broadband mid-IR comb generation.

2. Experiment

The OPO (Fig. 1) was pumped by a 1.56-µm Er-doped fiber laser (300 mW average power, 80 MHz repetition rate and 85-fs pulse duration) and is designed for doubly resonant near-degenerate operation. The cavity was composed of a dielectric incoupling mirror (M4) with a high transmission (>85%) at 1.56-µm and high reflection (>95%) at 2.4-4.2 µm and three gold-coated mirrors (M1-M3), two of which (M1 and M2) are parabolic (off-axis angle 30°, radius of curvature 30 mm), and M3 – a flat mirror (additional folding mirrors were also used for compactness). Broad-bandwidth gain was provided by a 0.5-mm thick OP-GaP crystal placed at the Brewster angle with pump and OPO polarizations aligned along <111>, with a QPM period 46.5 µm. The crystal was grown by a combination of molecular beam epitaxy (MBE) and low-pressure hydride vapor phase epitaxy (HVPE) [6]. A 1.12-mm thick CaF_2 wedge was used for dispersion compensation.

3. Results

The OPO pump threshold was measured to be 14 mW; this low threshold is a consequence of doubly resonant performance and high nonlinear coefficient of GaP, $d_{eff}=d_{14}\,(4/3)^{1/2}(2/\pi)=35\,(4/3)^{1/2}(2/\pi)$ pm/V. The output spectrum was acquired using an optical spectrum analyzer (Bristol Instruments 771). The instantaneous spectrum spanning more than one octave, 2110 - 4250 cm^{-1} (2.35-4.75 µm) at -24 dB, as seen from Fig. 2(a). Although the OPO cavity was purged with dry nitrogen, which reduced the CO_2 concentration to less than 5 ppm and H_2O concentration to 400 ppm, the spectrum was still affected by absorption by these two molecules present in the path to the measurement system.

We measured the output power of 29 mW at the maximum pump of 300 mW. The output pulse duration was 67 fs, measured by a 2-nd order interferometric autocorrelator (Fig. 2(b)); however this is the upper limit of pulse duration, since the latter was affected by the dispersion of the optical elements used, such as longpass filter and beam splitter.

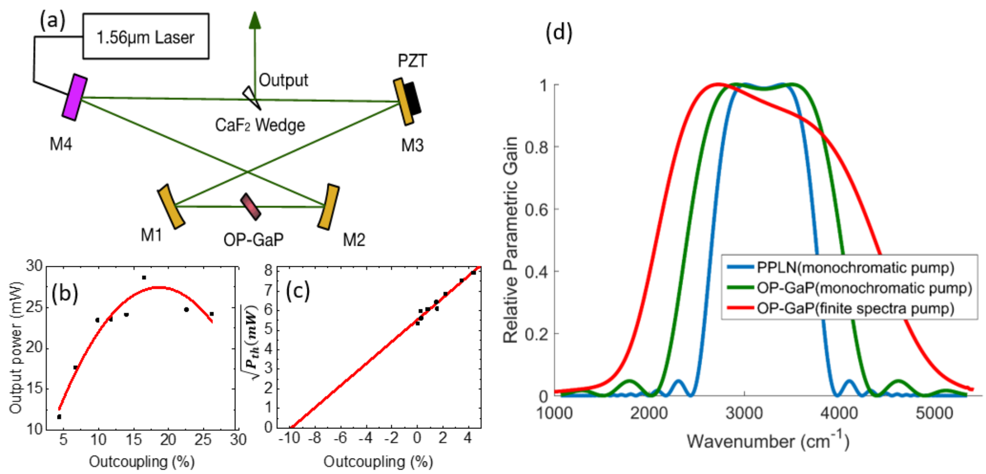

Fig. 1. (a) The OPO setup. M1 - M3 are gold mirrors. PZT is a piezoelectric translator to tune the cavity length. M4 is a dielectric incoupling mirror. (b) The output power of the OPO versus the outcoupling efficiency. (c) The square root of the OPO pump threshold versus the outcoupling strength that shows a typical doubly resonant behavior. (d) Normalized parametric gain calculated for 0.5-mm-long QPM crystals, 1.56-μm pump, and 3 scenarios: PPLN (monochromatic pump), OP-GaP (monochromatic pump), and OP-GaP (finite-spectrum pump corresponding to a real *fs* Er fiber laser).

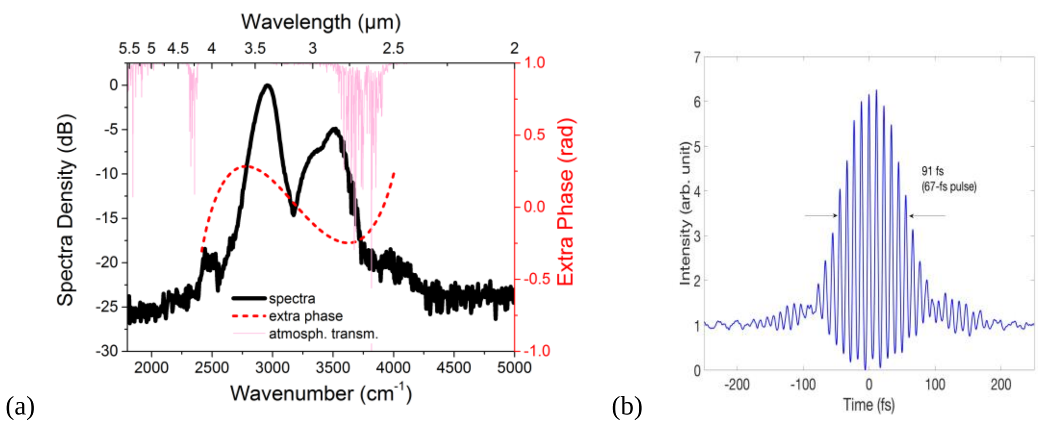

Fig. 2 (a) Black curve: octave-wide instantaneous spectrum covering 2.35-4.75 μm (2110-4250 cm^{-1}) at -24 dB. Pink curve: transmission window of the cavity (5 ppm CO_2 and 400 ppm H_2O). Red curve: the round trip accumulated phase in cavity (estimated tolerance is ± 0.5 rad). (b) Second-order interferometric autocorrelation trace, showing pulse width of 67 fs (upper limit).

4. Conclusion

An octave-wide spectral output of 2.35-4.75 μm was achieved in a robust OP-GaP-based Er-fiber-pumped subharmonic OPO with low (14 mW) pump threshold. The threshold was twice smaller and the spectral span was 85% broader, as compared to PPLN in the same pump configuration of [1]. That makes the system very attractive for broadband Fourier spectroscopy as well as for self-referencing via *f*-to-2*f* interferometry.

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