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Efficient, High-Power Mid-Infrared Laser for National Securityand Scientific Applications

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FINAL REPORT

Efficient, High-Power Mid-Infrared Laser for National Security and Scientific Applications

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Abstract

The LLNL fiber laser group developed a unique short-wave-infrared, high-pulse energy, high-average-power fiber based laser. This unique laser source has been used in combination with a nonlinear frequency converter to generate wavelengths, useful for remote sensing and other applications in the mid-wave infrared (MWIR). Sources with high average power and high efficiency in this MWIR wavelength region are not yet available with the size, weight, and power requirements or energy efficiency necessary for future deployment. The LLNL developed Fiber Laser Pulsed Source (FiLPS) design was adapted to Erbium doped silica fibers for 1.55 μm pumping of Cadmium Silicon Phosphide (CSP). We have demonstrated, for the first time optical parametric amplification of 2.4 μm light via difference frequency generation using CSP with an Erbium doped fiber source. In addition, for efficiency comparison purposes, we also demonstrated direct optical parametric generation (OPG) as well as optical parametric oscillation (OPO).

Background and Research Objectives

Short-wave infrared (2-3 μm) and mid-wave-infrared sources (3-5 μm) currently enable the remote detection and quantification of sub-parts-per-million detection of gaseous species such as methane (CH_4). Long-wave infrared sources (8-11 μm) have shown potential for standoff detection and identification of microgram (a literal fingerprint) quantities of explosive solid residue (TNT, PETN, TATP, etc.) (Fuchs et al. 2010). Pulsed coherent light in mid-infrared atmospheric transmission windows is currently generated through the use of either (1) a traditional architecture based on a crystalline laser host (Nd:YAG) pumping a nonlinear optical parametric oscillator (PPLN) (limited in overall efficiency) or (2) through the direct use of quasi-continuous wave sources such as quantum cascade lasers (QCL), a device with limited power scalability (Yao et al. 2012). In pursuit of improving deployable sensing systems capable of both high efficiency (>20%) and standoff detection (> 1 km), the goal of this project was to demonstrate the utility of a *fiber-based* laser source which is the simplest, most efficient and most power scalable architecture available. The pulsed fiber laser technology would likely be more robust than competing solid-state solutions (Tm:YAG, Er:YAG, Cr:ZnSe, Fe:ZnSe). Such an improvement in efficiency and peak power (leading to long detection distances) would enhance the utility of remote sensing systems.

In this work we developed a high-efficiency, frequency-agile pulsed source using LLNL's fiber-laser pulse source (FiLPS) architecture and parametric converters for a long-pulse (nanosecond) laser at wavelengths ranging from 2 to 7 microns, in addition to a short-pulse (femtosecond) laser at these wavelengths. We proposed to do so by enhancing an existing LLNL fiber laser system to higher energy, average power, and repetition rate and subsequently demonstrating parametric frequency conversion in solid-state candidate materials with desirable optical properties for mid-infrared generation.

We successfully assembled and demonstrated the potential of the fiber-based Raman source in the long-pulse regime. We scaled up the system to 1.7 mJ of pulse energy and 36 W of average power, exceeding our proposed goals of 1 mJ pulse energy and 20 W average power. Finally, in collaboration with our partners at BAE Systems and Air Force Research Labs Materials Directorate, this new source was successfully used to demonstrate parametric gain in Cadmium Silicon Phosphide (CSP), a new candidate crystal for mid-infrared generation.

Scientific Approach and Accomplishments

The LLNL fiber-based Raman source was adapted to 1.55 micron range by employing Erbium doped gain fiber. The pulsed nature of this source, >1 MW peak power and average power scalability makes this source attractive for nonlinear conversion. Cadmium Silicon Phosphide (CSP), a nonlinear optical crystal that is low-loss in a broad range spanning the mid-infrared (0.7 to 8 microns) was provided in a collaboration with BAE Systems. The subsequent demonstration of seeded amplification of a 2.4 μm diode laser source, a representative wavelength for mid-infrared generation, demonstrates the feasibility of a fiber-based alternative to competing solid-state systems.

