Compact, tunable, all-solid-state LWIR source for standoff chemical detection

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Abstract

A compact long-wavelength infrared (LWIR) source, based on the combination of a high-pulse-rate, 1-µm-wavelength solid-state laser with rapid and broadly tunable tandem optical parametric oscillators (OPOs) was demonstrated. Nanosecond pulses with up to 100 µJ energy, tunable within the 8-11 µm LWIR range were achieved.

Keywords: DIAL, Solid-state, Diode-pumped, OPO, Infrared.

1. Introduction

We report on a small size, lightweight, rugged, long-wavelength infrared (LWIR) source, based on the combination of a high-pulse-rate 1-µm-wavelength solid-state laser with rapid and broadly tunable tandem optical parametric oscillators (OPOs). The laser system includes a compact, diode-pumped, 1-kHz-repetition rate, Q-switched Nd:YLF oscillator combined with diode-pumped power amplifiers. The master-oscillator/power-amplifier (MOPA) system generates 15-ns pulses with up to 16-W average power in a near-diffraction-limited beam. The first stage of the tandem OPO system, an angle-tuned, KTA-crystal-based OPO, efficiently converts the output of the Nd:YLF pump laser into tunable energy in the 1.5-1.7 and 2.8-3.5-µm wavelength regions. The wavelength-tuning scheme for the KTA OPO is based on rapidly changing the angular position of the pump laser beam by a fast acousto-optic beam deflector (AOBD). The KTA OPO is used as a tunable pump source for the second OPO in the design, which uses the CdSe crystal and produces nanosecond pulses with up to 100 µJ energy, tunable within the 8-11 µm LWIR range. The rapidly tunable nature of the source allows application to DIAL standoff detection systems that can scan for and identify a large number of chemical agents. This is accomplished by scanning across the spectral features of a particular chemical and switching from chemical to chemical with a high accuracy (5 cm^{-1}), repeatability (2 cm^{-1}), and rate (up to100 Hz). Since the source can produce a wide variety of wavelengths in the IR, it may find extended applications to other standoff detection systems, including those designed to monitor and track clouds containing either chemical or biological agents.

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A block-diagram of the LWIR source is demonstrated in Fig.1. and followed by the detailed description of the system.

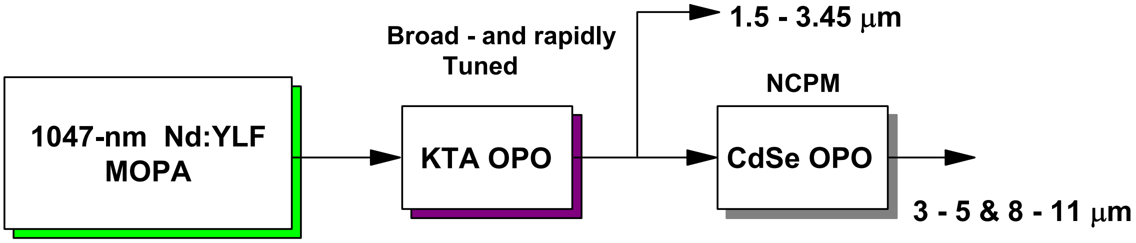

Figure 1. Block-diagram of the LWIR source.

2. MOPA system

The master oscillator is a fiber-coupled, laser-diode-pumped, all solid-state laser employing an acousto-optical Q-switch. The optical design is simple with a low component count, and is therefore extremely compact and rugged. The fiber-coupled 30-W diode pump source may be remote from the laser head allowing for optimal placement of the pump source for heat removal (several Watts) and optimal placement of the laser head for optical system integration. The optical schematic of the oscillator is presented in Fig. 2.

The gain element is a 15-mm long Nd:YLF crystal with undoped endcaps and plane faces wedged to prevent parasitic oscillation. The pump end face was coated for high transmission at the pump wavelength (804 nm) and high reflection at 1 μm. The other endface had an anti-reflection coating at 1 μm. As a plane mirror, we used a flat output coupler of 68%-reflectivity. The resonator is formed between the pumped face of the crystal and the output coupler. A 25-cm focal-length lens placed near the Nd:YLF crystal combined with the endcap flat face of the latter comprised the concave mirror. The separation, L_s, between the output coupler and the lens was set to be approximately equal to its focal length, f_l, which makes the resonator close to semi-concentric ($R \sim f_l \sim L_s$). This has been shown to provide a large mode volume in a laser medium placed near the concave mirror.

