Tunable infrared radiation for atmospheric profiling

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Abstract. An optical parametric amplifier has been developed to generate tunable 1570 nm radiation from a 1064 nm pump at high efficiency. A micropulse Nd:YAG with two amplifiers generating an average power of 2 watts (10 kHz) is used to pump a periodically poled lithium niobate crystal injection seeded by two CW distributed feedback lasers: one at 1570.824 nm and the second at 1570.973 nm. A conversion efficiency of ~28% from the pump into the signal wavelength has been demonstrated. The 1-nanosecond signal has a measured time-averaged jitter of <0.3 pm.

Keywords: optical parametric amplifier, nonlinear optics.

1 INTRODUCTION

A tunable IR source capable of generating radiation from 1.1μm to 10.0μm is being developed jointly by NASA's Goddard Space Flight Center and JMAR Technologies in San Diego, California. This device, an optical parametric amplifier (OPA), will enable researchers to exploit opportunities for measuring small molecules of interest to both the earth and planetary science communities. A number of important atmospheric molecules have absorption features within this spectral region – these include CH_4, CO, CO_2, H_2O, HCO_3, NO_2 and O_3. Current opportunities within the earth sciences involve making range resolved measurements of CO_2 within the planetary boundary layer and integrated column measurements from a space based platform. These measurements will help identify and characterize terrestrial sinks for this important greenhouse gas that has been rapidly increasing due to anthropogenic activity. Approximately 30% of the anthropogenically generated CO_2 cannot be accounted for after the uptake by the oceans and atmosphere has been accounted for; locating these sinks will provide a better understanding of their long term behavior and hence, CO_2's future impact on long-term global climate. Measurement opportunities in the planetary sciences include locating and characterizing CH_4 sources on Mars from orbit at high resolution; because biological processes on earth produce CH_4 and because it has a short lifetime in the Martian atmosphere, ~300 years, there must exist sources on the surface to constantly replenish the lost atmospheric CH_4. These sources can arise from either biological or geological activity. The location of these sources and their characterization in terms flow rates and diurnal (and seasonal) behavior will help identify scientifically interesting landing sites for Martian rovers to make the much more precise measurements required to differentiae between geological and biological produced methane.

Current options for generating high average power within this wavelength region are few. The first option involves dye lasers; they have been used successfully on land, aircraft and balloon platforms but have a number of issues that would restrict their deployment in space. Flammable dye solvents and frequent dye/solvent changes rules out this approach for a space-based instrument. Another option involves Raman shifting the output of a solid state laser such as a Nd:YAG. This requires a fortuitous coincidence between the shifted wavelength

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and the absorbing specie of interest – greatly limiting this approaches flexibility. The requirement for a high-pressure gas cell in space would make this approach difficult to get through the space qualification process and presents numerous practical limitations. A third approach is to employ a CO_2 laser. These lasers generate high average power within the 9-10 micron region and have already been space qualified but possess limited utility because of their restricted wavelength range. They have been employed to measure ozone since they have a number of emission lines whose output is coincident with ozone absorption lines. They would not, however, be suitable for measuring CO_2 because of the absorption cross-section's temperature sensitivity within this band. A fourth option involves diode lasers. They emit within certain regions of this wavelength band but their low power makes them unsuitable for use in a space-based instrument. Solid state lasers such as Nd:YAGs, Nd:YLFs and Ho:Tm:YLFs are potential candidates for space based operations; they have high power but are restricted to very small wavelength regions near 1 and 2 microns respectively. The final approach uses fiber lasers. Both erbium and ytterbium fiber lasers have been space qualified and can operate over a wavelength of several hundred nanometers within a spectral region that makes them extremely useful for integrated path measurements of CO_2, O_2 and H_2O. However when used to generate short pulses (required for making range resolved measurements) they suffer from extremely low duty cycles and, as a consequence, are not efficient. Currently their average emitted power in pulsed operation is not generally high enough to be useful under a number of interesting measurement scenarios. Together these issues suggested that a solid state device capable of converting a high power pump source into short pulses at high average powers could make a significant contribution to active remote sensing in the IR.

2 INSTRUMENT

A strong potential candidate for generating tunable IR is the optical parametric amplifier (OPA), a simple solid-state device that converts a pump photon into two longer wavelength photons using a parametric process [1] – see figure 1.

