Compact, High-Energy, Mid-Infrared Pulsed Parametric Source for High-Resolution Gas Sensing and Ablation

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1. Introduction

Portable mid-infrared remote sensing systems and some infrared tissue ablation applications have been inhibited by a lack of suitable laser sources. Distributed feedback (DFB) and external-cavity diode lasers offer narrow linewidths up to about 3 μm[1], but lack the peak power for ablation or single-pulse remote sensing. Lead-Salt Diode Lasers, and semiconductor lasers, such as heterojunction laser diodes and antimonide quantum well laser diodes can cover small windows of the mid-IR; however, they require cryogenic cooling and offer only meager peak powers.[1] Several powerful solid state lasers (primarily those based on rare-earth ions, etc.) can operate in limited bands in the mid-IR, but often lack the required wavelength, the spectral purity for high-resolution spectroscopy, the high peak power for ablation applications, the low cost for widespread integration, and/or the compact size for hand-held operation or unmanned aerial vehicle applications.[1]

One important application for such an optical source is remote sensing of carbon dioxide (CO_2). In 2007, the U.S. Supreme Court ruled that carbon dioxide (CO_2) is a pollutant under the federal Clean Air Act. The ruling allows the EPA to regulate CO_2 emissions from a wide variety of pollution sources including automobile exhaust systems, industrial emission sources, and carbon sequestration sites. With presently available technologies, EPA personnel need to perform on-site scans of possible pollution locations by tediously sampling emitted gases with point-source gas-intake measurement devices. This makes it difficult or impossible for EPA personnel to identify or quantify critical CO_2 pollution sources such as many smokestacks/vents or unknown leaks in large search areas such as carbon sequestration sites. No technology currently exists that can remotely measure and pinpoint (to within a few meters) the location of elevated CO_2 concentrations. The presence of attractive CO_2 molecular absorption features near 2.0 μm allows for the development of such a remote sensor. However, compact, high-energy, narrowband, affordable pulsed lasers do not exist at 2.0 μm.

2. Body of Paper

To address these needs, Bridger Photonics, Inc. (Bridger) has developed an optical parametric source that can emit high-energy pulses in a compact package anywhere from approximately 1.4 μm to about 5.0 μm. In this work, we characterize the source's output and demonstrate detection of CO_2 in a gas cell.

Our system is an optical parametric generator that can be seeded to achieve narrowband emission for spectroscopic applications. We use a diode-pumped Nd:YAG laser as the pump source, which emits greater than 8 mJ at 1.06 μm in a single longitudinal and nearly single spatial mode at greater than a 10 Hz pulse repetition frequency (20 Hz demonstrated). We focus pulses from this laser into a parametric generation crystal with a poling period designed for the desired emission wavelength.

Figure 1 shows the output pulse energy at the signal wavelength (1.5 μm for this case) as a function of the input pulse energy at the pump wavelength (1.06 μm). For this data, we used a low-pass spectral filter to block the idler emission. The figure shows that we achieve a peak output pulse energy of 2.6 mJ at this wavelength. Conservation of energy in the parametric process requires that longer wavelengths yield lower output energy. However, we have demonstrated greater than 1 mJ for wavelengths as high as 3.5 μm (idler) and predict we can do so up to about 5 μm (idler). For larger input energies, we began to observe crystal damage. The output pulse durations that we have observed across different wavelengths have been consistently below 10 ns and as low as 5 ns.

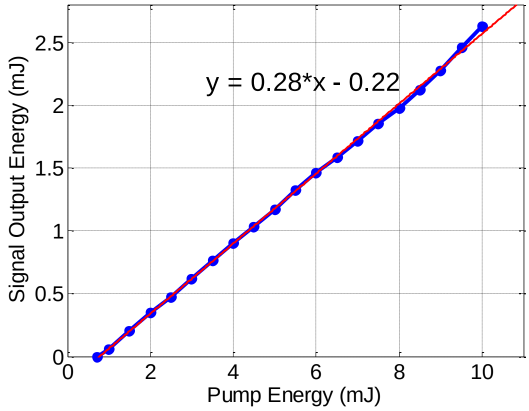

Figure 1. Output signal pulse energy as a function of input pump pulse energy for a 35-mm PPCLN crystal.

An important characteristic for many applications is the spatial beam profile. We used a pyroelectric camera to image the output beam at the idler wavelength (this time at 3.2 μm). Figure 2 shows the results for the unfocused (top) and focused (bottom) pulses. The beam quality is sufficient to allow focusing to a spot diameter (FWHM) of 160 μm with a 50 mm lens. This indicates a beam quality M^2 parameter of less than 2. This feature of the system is important for nonlinear applications such as ablation that rely heavily on the energy density.

