Efficient 1.6 Micron Laser Source for Methane DIAL

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ABSTRACT

Methane is a potent greenhouse gas and on a per molecule basis has a warming influence 72 times that of carbon dioxide over a 20 year horizon. Therefore, it is important to look at near term radiative effects due to methane to develop mitigation strategies to counteract global warming trends via ground and airborne based measurements systems. These systems require the development of a time-resolved DIAL capability using a narrow-line laser source allowing observation of atmospheric methane on local, regional and global scales. In this work, a demonstrated and efficient nonlinear conversion scheme meeting the performance requirements of a deployable methane DIAL system is presented. By combining a single frequency 1064 nm pump source and a seeded KTP OPO more than 5 mJ of 1.6 µm pulse energy is generated with conversion efficiencies in excess of 20%. Even without active cavity control instrument limited linewidths (50 pm) were achieved with an estimated spectral purity of ~95%. Tunable operation over 400 pm (limited by the tuning range of the seed laser) was also demonstrated. This source demonstrated the critical needs for a methane DIAL system motivating additional development of the technology.

Keywords: Optical parametric oscillator, lidar, frequency conversion, solid state laser

1. INTRODUCTION

Lidar remote sensing of atmospheric gases requires high-quality laser sources throughout the spectrum from the ultraviolet (UV) to the infrared (IR). Requirements for these sources include output power of several watts, tunability while maintaining narrow linewidth and high beam quality. Electrical efficiency is also essential for space or Unmanned Aerial Systems (UAS) deployment. On a recent Phase I SBIR program funded by NASA LaRC, Fibertek demonstrated a tunable nonlinear parametric converter for efficient one-micron lasers providing the wavelength near 1.645 µm required for DIAL measurements of methane. This successful proof of concept research motivated a Phase II proposal and subsequent award for an effort to deliver a DIAL transmitter for remote methane measurements with the goal of raising the technical readiness level (TRL) from 3 to 5.

There are several motivations to develop a methane DIAL lidar system. First, methane is cited as an important atmospheric variable by several panel reports in the National Research Council Decadal Survey (DS) [1]. Second, the plan for a climate-centric architecture by NASA recognizes the importance of CH_4 and discusses the potential for the gas sensing capability on the follow-on to OCO-2. Third, a U.S. Carbon Cycle Science Plan (CCSP), currently under development, recognizes the importance of CH_4. CCSP emphasizes the need of an integrated system to collect and maintain essential data that drive scientific understanding of the gas processes [2]. Finally, methane's strong infrared (IR) absorption makes it a potent greenhouse gas due to its per molecule warming influence being 72 times that of CO_2.

2. TECHNICAL APPROACH

The goal of the Phase I program was to demonstrate line narrowed OPO performance in the near-IR close to the R6 methane absorption feature at 1.645 µm. Figure 1 shows a 2008 HITRAN spectrum of methane in the atmosphere at 760 torr total pressure [3]. In the lower atmosphere, the major feature is pressure broadened so the at the two spectral lines merge into a single broad feature with ~ 0.1 nm linewidth. Operation off resonance near 1645.37 nm assures minimum interference with the reference line transmission from methane or other atmospheric trace species.

