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Megawatt peak power 8–13 μm CdSe optical parametric generator pumped at 2.8 μm

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Abstract

Infrared pulses, continuously tunable in the 8–13 μm range, and with up to 1 MW peak power, have been achieved using single-stage frequency conversion in a CdSe travelling-wave optical parametric generator, pumped by 100 ps pulses from an actively mode-locked, Q-switched and cavity dumped 2.8 μm Cr,Er:YSGG laser. The external quantum conversion efficiency reached 10%. © 1998 Elsevier Science B.V. All rights reserved.

As it was shown recently, short Er-laser $\lambda = 2.8$ μm pulses can be successfully used for pumping travelling-wave optical parametric generators (OPG) based on highly nonlinear $ZnGeP_2$ and GaSe crystals – to achieve high peak power mid-infrared radiation with extra-wide tunability [1]. The principle of operation is based on the high gain ($> 10^{10}$) amplification of quantum noise in a nonlinear crystal pumped by intense short light pulses. The main advantage of such devices is that the travelling wave configuration makes it possible to have the OPG output in the form of a single intense burst of radiation.

The travelling-wave OPG based on $ZnGeP_2$, which is remarkable for having one of the largest nonlinear-optical coefficients, among all the nonlinear-optical crystals in practical use, has the smallest pump threshold (< 100 MW/cm^2) [2,3]. However its long-wave tunability is limited to $\lambda = 10$ μm; and its efficiency at $\lambda > 8$ μm is reduced due to linear losses associated with the multi-phonon absorption peak. As for the GaSe OPG, pumped by a 2.8 μm Er-laser, its tunability range of 3–19 μm [1] has not been surpassed so far, but its linewidth is quite large (characteristic of the type-I phase-matching). For example in the 8–12 μm range, which is of special interest for spectroscopy, its linewidth is typically 50–100 cm^{-1}. In addition the maximum length of good quality GaSe crystals is limited to 1–2 cm, and that is why the pumping threshold is high, ≈ 1 GW/cm^2.

The CdSe crystal was first explored as a nonlinear optical material for optical parametric oscillators [4,5] and difference frequency generation [6,7] at the beginning of the 70's. Despite its nonlinear optical coefficient of $d_{31} =$ 18 pm/V being 3 and 4 times smaller [8] than that of GaSe and $ZnGeP_2$ respectively, it has certain advantages. CdSe is a binary crystal with a mature growing technology, has a wide transparency range (0.75–25 μm) and extremely low optical losses (< 0.01 cm^{-1} over the 1–10 μm region); long (> 5 cm) crystals can be grown routinely, and it possesses small birefringent walk-off.

Recently a CdSe optical parametric oscillator pumped by a nanosecond 2.8 μm Cr,Er:YSGG laser was reported [9] which yielded a 39% quantum conversion efficiency with the idler beam tuning range of 8.5–12.3 μm. Using sequential parametric downconversion of 1.064 μm Nd:YAG pulses in a KTP crystal and then in a CdSe crystal [10], tunable infrared radiation from 10 to 20 μm with energies ranging from 40 to 5 μJ in 11-ps pulses was generated.

Here we report for the first time travelling-wave (resonator-free) optical parametric generation based on CdSe.

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The crystal was pumped by short 3 μm pulses and mid-IR radiation, continuously tunable in the range 8–13 μm, with up to 1 MW peak power was achieved using a simple setup with a single-stage frequency conversion. Such a device is of interest for molecular and solid state saturation spectroscopy, where high peak powers and short pulse durations are crucial, and for remote sensing in the 8–12 μm atmospheric window.

We used the CdSe crystal from the General Physics Institute, Moscow, 7 × 14 × 50 mm long, cut at 76° for the type-II phase-matching, with 0.01–0.02 cm^{-1} absorption in the 1–10 μm range, and with no AR coating. As a pumping source we used single pulses of an actively mode-locked, Q-switched and cavity dumped Cr^{3+},Er^{3+}:YSGG laser [2] (using the Er^{3+} ion $^4\mathrm{I}_{11/2}$–$^4\mathrm{I}_{13/2}$ transition, $\lambda = 2.797$ μm) operating at a repetition rate of 3 Hz. The laser pulses had 100 ps duration and an energy of 2–3 mJ in the TEM_{00} mode. A small photon energy of an Er-laser ($2h\nu < E_g$, where E_g is a bandgap) ensures that there is no two-photon absorption in CdSe which may become a severe obstacle at pump intensities > 100 $\mathrm{MW/cm^2}$.

A tilted 30 cm LiF lens was used to (astigmatically) focus the laser beam onto the CdSe crystal (resulting in an elliptical spot size, ~ 0.5 × 1 mm). The elliptical focussing ensured that the spread of the beam in the walk-off plane is much greater than the walk-off distance (0.19 mm at $L = 5$ cm, $\theta = 76°$). The single-pass OPG pumping threshold (i.e. the minimal laser pump intensity when the OPG output is detectable) was found to be 0.47 $\mathrm{GW/cm^2}$, which is higher than that for $\mathrm{ZnGeP_2}$ but 2–3 times lower compared to GaSe [1]. The optical surface damage threshold intensity (at 10^4 shots) for 100 ps pulses was 7 $\mathrm{GW/cm^2}$.