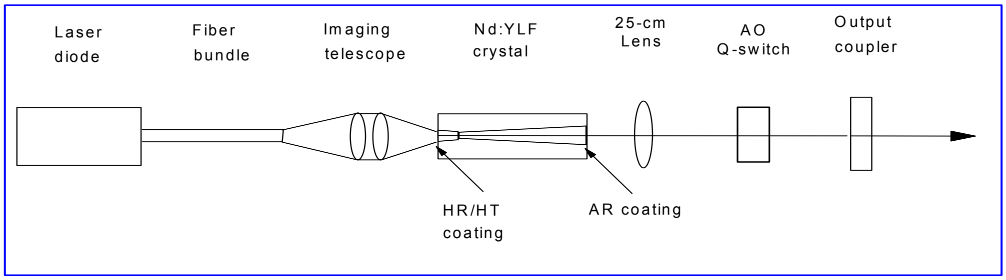

Figure 2. Quasi-cw diode-end-pumped, Q-switched Nd:YLF oscillator.

The fiber-coupled diode for the oscillator was powered in a quasi-cw mode at a 1 kHz rate with 500-μsec pulses. The oscillator generated 2.2 mJ, 15-nsec pulses in a nearly diffraction-limited beam. The output pulses were amplified using a two-stage, quasi-cw pumped amplifier, which is based on the Q-Peak multi-pass-slab (MPS) design that we have developed extensively over the past 8 years.

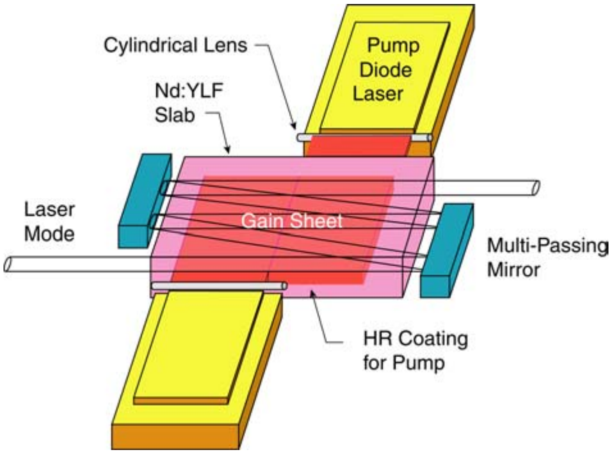

Figure 3. Multi-pass slab (MPS), US Patent 5,774,489.

The starting point of our MPS design is a patented five-pass Nd:YLF gain element, with external high reflectors (see Fig. 3). The 2.8-cm long Nd:YLF crystal is transversely pumped by a pair of 1-cm long, 40-90-W diode-laser bars. The diode-laser bars are coupled to the gain element through a single cylindrical lens attached directly to each bar package. These lenses minimize the divergence of the pump light in the plane perpendicular to the linear emitter. The bars are offset on opposite sides of the Nd:YLF crystal to create a sheet of gain in the crystal. The pump faces of the crystal have segmented dielectric coatings (AR/HR) to allow double-pass pump absorption. The pump geometry is a central feature of the design in that it yields a laser that is relatively insensitive to the alignment, spectra, and temperatures of the diode-laser bars. This is in contrast to some of the complex, multi-element imaging schema that have been developed for similar purposes, and benefits both the reliability and cost of the technology.

Power is extracted efficiently and high gain per pass is obtained by passing the laser cavity mode five times through the gain sheet that is produced in the slab. The relatively low pump power density in the crystal minimizes excess heating and loss due to upconversion. The Nd:YLF slab geometry developed at Q-Peak is unique in providing high gain while avoiding many of the difficulties encountered in end-pumping laser media (such as achieving good overlap between the pump and laser mode and thermal aberration of end faces). The MOPA system design is shown in Fig. 4.