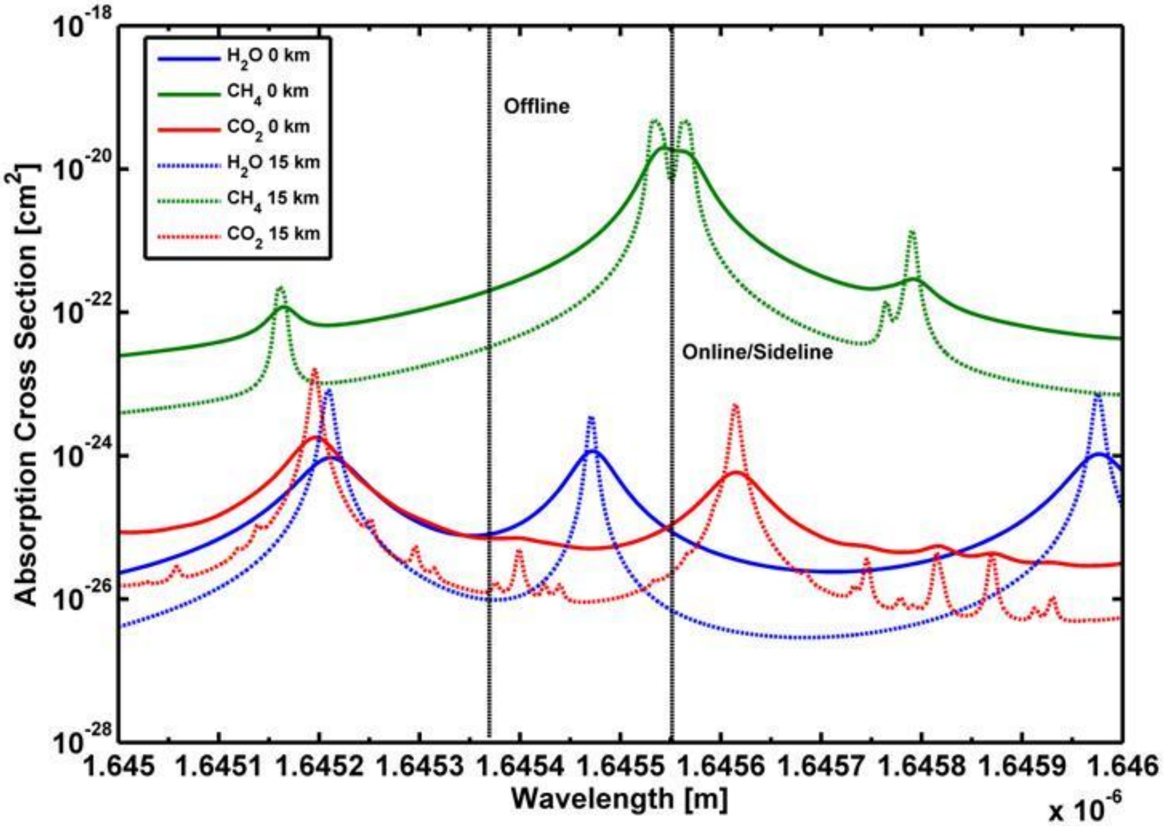

Figure 1: Methane absorption cross section compared to water vapor and CO_2 near 1.645 µm from HITRAN at a total pressure of 760 torr.

Fibertek selected an optical parametric oscillator (OPO) approach to generate the 1.6 µm output. Its higher efficiency and ability to power scale to high energies make it superior to an optical parametric amplifier (OPA) scheme. A unique aspect of this approach was the evaluation of a volume Bragg grating (VBG) output coupler to provide narrow line output sufficient for the off-line operation without other intracavity line-narrowing elements. The goal is to set the reflective band wide enough to provide feedback at both the on-line and off-line wavelengths. Off-line operation would be determined by the reflective properties of the VBG and on-line operation would occur when seeding which would have enough gain to resonate on the seed even though the wavelength is detuned from the VBG center wavelength.

Due to the complexity and cost associated with the electronics required to lock the OPO output to an external seed source, they were not implemented in the Phase I effort. Instead, single pulse measurements demonstrating seeded operation were made to validate this technical approach. The system built in Phase II will incorporate the necessary electronics and components to ensure reliable locking to a single frequency seed laser.

To summarize, the performance goals of the phase I effort were:

- OPO operation with tunability near 1.6455 µm
- Demonstrate seeded operation (not line locked) using fiber coupled distributed feedback laser
- Show spectral purity approaching 99%
- Achieve laser pulse energies between 1 and 5 mJ

3. OPO DEVELOPMENT

In this work we evaluated a two-step approach to frequency control and line narrowing. Gross control of the center wavelength of the tunable OPO would utilize a volume Bragg grating (VBG) as the OPO output coupler. These optics can be fabricated with a range of wavelength selective reflectivities and linewidths ranging from 0.1 to 1 nm. This optic ensures the laser output occurs in the spectral region of interest and allows for fine tuning of the output via temperature tuning the VBG (~0.015 nm/°C). For the precise frequency control required to operate the transmitter on and off resonance the OPO would be injection seeded. This approach is best implemented in a ring laser configuration with the ring cavity length feedback controlled to remain resonance with the seed laser. This feedback control was not implemented in this work.

Both approaches for linewidth control were successfully demonstrated. Figure 2 contains a schematic of the linear OPO used to demonstrate wavelength control using the VBG mirror. Injection locking of the OPO was demonstrated using a unidirectional ring OPO configuration, shown in Figure 3. Both OPOs utilized KTP. A pair of 20 mm crystals cut for phase matching at 1.645 µm was used in tandem for walk-off compensation in all of the OPO tests. KTP was selected for its availability on a short duration program. For all of these experiments the pump laser for the OPO was a Fibertek-developed single frequency (injection seeded and locked) Nd:YAG slab oscillator. It has heritage in the NASA ALHAT and HSRL transmitters developed for LaRC by Fibertek. This laser had an output of up to 50 mJ at a pulse repetition rate of 50 Hz. The laser pulse energy was limited to ~25 mJ in these experiments. An optical isolator was used to protect the pump laser from feedback from the OPO.