In FY16 we (1) demonstrated the activation of an all-fiber-laser-based system operating in the shortwave infrared with an energy-scalable architecture; (2) demonstrated narrowband and tunable seeding in the short-wave infrared, without the need for galvanometers or other motion based tuning systems; (3) and conceptually developed a potentially high-efficiency parametric conversion scheme based on the characteristics of our all-fiber-laser-based system. Finally, we demonstrated 1.7 mJ of pulse energy and 36 W of average power at a high repetition rate of 25 kHz.

In FY17 we (1) demonstrated the pulse-width and repetition rate versatility high energy FiLPs source (0.5 – 1.5 ns; 1kHz – 25 kHz at constant energy 1.7 mJ); (2) demonstrated nonlinear conversion via optical parametric amplification of light at 2.4 microns which agreed with a modeling-based expected gain; (3) developed understanding of CSP mid-infrared frequency conversion performance in optical parametric amplification, generation and oscillation configurations.

Our collaborators supplied two crystals of CSP, dimensions were 5.3 mm x 5.7 mm x 16.7 mm and. Antireflective coatings were added to these crystals to transmit light at 1553, 2400 and 4400 nm with the lowest loss possible. Losses of <1% were achieved at all three wavelengths. Figure 1(a) shows a picture of the optical parametric amplifier (OPA). A continuous wave (CW) 2400 nm seed (Brolis) is aligned into the crystal to be collinear with the pump. The output of the OPA is separated from the pump at a dichroic reflector (high reflection at 2400 nm and 4400 nm with high transmission at 1550 nm, 45° angle of incidence, Twinstar) and the signal pulse is measured at a photodetector that is sensitive to wavelengths as long as 2.8 microns (Thorlabs DET050). The pulse energy is measured here as the integral of the detector response over 17.5 ns while the true signal pulse is expected to be closer to the duration of the pump pulse of about 1.3 ns, due to the limited bandwidth of MWIR photodiodes. Comparison of pulse energy measured at 2400 nm to the CW seed power in the duration of the pump pulse is taken to be the OPA gain.

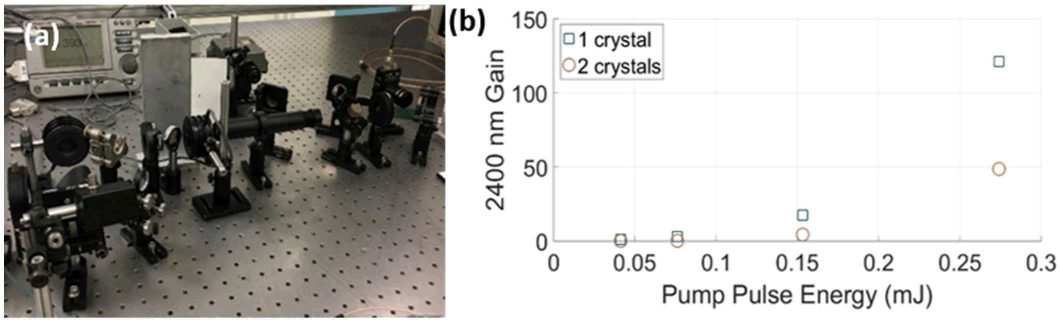

Figure1: (a) Picture of the optical parametric amplifier setup (b) Gain measured from the parametric amplifier for a single crystal and for two crystals.

In an effort to generate as much gain as possible as a starting point, we placed both available crystals in the beam path. This resulted in a dual crystal gain of 49x for 0.274 mJ of pump energy. The best performance of the OPA with two crystals is less than the gain obtained using only one crystal. Removing the second crystal and tuning the crystal orientation axis of only the first crystal into an alternative alignment resulted in a gain of 121x at a pump pulse energy of 0.27 mJ. This is due to the fact that pump exits the first crystal with some displacement from its original path and a displacement, due to walkoff, from the signal beam. The interaction length for two crystals is basically no better than for that of a single crystal. The gain is exponential and does not show saturation. Pumping power for this measurement was well below the maximum available power to maintain pump fluence below the damage threshold. An expansion of the pump beam size would allow for more pumping power to utilized. We also characterized the transmission of the CSP crystal itself, which exhibits lower absorption the $ZnGeP_2$, and appears to have a substantially higher damage threshold than other materials such as $AgGaS_2$.