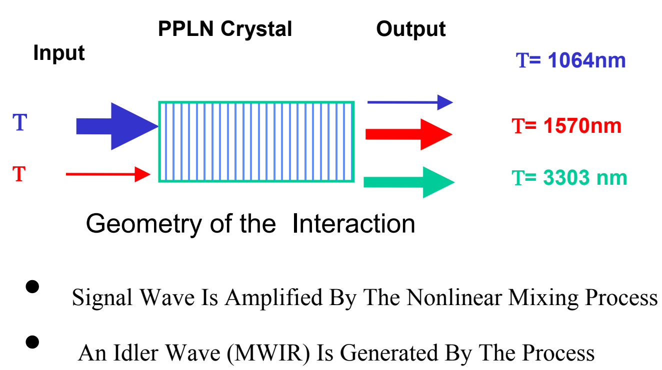

Fig. 1. The optical parametric amplifier is pumped by a Nd:YAG and seeded using the CW output of a distributed feedback laser at 1570.8235 nm. The idler is at 3.3µm.

OPAs have been studied for a number of years but because of the specific needs involved in making range resolved CO_2 measurements in the lower atmosphere a new effort was undertaken as part of NASA's Laser Risk Reduction Program. This approach was designed to enable an experimenter to leverage parallel efforts focused on developing efficient, high power, solid state light sources such as Nd:YAG, Nd:YLF and Ho:Tm:YLF lasers for the pump. All three pump lasers can generate signal wavelengths longer than their pump with high efficiencies. The OPA described in this paper has generated 1.57-micron radiation using a Nd:YAG pump with an efficiency of ~28%, efficiencies greater than 50% are believed possible. OPAs consist of several distinct components: an oscillator, a pump and a nonlinear crystal. The oscillator defines the pump wavelength, pulse width and beam quality. A small passively Q-switched microchip Nd: YAG from Northup-Grumman was employed for this instrument – see figure 2. It operates at a repetition rate of ~10 kHz with a per pulse energy of ~20 microjoules in a 1 nsec, single mode, pulse. The spatial beam quality is TEM_{00}.

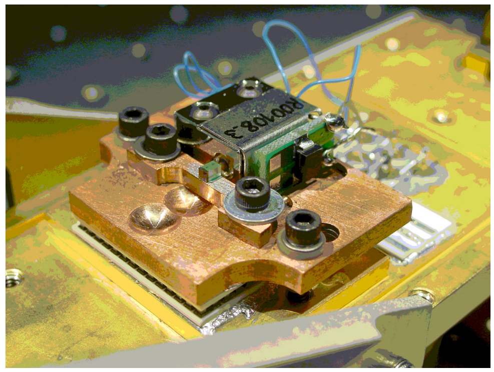

Fig. 2. The OPA's microchip Nd:YAG oscillator positioned on a cooling block. The 10-32 screws demonstrate the small size of the oscillator.

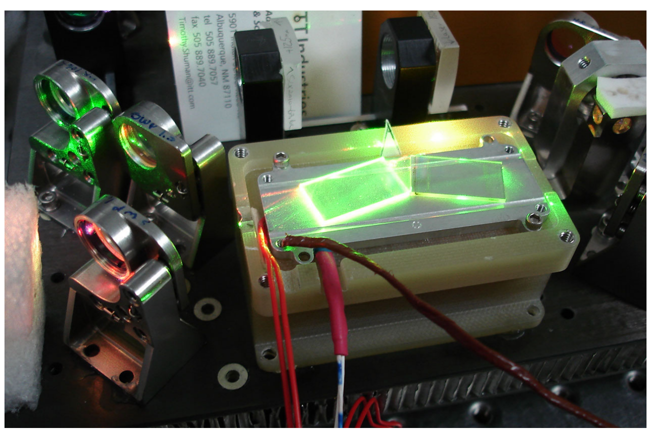

Fig. 3. Two PPLN nonlinear crystals undergoing testing at ITT.

The oscillator pulse is then amplified using two, single pass, diode pumped amplifiers to a total energy of ~180 microjoules/pulse. This pulse is injected into a crystal of periodically poled lithium niobate (PPLN) that is being seeded using a CW source at the desired signal wavelengths (one at 1570.8235 nm is strongly absorbed by CO_2, the second at 1570.9735 nm is not absorbed). Seeding is accomplished by using two DFB (distributed feedback) lasers, one for each wavelength. The seeder outputs are injected into the OPA sequentially to generate one and then the other wavelength at a rate of 10 kHz. The seed drives a parametric process that converts a pump photon at 1064 nm into two, longer wavelength, photons: the signal and an idler. For the current configuration the idler at approximately 3.3 microns is not used. To enhance the conversion from the pump at 1064 nm into the signal at 1570 nm the idler is rejected after each stage – this effectively inhibits back conversion into the pump by raising its threshold – Figure 3 and 4. The maximum theoretical conversion efficiency for the configuration shown in Fig. 4 is given in Fig. 5 with a peak value of ~50% for an effective crystal length of 45 mm.