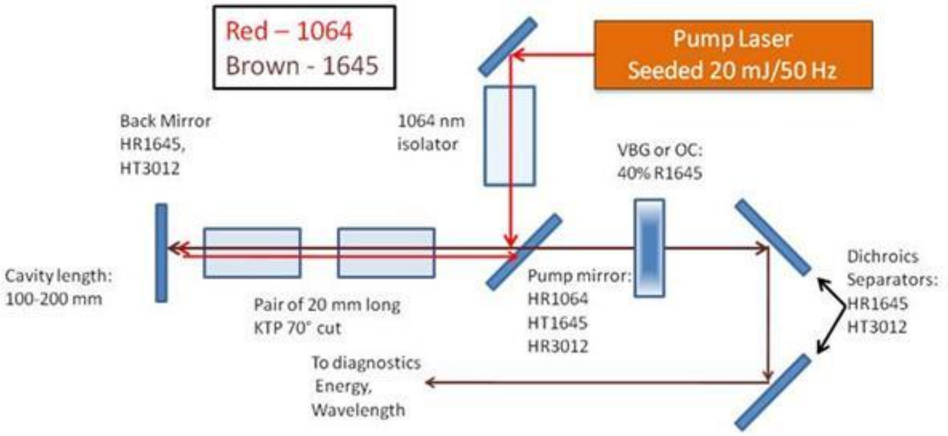

Figure 2: Schematic of the linear OPO configuration used to evaluate the line narrowing capabilities of volume Bragg grating output couplers. The VBG was sheltered from the intense pump light and idler frequency in order to avoid damage.

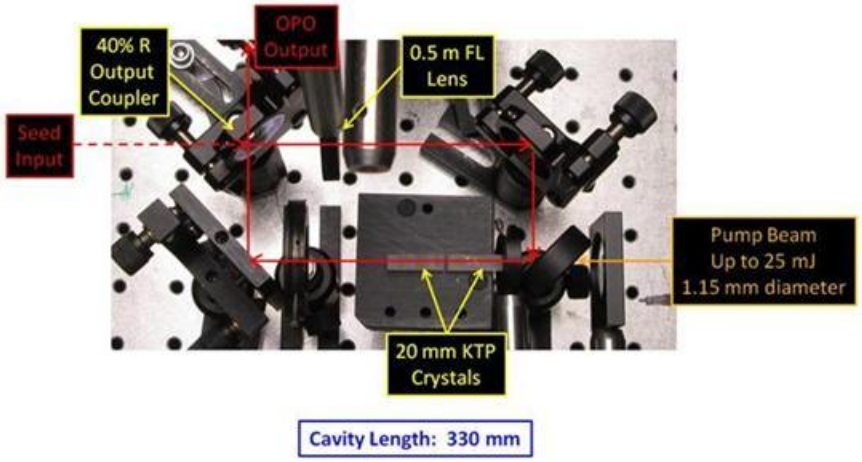

Figure 3: Ring OPO cavity used to demonstrate seeded operation.

The linear OPO used to test the VBGs had a conventional design (see Figure 2). The only critical need was to prevent the high intensity 1064 nm pump light and the 3 µm idler light from reaching the VBG optic to avoid damaging it. This was accomplished by introducing the pump into the OPO and through the crystals via a dichroic mirror. Once the resonator and crystals were aligned, OPO operation at 1.645 nm was readily achieved. With 20 mJ pump, more than 2.5 mJ output was obtained.

Figure 4 shows output spectra from the linear OPO using normal and VBG output coupling mirrors. The broadband output from the OPO without the use of a VBG has a linewidth of ~ 2.5 nm, determined by the acceptance bandwidth of the KTP crystals. Two VBG output couplers having bandwidths of 0.51 and 0.19 nm with a line center reflectivity of 40% were purchased from Opti-Grate. The results in Figure 4 show that the output linewidth from the OPO equaled the nominal linewidth of the VBG mirror installed (0.5 and 0.2 nm respectively). The narrowest VBG (0.19 nm) possessed barely enough spectral resolution to separate the on and off line wavelengths from the OPO, but in itself would not be sufficient for a reliable DIAL system. The results from this work demonstrate that a low cost DIAL system using VBG wavelength control could be developed using this approach. However for the NASA methane DIAL system higher spectral resolution and control is needed. Therefore we implemented the ring OPO resonator shown in Figure 3.