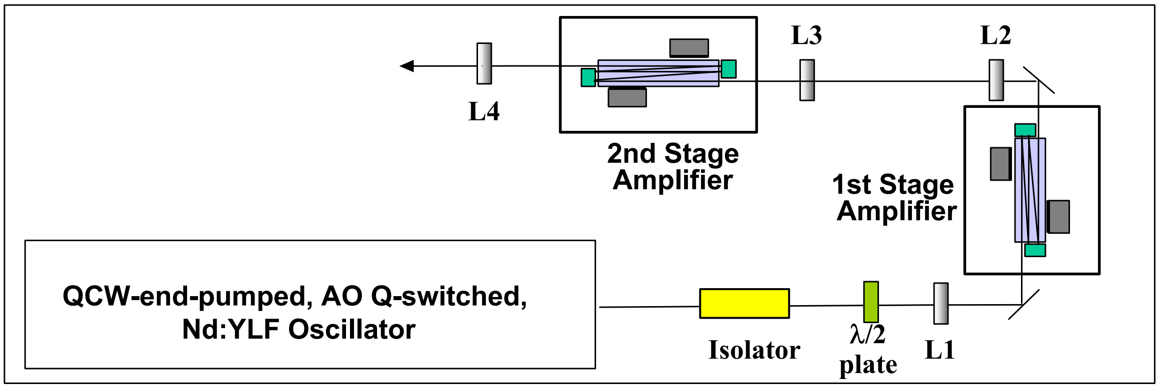

Figure 4. Nd:YLF MOPA system. L1 & L4, collimating lenses, L2 & L3, relay-imaging lenses.

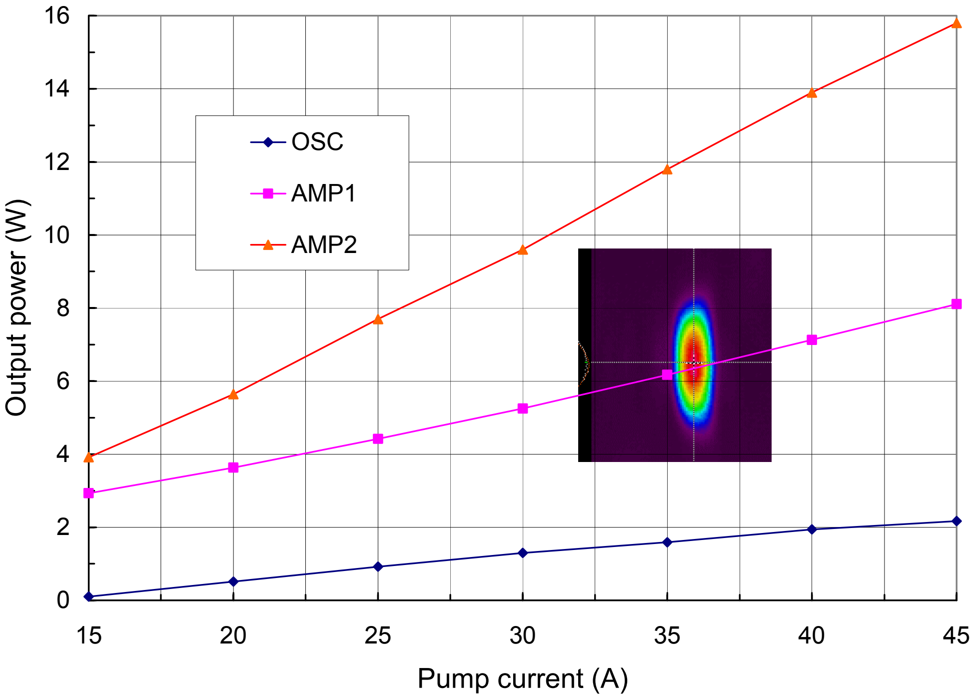

Figure 5. MOPA system output pulse energy as a function of current amplitude at quasi-cw pumping with a 1 kHz repetition rate. Also shown is the output beam profile.

3. Tandem OPO

The optical layout of tandem OPO is presented on Fig. 6. The first stage of the tandem OPO system, an angle-tuned, KTA-crystal-based OPO, converts the output of the Nd:YLF MOPA into tunable energy in the 1.5-1.7- and 2.8-3.5-µm wavelength regions.

The choice of KTA crystal was made for the following reason: although KTA and KTP crystals have similar characteristics in term of damage threshold and nonlinearity, KTA has a much lower absorption loss than KTP at the OPO idler wavelength. In order to obtain the spectral interval from 2.8 to 3.5 µm one needs to, according to the angle tuning curves plotted in Fig.7, provide beam propagation angles in a KTA crystal within a range of θ from 60 degrees to 90 degrees and employ both X (φ=0 degree) and Y (φ=90 degrees) cut crystals. To achieve this goal we designed the KTA OPO resonator as a concentric cavity, consisting of two concave spherical mirrors of equal radii of curvature. This cavity allows parametric oscillation to occur with a variable direction of the pump beam. Different angles of parametric oscillation in the KTA crystals correspond to different signal and idler wavelengths. Thus, by rapidly changing direction of the pump beam, we can achieve rapid wavelength tuning of the KTA OPO. The pump beam angle scanning is accomplished using the AOBD and magnifying telescope to increase the scanning angle. The following parameters needed to be achieved to apply such design to DIAL: for 100 nm tuning around a wavelength of 10 µm (ON/OFF wavelength excursion) one needs to have approximately 13-nm tuning of the output of KTA OPO at the wavelength of 3.44 µm. This corresponds to angular sweep of 7.3 degree between θ1 (90 degrees) and θ2 (85.9 degrees) of the pump beam.