To be useful as a light source for remote sensing the OPA's beam quality must be good in order to obtain and maintain good overlap between the outgoing laser beam and the telescope's field of view. The current system's output is TEM_{00} – Fig. 6. Range resolved measurements of CO_2 require a measurement precision of ~1 ppmv (parts per million volume; the current CO_2 mixing ratio is ~380 ppmv) to be able to locate and track CO_2 fluxes with sufficient resolution to identify terrestrial CO_2 sinks at a precision of several kilometers. To help achieve this precision, the uncertainty associated with the wavelength jitter has been constrained to be less than ~0.6 pm (this restricts the actual, time averaged, uncertainty in the absorption cross section to less than 1 part in 1000) which directly translates into a reduction in the CO_2 number density uncertainty. Jitter as employed here refers to how the peak

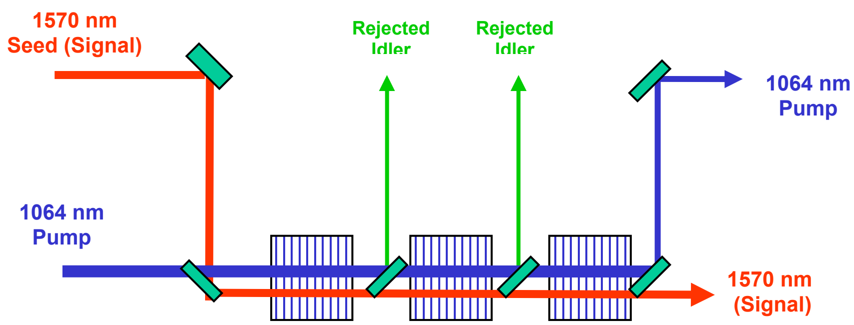

Fig. 4. The schematic clearly shows the approach used to generate high peak power pulses at 1570 nm. After each PPLN crystal the idler at 3.3 microns is rejected thereby inhibiting the back conversion of signal and idler into the pump.

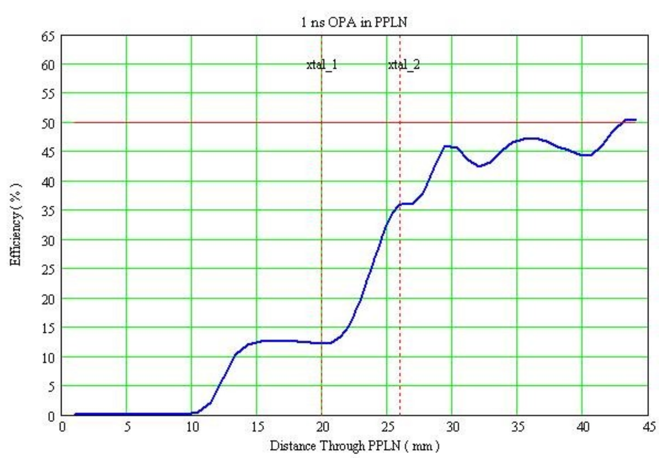

Fig 5. The conversion efficiency of PPLN crystal for a 1064 nm pump and 1570 nm signal.

wavelength changes on a shot by shot basis and is distinct from linewidth. Its origin is primarily due to small wavelength changes associated with the passively Q-switched micro chip Nd:YAG laser, these changes appear initially in the idler which then interacts with the 1064 pump to generate a shifted signal output.