The ring OPO is ideally suited for injection seeding and narrow line operation. Unidirectional output is assured by the phase matching condition in the OPO crystals which has gain only in the propagation direction of the pump beam. The output coupler also serves as the input coupler for the seed beam without introducing additional system loss. The ring laser resonator was initially set up with a broadband 40% output coupler and operated without seeding. Figure 5 shows that parametric conversion was readily obtained for pump energies above ~ 15 mJ. Broadband output was achieved with a linewidth of approximately 1 nm (a factor of 2 narrower than with the linear resonator). The seeded and unseeded OPO output spectra measured with an optical spectrum analyzer are shown on a log scale in Figure 6. Seeding of the ring resonator with the aligned DFB laser at a power level ~5 mW resulted in narrowing of the OPO spectrum to ~ 0.05 nm, the resolution limit of the OSA. Figure 6 also shows that the broadband noise background from the OPO is attenuated by over 25 dB. Comparison of the integrated seeded and background output from the OPO indicates the spectral purity is at least 95%, limited by the resolution of the OSA. The seeded output spectrum from the ring OPO shown on a linear scale is included in Figure 7, and there is no evidence of underlying broadband output.

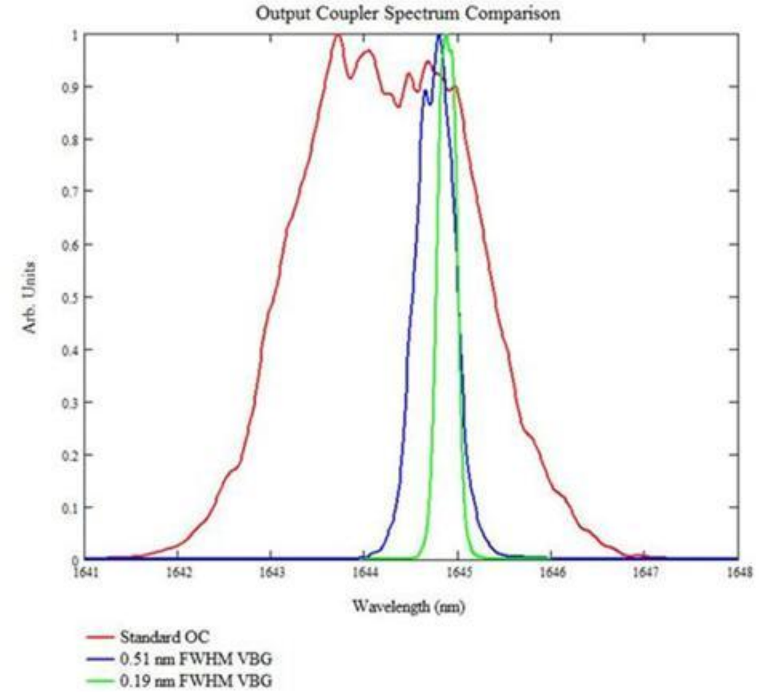

Figure 4: OPO spectra for conventional and volume Bragg grating output couplers.

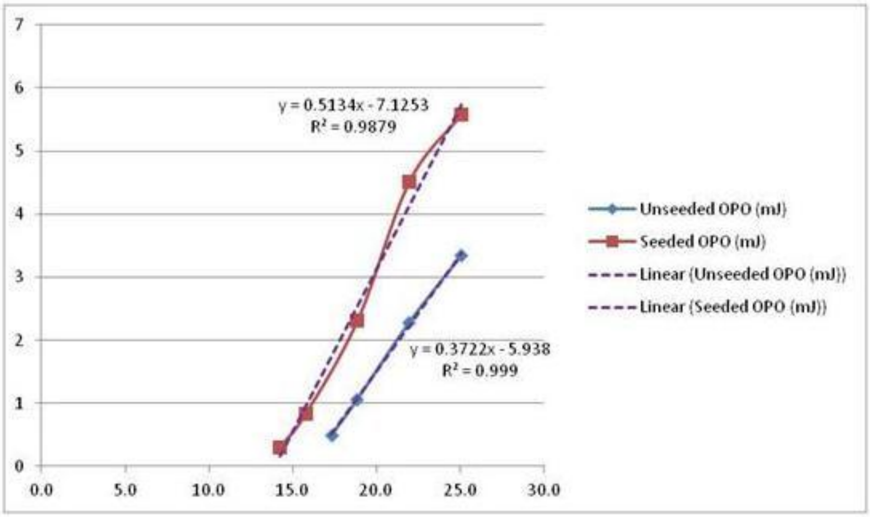

Figure 5: OPO output pulse energy vs. input pump pulse energy for seeded and unseeded operation of the ring OPO.