In an OPO configuration, a single crystal was placed in an oscillation cavity. The oscillation cavity serves to provide feedback of the amplified signal back into the gain medium so that it can further interact with the pump resulting in increased frequency conversion. Mirrors (high reflection at 2400 nm with high transmission at 1550 nm, normal incidence, Twinstar) were placed as close as possible to the gain crystal to maximize the duration of the interaction. The cavity length is 4 cm +/-0.1 cm. When a pump pulse enters the crystal, signal and idler are immediately generated. At the end of the cavity, the pump pulse exits while some fraction of the signal pulse gets reflected back into the cavity. At 1.3 ns in duration, the pump pulse occupies about 39 cm in space. Taking the refractive index of the material portion of the cavity to be 2.2, the corresponding single-pass cavity length is 5.9 cm. The reflected signal can only make fewer than 3 trips around the cavity before the pump is no longer in the cavity and the amplification process dies out. The additional gain from signal feedback is limited by the small number of interactive roundtrips and walkoff of pump and signal beams so the single-pass gain is the dominant contribution to the OPO performance. One way to address this inefficiency is to directly coat reflective surfaces onto the crystal end faces. This represents the shortest possible cavity and thus the longest pump interaction for a non-synchronously pumped OPO. As an alternative, a synchronously pumped configuration arranges the cavity length to be such that the signal round trip time matches the repetition rate of the pump. This is not feasible for a source with kHz repletion rate as the cavity would have to be kilometers in length. However, this would be feasible if CSP were utilized in a traditional mode-locked cavity architecture operating near 100 MHz. Figure 2 (a) shows the beam profile for the OPO output with both sidebands. Figure 2 (b) shows the OPO output power as a function of pumping power demonstrating a slope efficiency of 10%. The pump depletion shows that over 50% of the pump is depleted by the conversion combined with the crystal losses at the pump wavelength.

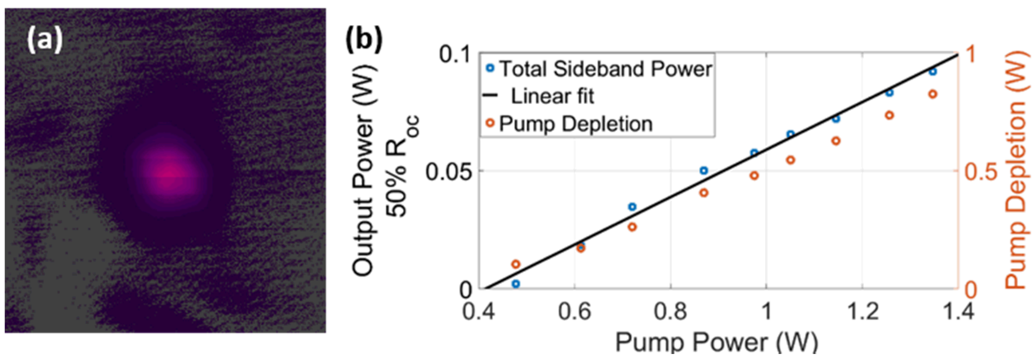

Figure 2: (a) Picture of the combined 2.4 and 4.4 micron sideband output of the OPO (b) Left axis: plot of total OPO output power as a function of pump power, linear fit shows a slope efficiency of 10%. Right axis: plot of pump depletion as a function of OPO pumping.

Impact on Mission

This research project supports the development of new efficient, scalable, pulsed-laser technology, which increase the Laboratory's core competency in lasers, optical science, and mid and long wave infrared technology and techniques. Long-pulse applications include active remote sensing, infrared countermeasures, and remote sensing exploitation. Short-pulse applications include high harmonic generation, pump–probe experiments, and sources for high-energy-density science. This advancement in laser development also supports the Laboratory's cyber security, space, and intelligence focus area with technology relevant to remote sensing. Finally, in keeping with the long-term workforce development goals this project has supported and been managed by a recent postdoctoral graduate.

Conclusion

We have demonstrated a high average power (36 W), scalable, temporally agile (0.5 – 2 ns), erbium doped fiber pump source. The architecture we developed can operate at 1 micron (Yb:silica), 1.55 micron (Er:silica), and 2 micron (Tm:silica). We have demonstrated the first amplification at 2.4 micron (and 4.4 micron) using a pulsed, 1.7 mJ, 1.3 ns output from a 1.55 micron fiber source. Optical parametric amplification performance, characterization, and comparison with direct optical parametric generation as well as optical parametric oscillation will result in at least two publications.

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Bonus picture