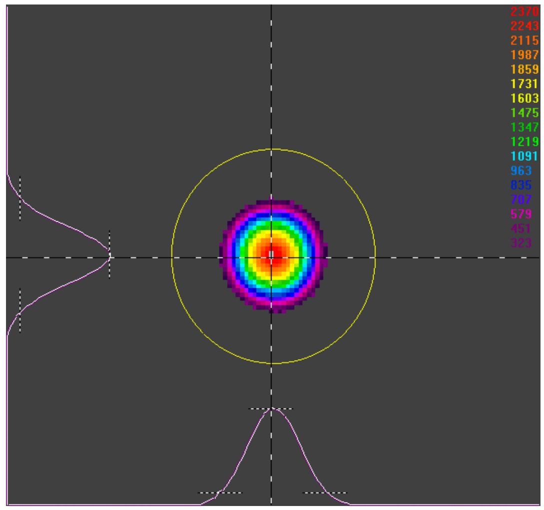

Fig. 6. Nd:YAG beam profile

A picture of the OPA's spectral stability is given in figure 7. Here a CH_4 line was scanned using the idler output near 3.3-microns, the scan displays virtually no jitter. The seeder in this case was a DFB laser operating at 1.57 microns – a much simpler process than trying to seed with 3.3 microns. The methane line is ~20 picometers wide and any jitter is less than 0.5 pm. The 3.3-micron line in methane was used rather than 1.57 microns in CO_2 because this particular OPA design was initially employed to detect chemicals and aerosols near 3 microns. It should be noted that any jitter in the 1064 nm pump, when the OPA is seeded at 1.57-microns, would appear in the 3.3 micron idler and not the 1.57 micron signal.

The long-term wavelength stability of the OPA has been measured under a number of conditions. Using a DFB laser with an output of ~30 milliwatts and a linewidth of ~0.02 pm for the seeder allowed the wavelength stability to be determined under a variety of conditions: 1570.8243 +/- 0.001 nm (the approximate resolution of the wavemeter) over a period of ~200 minutes – figure 8.

3 FUTURE DIRECTIONS

OPAs have a number of attributes that make them highly desirable light sources for remote sensing applications. Their all solid-state construction allows for a compact and rugged design. The ability to convert a high-powered pump source into tunable IR radiation at high efficiency makes them ideal candidates for an active space based mission. We intend to demonstrate the capabilities of this technology as part of an instrument designed to make range resolved measurements of CO_2 within the planetary boundary layer. The short pulse widths (~1 nsec) and high per pulse energies will facilitate the use of direct as opposed to coherent detection thereby reducing the cost and complexity of the instrument.

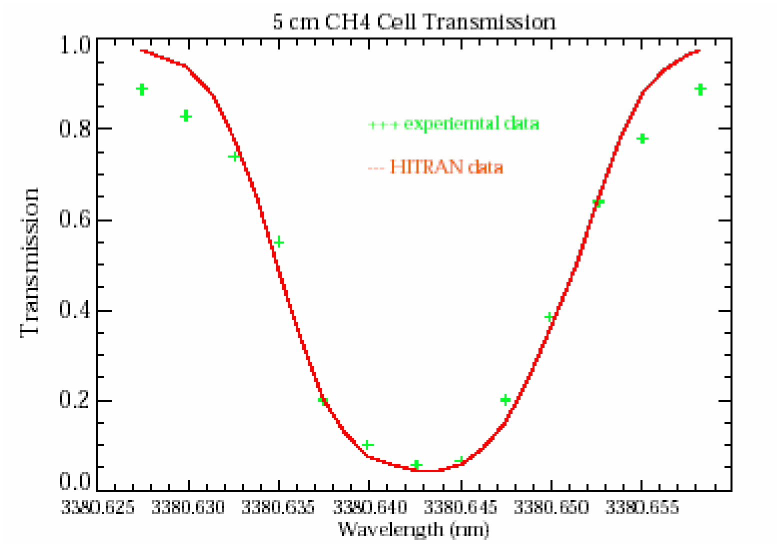

Fig. 7. The OPA's 3.3 μm output being scanned over a CH_4 line.

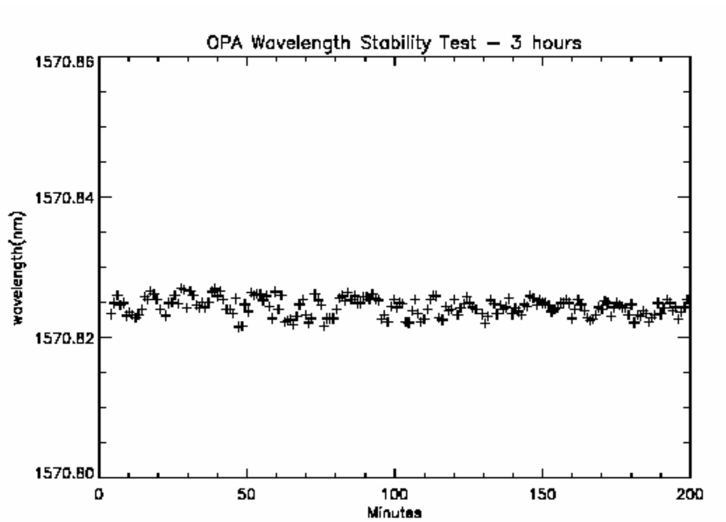

Fig. 8. Measurement of the OPA's wavelength stability over ~200 minutes.