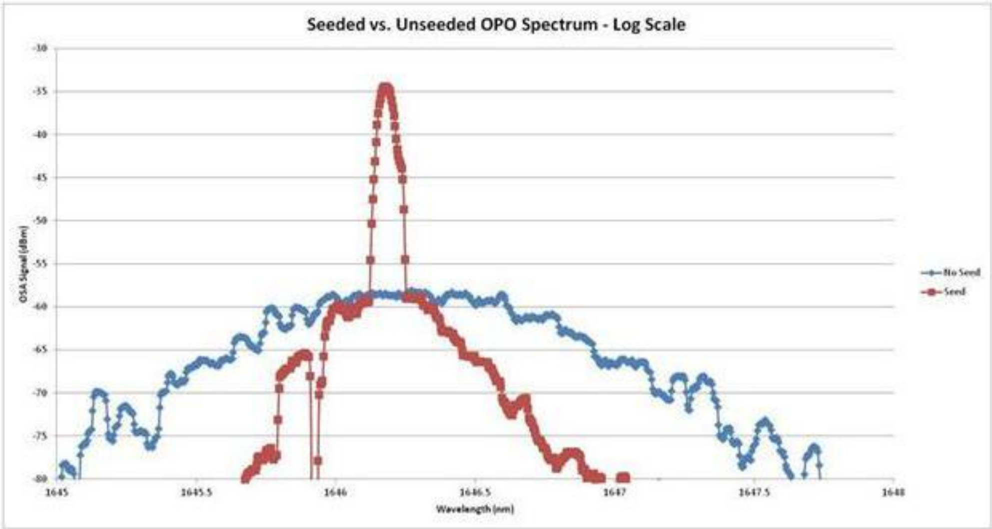

Figure 6: OPO output spectra for seeded and unseeded operation of the ring OPO shown on a log scale. The background is 25 dB below the peak.

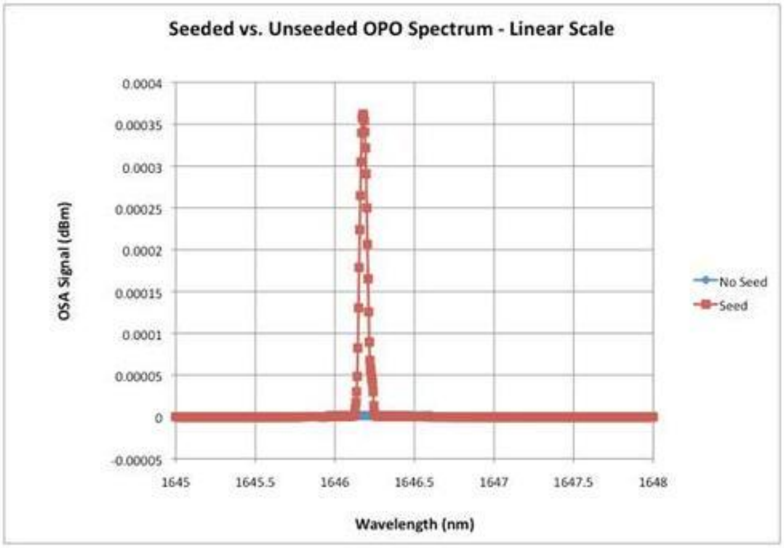

Figure 7: Seeded and unseeded ring OPO spectra presented in a linear scale to demonstrate the lack of observed broadband output.

To demonstrate the ability of the OPO to operate on both an on-line and an off-line, seeded OPO spectra were collected while temperature tuning the seed laser to shift its wavelength. Figure 8 shows the OPO output at two different temperatures illustrating the shift in the wavelength of the seed and corresponding shift in the OPO output central wavelength without broadening of the OPO spectrum. The frequency shift shown here is just under 0.5 nm; nearly double the tuning required between the online and offline wavelengths identified for the methane system in section 1.