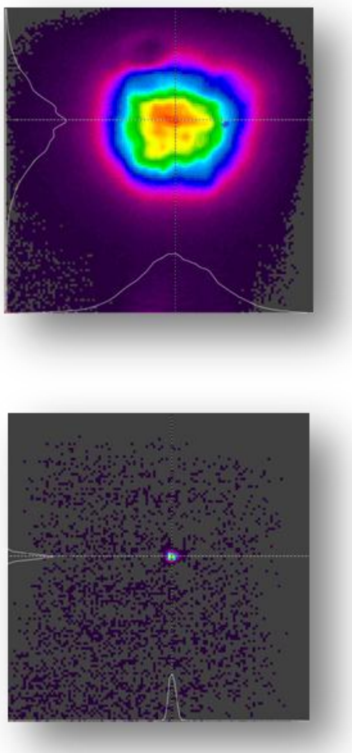

Figure 2. Top: Unfocused output from our parametric source at the idler wavelength. Bottom: The same beam after focusing with a 50 mm lens to obtain a beam diameter (FWHM) of 160 μm. This is within a factor of 2 of the diffraction limit.

Another important characteristic is the pulse-to-pulse fluctuations, and long term pulse stability. Figure 3 shows the excellent pulse stability that we can achieve with this system. The figure shows that we can achieve relatively long-term operation (greater than 0.5 hours shown and greater than 2 hours demonstrated) with pulse-to-pulse fluctuations (standard deviation) of 0.34% of the mean pulse energy level, and no pulses greater than +/- 5% of the mean pulse energy level.

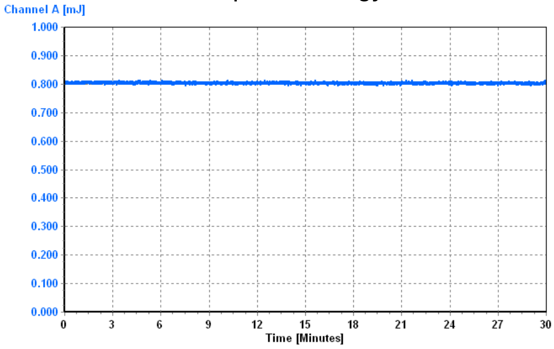

Figure 3. Pulse energy as a function of time. The fluctuations were 0.34% of the mean pulse energy.

Portability is also important for a number of applications including hand-held remote sensing. Figure 4 shows our preliminary form factor for the laser with a package size of 3.75" × 7" × 8", and a total weight of less than 10 pounds. However, we anticipate being able to reduce this by a factor of four in volume for future revisions to enable truly hand-held operation.

Figure 4. Bridger's preliminary MIR laser system form factor.

Although our source currently emits in a relatively broad (1-2 nm) bandwidth, we have also investigated seeding for spectroscopic applications. We have shown that seeding with a DFB diode laser narrows the emission spectrum to less than 1 GHz for 70% to 98% of the output light, depending on pump energy, seed power, and wavelength. Moreover, because our pump laser is single longitudinal mode, the high spectral purity of the seed laser at the signal wavelength is also transferred to the idler output further in the infrared. To demonstrate the utility of our seeded source for gas sensing, we constructed a system operating narrowband at 2.0 μm (signal) for CO_2 gas detection. We passed the narrrowband output through a gas cell, spectrally filtered it from undesired residual emission using a diffraction grating, and measured the light in the narrowband mode. We then tuned the narrowband pulsed emission across several CO_2 transitions by temperature tuning the seed laser. Figure 5 (red circles) shows the normalized measured pulse energy in the narrowband mode with respect to the emission wavelength. For reference, we also show an overlay of the theoretical transmission (blue line) obtained from the HITRAN database using the estimated concentration and pressure inside of our gas cell. We identified the spectral lines over which we were tuning based on comparing the manufacturer-supplied data for the DFB laser seed laser to the HITRAN database. We then qualitatively matched our spectra to that of the HITRAN database.

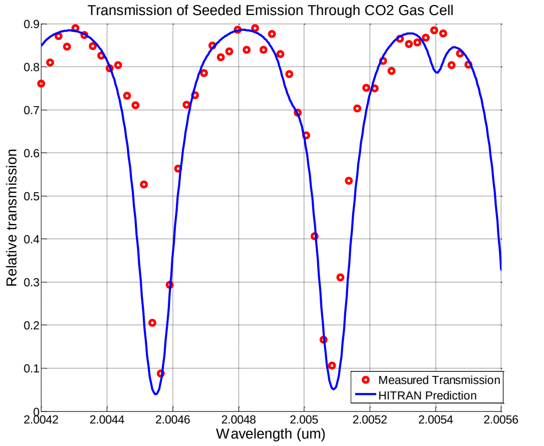

Figure 5. Relative transmitted pulse energy as a function of wavlength.

3. Conclusion

We have designed and constructed a compact mid-infrared parametric source for applications ranging from tissue ablation to remote gas sensing. For our preliminary demonstrations, we measured several CO_2 lines in the 2-micron manifold. Our future work will focus on performing precise long-range integrated column measurements of atmospheric CO_2 concentrations, and range-resolved atmospheric measurements, and further reducing the size of our system to promote hand-held and UAV applications.

4. Acknowledgements

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5. References

[1] I.T. Sorokina, and K.L. Vodopyanov, (Eds.), *Solid-State Mid-Infrared Laser Sources*, Springer Topics Appl. Phys. **89** (2003).