For a space-based system, gating the detection system removes the impact of backscattered signals originating from optically thin clouds and aerosols on the data. The differential absorption lidar technique (DIAL) will be used to determine the CO_2 number density. Since both on and offline channels are separated by only 0.15 nm, differential extinction originating with optical thin clouds, high altitude subvisible cirrus and aerosols will not impact the measurement.

Because of thermal issues observed with the small microchip oscillator its replacement will be a high priority. These issues have impacted the OPA's long-term alignment stability and efficiency and have the potential to create beam quality issues. Space operations would utilize the high average power Nd:YAG lasers being developed under the Laser Risk Reduction Program – these are currently envisioned to emit approximately 1 Joule per pulse at a repetition rate of 100 Hz. Ground based operations within the boundary layer and lower free troposphere benefit from high repetition rates that help minimize the impact from atmospheric motion. For deployment from either a ground or aircraft platform a pumping source having ~1 millijoule/pulse at a repetition rate of 10 kHz would provide enough signal to reach the required measurement precision very rapidly. Indeed for a ground based instrument it should be possible to acquire data both within the boundary layer and extending into the free troposphere over ~1000 m at 150 m resolution within 1 minute (since the free troposphere is clean in comparison to the planetary boundary layer, returns fall off very rapidly with distance when using Rayleigh backscattering as the signal source). This would enhance the measurement capabilities of an instrument by allowing the study of transport processes across the boundary layer - free troposphere interface. Although PPLN is a satisfactory material for non-space applications, deployment in space would require a more robust material because of PPLN's susceptibility to damage at high pumping powers and its radiation sensitivity. A better choice for the nonlinear crystal would be KTP; it has a high damage threshold, excellent efficiency and is resistant to radiation damage. Its higher damage threshold will allow higher pumping powers and should result in conversion efficiencies similar to those for PPLN.

The light source demonstrated in this work opens up number of interesting opportunities for laser remote sensing. A source at ~3.3 microns (~1 mJ/p) would prove valuable in identifying sources of Martian CH_4 from orbit at extremely high resolution (methane in the Martian atmosphere has a lifetime of ~300 earth years thereby requiring a surface source to maintain a steady state value). This would be a first step in determining whether life has ever existed on Mars. Both biological and geological processes can produce methane and the ability to localize these sources on the surface would help identify suitable landing sites for a Mars rover type mission [2]. The rover would carry an in situ instrument (possibly a cavity ringdown spectrometer) capable of making the isotopic measurements necessary to characterize the origin of the observed CH_4. A small CH_4 plume with a mixing ratio of 10 ppmv and a thickness of 100 m could be easily identified from orbit at high precision. Repeated passes over the site would enable both the diurnal and seasonal behavior of the source to be determined. A number of interesting measurements would be possible for upcoming missions to the icy moons of Jupiter and Saturn. Maps of the surface at high resolution could identify cracks and temporary pools of liquid water therein and determine the crust's thickness by observing how tidal forces modify the local surface height. Maps of water vapor could locate the liquid sources for this gas. The complex chemistry of Titan recently studied by the Cassini mission could be explored in greater detail through measurements of hydrocarbons such as methane and ethane.

4 CONCLUSIONS

We have described the development of a tunable optical parametric amplifier suitable for laser remote sensing applications requiring high peak power in the IR. This device uses a small, diode pumped, passively Q-switched Nd:YAG laser as an oscillator whose output is boosted to ~180 microjoules per pulse in two amplifiers at a repetition rate of 10 kHz . Two DFB lasers are used as seeders for the OPA, one for the online absorption wavelength and the other for the offline wavelength. Both DFB lasers operate CW and are stable to ~ 0.02 pm. Periodically poled lithium niobate was chosen for the nonlinear crystal because of its good efficiency. The current OPA produces ~50 microjoules per pulse at 1570 nm for a conversion efficiency of ~28%. The maximum theoretical conversion efficiency is believed to be ~50%.

Acknowledgments

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