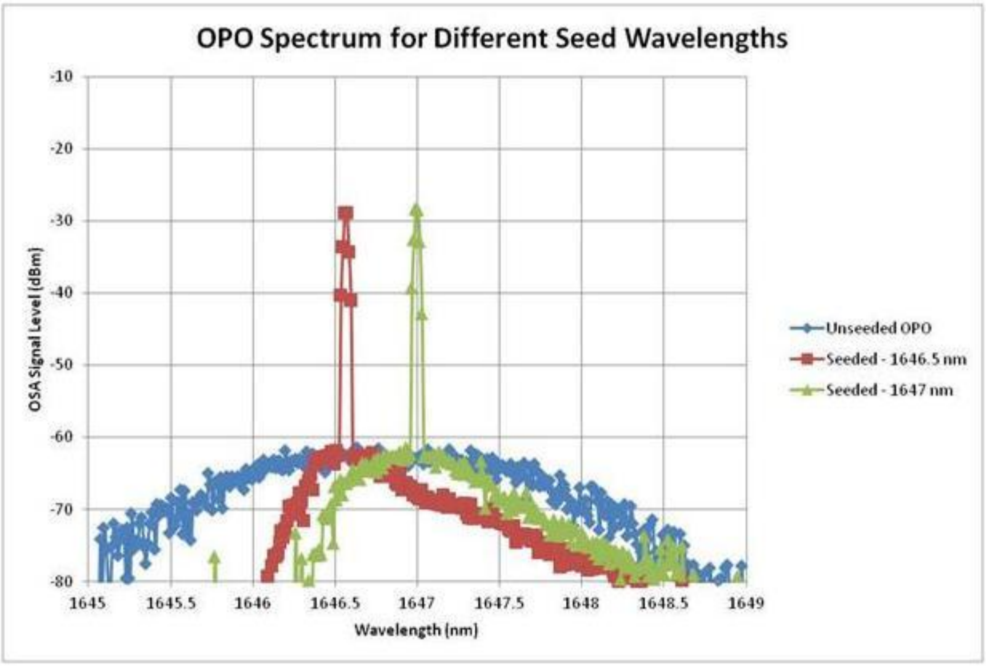

Figure 8: Plot showing the ability to tune the single frequency output of the OPO spectrum by tuning the wavelength of the seed laser via temperature. Note the spectral purity, linewidth and background level remain unchanged when tuning the wavelength.

An encouraging feature of this demonstration is that the seeded OPO was able to run seeded for periods of time exceeding 15 minutes without any cavity control. This suggests that locking the resonator and seed laser wavelengths using the Pound-Drever-Hall (PDH) control technique will prove to be a simple robust process. We also characterized the input/output performance of the ring resonator OPO operating both with and without seeding. These results are shown in Figure 5. The unseeded OPO reaches threshold at about 15 mJ input at 1.06 µm from the pump laser. The threshold is mainly determined by the pulse buildup time in the resonator cavity. With seeding this buildup time is greatly reduced since the OPO output builds up from the seed input (~5 mW) rather than spontaneous noise ($\sim 10^{-15}$ W). This effect is clearly seen in the graph where the threshold is reduced to 12 mJ in the seeded OPO. The slope efficiency of the OPO is also increased in the seeded OPO from 37% to nearly 50%. This is also a consequence of the seed input allowing the OPO to deplete a larger fraction of the pump, resulting in higher energy output. At the maximum output energy of the OPO (>5 mJ) the overall conversion efficiency was over 20%. The measured input/output characteristics of the OPO demonstrate the potential for a reliable design of the Phase II system. The accomplishments of the Phase I work are summarized below:

- OPO operation with tunability near 1.6455 µm with no impact on the spectrum or output power observed with tuning of more than 0.5 nm
- Demonstrate seeded operation (not line locked) using a fiber coupled distributed feedback seed laser and achieved >5 mJ pulse energies
- With available instruments the spectral purity was measured to be 95% with this measurement impacted by the OSA instrument resolution

4. PHASE II DESIGN CONCEPT

Building on the results presented in section 3 we developed a design concept for the transmitter capable of meeting the performance requirements for a Phase II follow-on program. These requirements are listed in Table 1 along with comments on the achievements made in this Phase I effort.

Table 1: Performance requirements for the Phase II program.

#	PARAMETERS	Target	Phase I	Phase II
1.	Pulse Energy	2-5 mJ	Demonstrated >5 mJ at 20% OPO efficiency	Design for 2-3 mJ
2.	Linewidth	~100 MHz	Seeding demonstrated	Seeded and tuned to DIAL wavelength
3.	Pulse Repetition Rate	Up to 1 kHz	50 Hz	1 kHz
4.	Avg. Power	Up to 5 W	0.25 W @50 pps	3 W nominal
5.	Pulse width	~10 ns	5 ns	10 ns
6.	Wavelength (on/off line)	1645.55 / 1645.75 nm	Seeding demonstrated	Tuned using seed lasers
7.	Wavelength Stability	5 MHz	<0.05 nm, OSA resolution limited	To be measured
8.	Spectral Purity	>99.9%	>95%, OSA resolution limited	To be measured
9.	Beam Quality	<2 x DL	Not measured	Design for TEM_{00}
10.	Transmitter Efficiency	>1% from prime power	20% OPO	20% OPO * 10% pump laser efficiency
11.	Polarization Ratio	>100/1	Implicit with OPO	Implicit with OPO