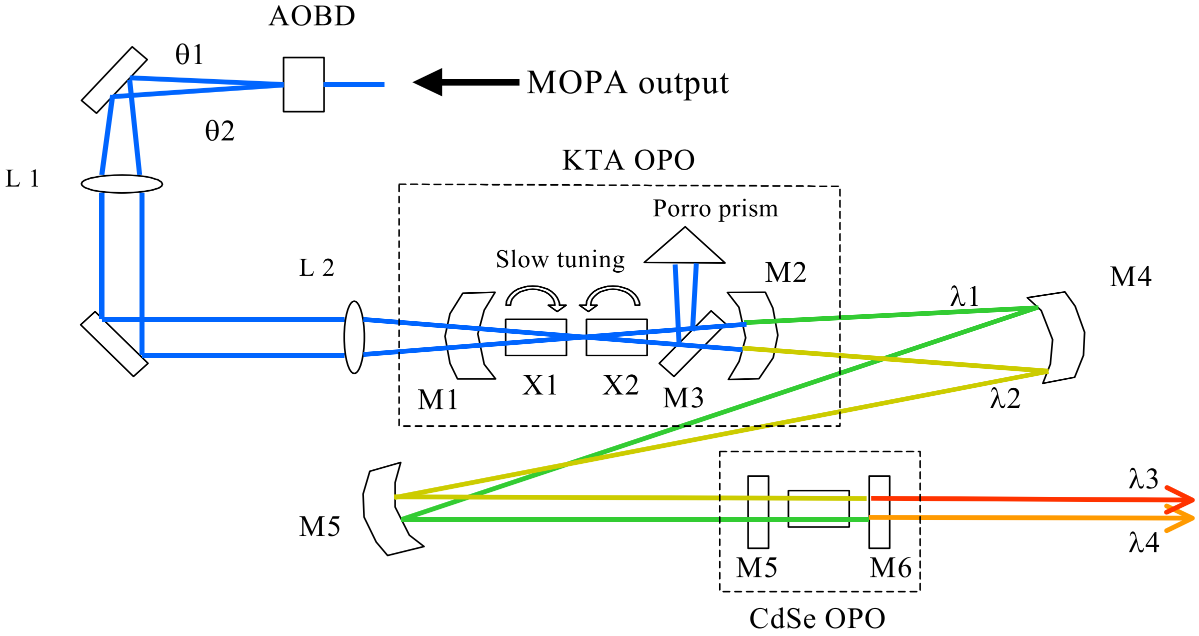

Figure 6. Optical layout of tandem OPO.

Lenses L1-2 (see Fig. 6) are the magnifying telescope for the angular scanning setup. The input mirror of the KTA OPO cavity, M1, has a radius of curvature (ROC) of 50 mm, and is HR-coated at 1500 nm and AR-coated at 1047 nm. The output coupler, M2, has ROC of 50 mm and R=70% at 1500 nm. The resonator contains two KTA crystals to obtain high gain. The beamsplitter, M3, is placed inside the cavity at 45 degrees to reflect the pump beam out of the resonator. A Porro prism is used to reflect the pump beam back into the resonator for double-passing through the crystals. Both crystals are mounted on individual computer-controlled rotary stages to allow slow wavelength tuning over an extended tuning range. Rapid angular tuning is achieved by synchronization of each individual laser pulse coming out of MOPA with RF pulse provided by the AOBD driver. Specially developed software allows the system to operate in a burst mode where the desired number of pairs of pulses can be generated over a certain period of time. Each individual pulse can then be synchronized with the acquisition system to facilitate data collection and analysis.