The OPG output was registered using a 25 cm grating monochromator and an InSb- (signal wave) or a HgCdTe- (idler wave) detector. To block the scattered pump laser (2.8 μm) radiation we used an InAs window (transmits at $\lambda > 3.9$ μm). In addition an InSb window ($\lambda > 7$ μm) or a longwave-pass interference filter ($\lambda > 6$ μm) were used to separate the idler OPG beam from the signal. In the case of the absolute energy measurements we have used a calibrated pyroelectric detector.

The experimental angular tuning curve is shown in Fig. 1 and manifests an excellent agreement with the calculated tuning curve (solid line) based on dispersion relations of Ref. [11]. The tuning range achieved was 8–13 μm with the idler and, accordingly, 3.57–4.3 μm with the signal. Fig. 2 shows the quantum conversion efficiency as a function of the idler wavelength. The peak value of ~ 10% is reached between 8 and 9.5 μm. This conversion efficiency corresponds to 200–300 μJ of the signal-plus-idler output energy, giving up to 1 MW output peak power of the idler wave.

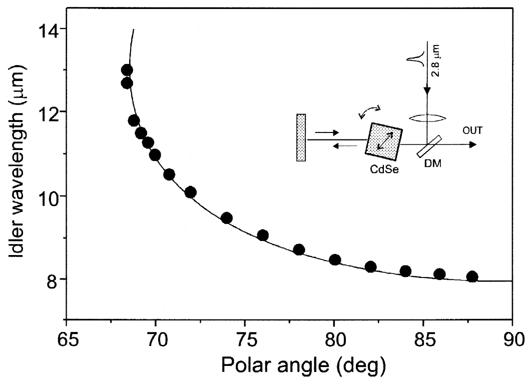

Fig. 1. CdSe angular tuning curve (idler wave). Solid line – calculated using the data from Ref. [11]. Inset shows the schematic of the two-pass travelling-wave OPG.

In the two-pass travelling-wave OPG setup (inset, Fig. 1), we used a dichroic beamsplitting mirror (DM) which reflects the laser beam and transmits the OPG signal and idler output ($R = 99.8\%$ at $\lambda = 2.8$ μm and $T > 68\%$ at $\lambda = 3.74$–12 μm). The back reflecting gold mirror was located about 3–4 cm from the end of the CdSe crystal. The laser beam was astigmatically (resulting in an elliptical beam-shape, similar to the single-pass scheme) focused into the crystal in such a manner that the pump laser intensity was approximately 1 $\mathrm{GW/cm^2}$ on the first pass through the crystal and 4 $\mathrm{GW/cm^2}$ on the second pass (stronger focusing on the second pass compensates for the absorption and Fresnel reflection losses). Thus the first pass served as a superluminescent seed, while the second as a parametric amplifier. The advantages of the two-pass (as compared to a single-pass) scheme are the absence of the walk-off of the output beam when the crystal is angular-tuned (which is quite important for our applications in pump-probe spectroscopic measurements), suppression of the off-axis parametric generation, and improved spectral and spatial quality of the output pulses [1]. For instance the linewidth and divergence are improved by a factor of ~ 4 in a two-pass scheme. Fig. 2 shows

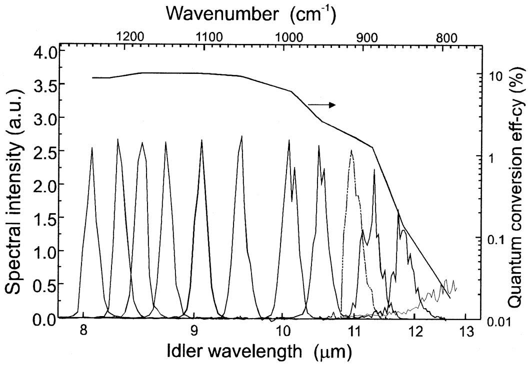

Fig. 2. OPG line-shape and quantum conversion efficiency as a function of the output wavelength.

spectral lineshape as a function of the idler wavelength; the linewidths were typically 10 cm^{-1} for both signal and idler waves, except in the vicinity of the ''turning point'' near $\lambda = 13$ μm (Fig. 1), where the spectrum becomes much broader, typically ~ 100 cm^{-1}. The OPG divergence in our experiment was measured to be $\sim 2 \times$ (diffraction limit), which enabled us to routinely focus the idler beam into a 70 μm spot with $> 10^9$ $\mathrm{W/cm}^2$ peak power density.

In summary, travelling-wave OPG was achieved in CdSe with a 8–13 μm tunability range, 1 MW peak output power and up to 10% quantum conversion efficiency. We estimate that this efficiency could be increased by at least 1.5 times with the use of AR coatings. From the viewpoint of applications in the spectral range of 8–12 μm, Er-laser-pumped OPG based on the CdSe crystal, is superior (in the sense of efficiency and the linewidth) to $ZnGeP_2$ or GaSe.

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