In order to meet these requirements, the demonstrated Phase I seeded OPO technology will be pumped by a high efficiency single frequency Nd:YAG laser operating at 1 kHz PRF and a maximum of 15 W of average power. This laser was developed under an ongoing LaRC Phase II SBIR for High-Efficiency Lasers for Lidar Applications. This pairing will generate 3 W of single frequency 1.6 µm light based on the 20% conversion efficiency demonstrated on Phase I. At these average power levels, KTP remains the nonlinear crystal of choice since the absorbed idler power is not expected to be large enough to impact the conversion efficiency. Should thermal issues appear, the nonlinear crystal material may need to be switched to KTA which has no idler absorption but is difficult to grow with high quality. A block diagram of the laser design concept is shown in Figure 9. Also shown in this diagram are the components required to lock the OPO cavity to a methane cell for long term, stable, single frequency operation which is not included in the Phase II effort. Without locking the Phase I program proved the OPO capable of sustaining single frequency operation for up to 15 minutes without any active cavity control. This combined with Fibertek's significant experience in implementing the Pound-Drever-Hall (PDH) technique for cavity locking on OPOs should make the cavity locking a simple and robust process. Fibertek's PDH capability was developed under DARPA/Navy support for a blue laser source locked to atomic cesium transitions near 455 nm and the same approach is applicable to locking to the methane transitions in the near IR. To achieve the dual wavelength operation required a single seed laser can be temperature tuned or a pair of seed lasers can be utilized and switched into the OPO cavity using a commercial fiber-based electro-optic switch. The use of intracavity volume Bragg gratings is not required to successfully implement this scheme but they may provide an additional capability for controlling the spectral linewidth and increasing the spectral brightness of the DIAL system.

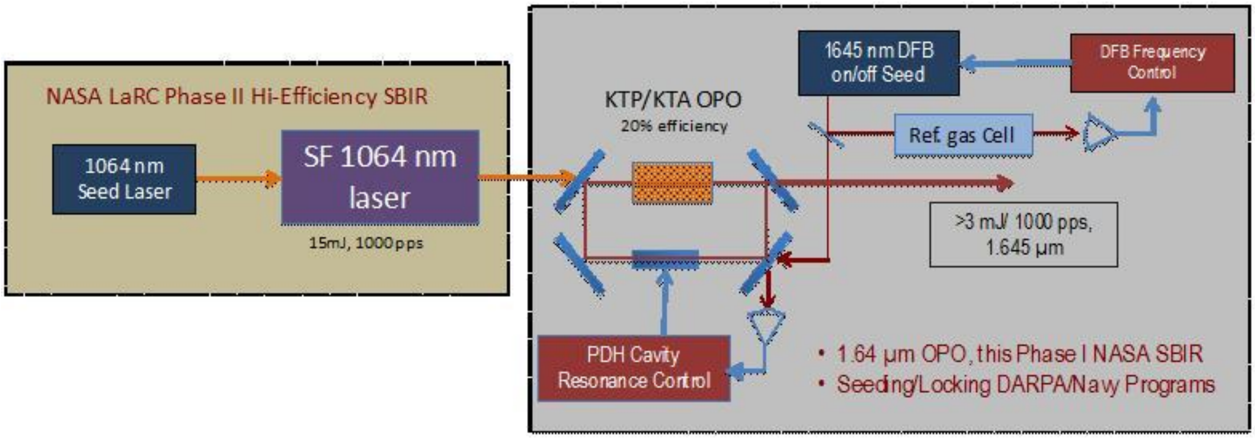

Figure 9: Block diagram of proposed phase II methane DIAL laser transmitter.

Existing Fibertek mechanical designs, such as those from the ICESat-2 or ISS CATS programs will be leveraged to provide a deliverable transmitter capable of ground and airborne operation. Environmental specifications provided by NASA will be used to guide the mechanical design process appropriately. The resulting transmitter will exit Phase II with a technology readiness level (TRL) of 5 for the phase II prototype and the delivered hardware will be compatible with environmental qualification for airborne operation at TRL-6.

Figure 10 contains a conceptual layout of the methane DIAL laser LOM (laser optical module). The sealed laser housing is based on a design developed for an HSRL laser transmitter having single-frequency output of 30 W split between 1064 nm and the second harmonic at 532 nm. Versions are being built by Fibertek both for space (ISS-CATS) and airborne (LaRC-HSRL) platforms. For the methane DIAL laser the optical amplifier stage will be replaced by the OPO wavelength converter to provide output at 1.645 µm. The design of the OPO itself is based on a similar device developed on a previous Fibertek laser program and is depicted in Figure 11. This device also incorporated a seeded ring laser to provide output at 455.5 nm for use in conjunction with an atomic cesium Faraday optical filter. In this case the OPO was locked to the Cs transition and provided a linewidth of ~ 300 MHz (equivalent to 75 MHz frequency selectivity at 1645 nm).