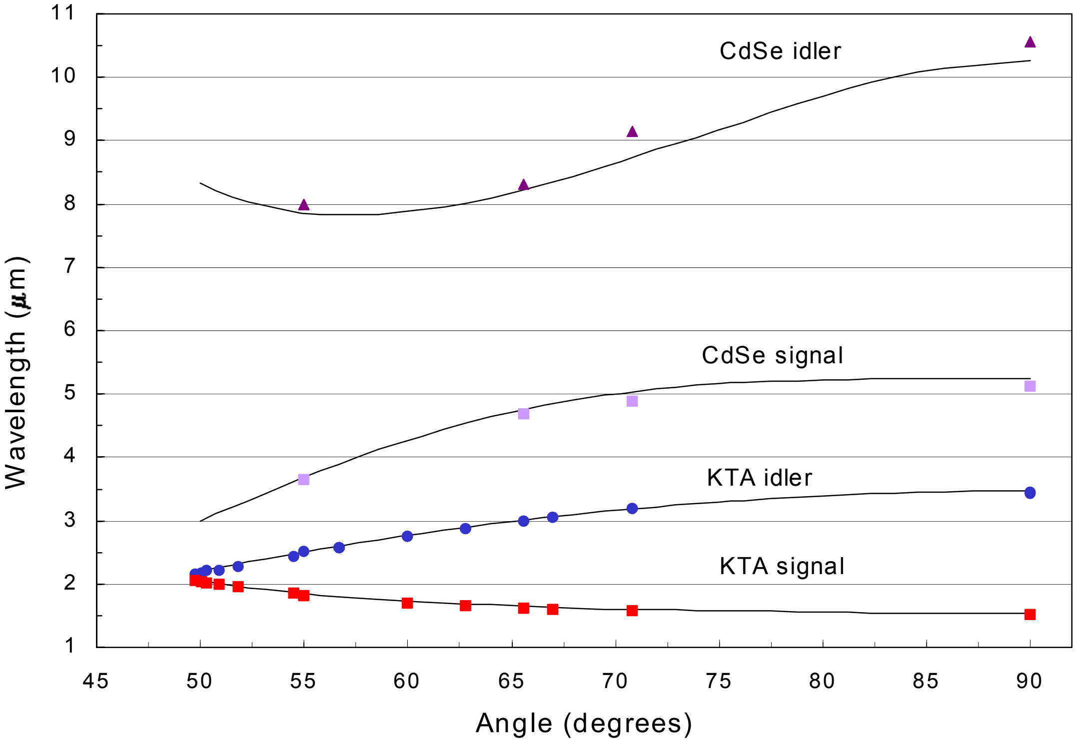

Figure 7. Calculated angle-tuning curves for KTA OPO and CdSe OPO.

Fig. 8 represents the result of angular tuning of the KTA OPO. We limited the pump power for this experiment by 6.5 W. A change in the RF from 27 MHz to 45 MHz corresponds to an angular deviation of the pump beam of 5 degrees (2.8 degrees inside the crystal). The KTA crystals were placed at the NCPM position (θ=90 degrees). The variation of the output power observed can be explained by a variation in the diffraction efficiency of the AOBD. The wavelength measurements showed that in this case the wavelength was switched by approximately 1 nm, which corresponds to the calculated value.

The second stage of the tandem OPO uses a CdSe crystal pumped by the idler output of the KTA OPO. As shown in Fig. 6, two concave mirrors (M4 with ROC=200mm and M5 with ROC=100 mm) are used for pumping the CdSe OPO. This allows us to easily adjust the pump size and also to deliver more power into the crystal than with the use of transmitting focusing optics. For the CdSe OPO we used a crystal and optics purchased from Cleveland Crystals Inc. The crystal is cut for type II NCPM and 35-mm in length, with a 5x5 mm cross-section and AR coatings for the signal and idler wavelengths. The OPO cavity is a simple, two-flat mirror design, singly-resonant for the signal. The input mirror is highly transmitting within the range from 3.2 to 3.6 µm and highly reflecting within the 4.7-5.3-µm range. The output mirror is highly reflecting for the pump wavelengths and coated for ~80% reflectivity within the signal wavelength range and high transmission within the 8 - 11 µm range. Both mirrors were deposited on ZnSe substrates.

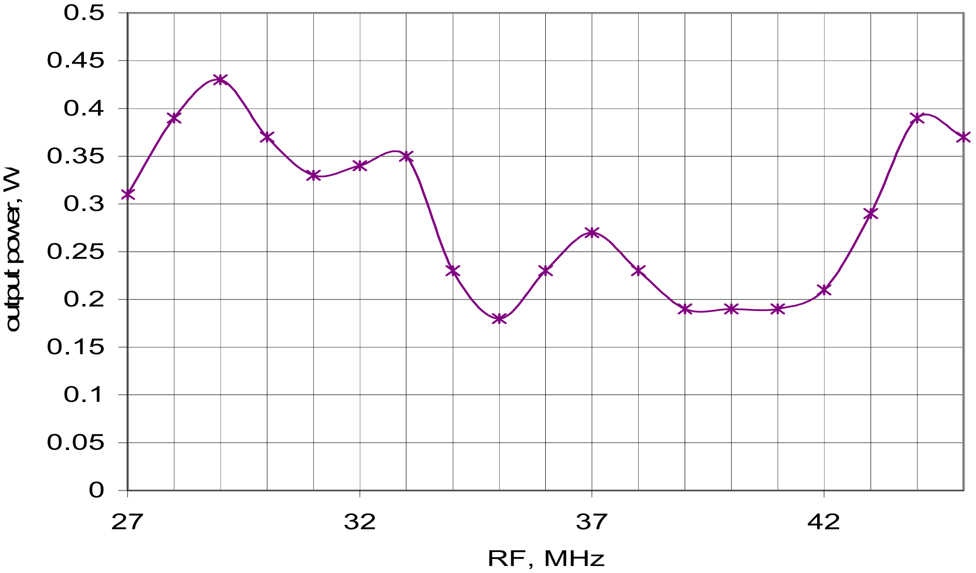

Figure 8. Output power of the angular tuned KTA OPO.

Fig. 9 is a plot of the CdSe OPO total output versus pump power. The maximum total pulse energy generated so far is 290 µJ for 1.45-mJ of pump energy at 3.45 µm, which corresponds to 20% efficiency . Using a long pass filter we measured 96 µJ of pulse energy at 10 µm. This result was obtained with AOBD operating at a constant deflection angle with highest diffraction efficiency. Currently we are working on getting efficient performance of the tandem OPO over the full scanning angle of AOBD.

In conclusion we have demonstrated a compact long-wavelength infrared (LWIR) source, based on the combination of a high-pulse-rate, 1-μm-wavelength solid-state laser with rapid and broadly tunable tandem optical parametric oscillators (OPOs). The latter deliver nanosecond pulses with up to 100 μJ energy, tunable within the 8-11 μm LWIR range.

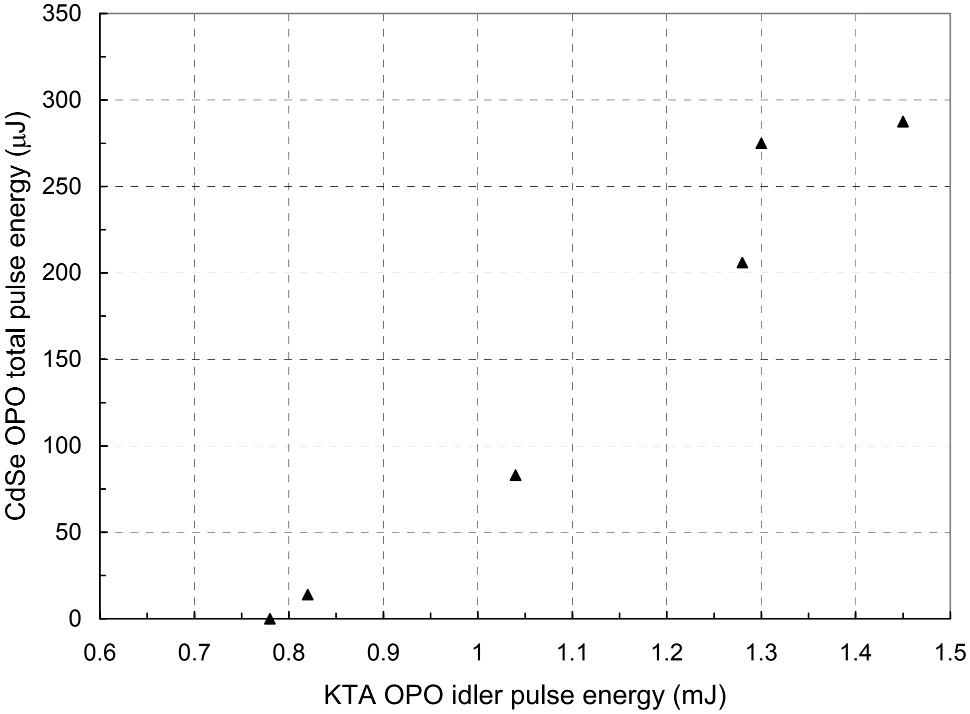

Figure 9. CdSe OPO total output pulse energy as a function of pump pulse energy.