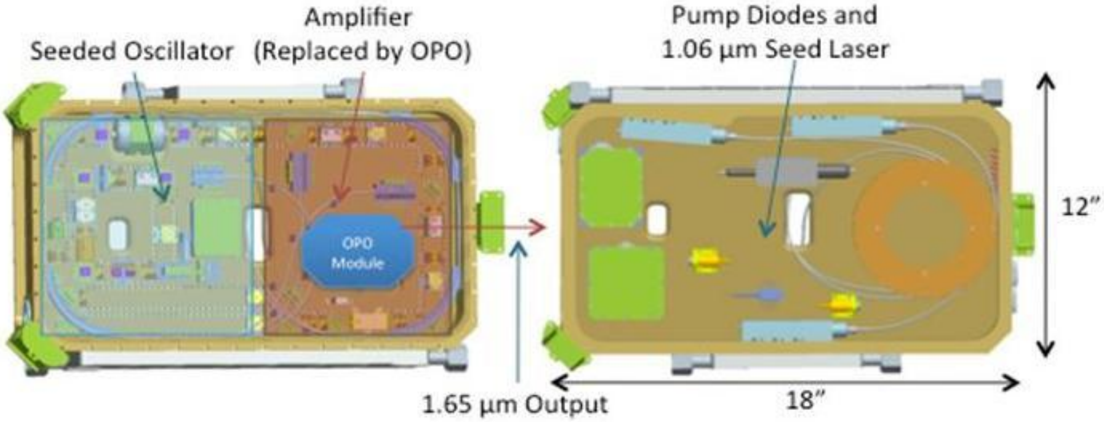

Figure 10: Design concept for the methane DIAL transmitter. The housing is based on an HSRL module being developed for airborne and space-based lidar missions.

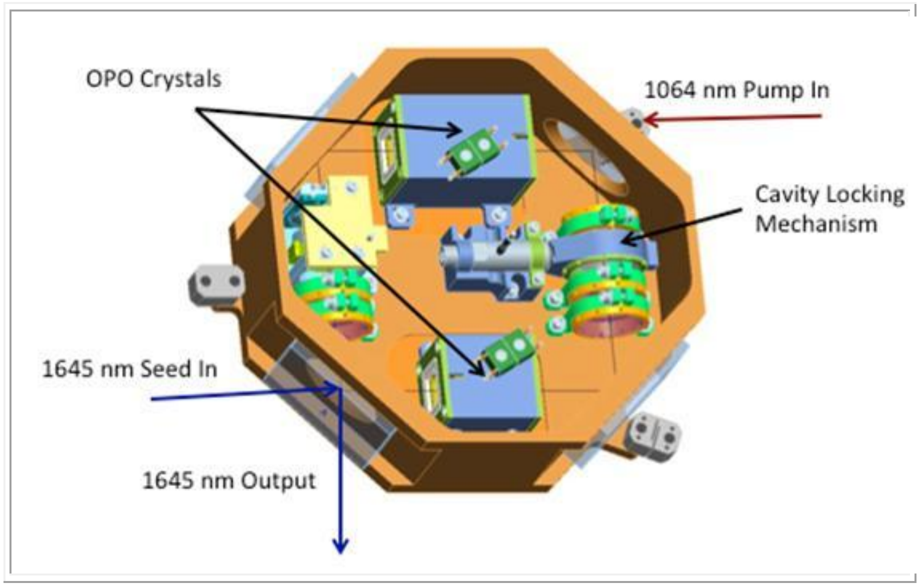

Figure 11: Concept for the seeded OPO wavelength converter.

5. CURRENT PHASE II EFFORT

The Phase II program was awarded in January 2013. Preliminary mechanical, electrical and optical design work has been completed. As of July the program effort is focused on risk reduction activities to demonstrate PDH locking of the OPO cavity to an external seed laser. In these experiments the OPO design demonstrated in the Phase I work is being pumped by a breadboard version of the 15 W, 1 kHz oscillator planned for the Phase II effort. The Phase II program has a completion date of October 2014.

6. CONCLUSION

To conclude, the key achievements demonstrated in the Phase I program are listed below:

- An injection seeded optical parametric oscillator operating in the infrared near 1.645 µm, in the vicinity of on- and off-resonance absorption lines in methane was demonstrated.
- The capability of Volume Bragg Gratings (VBGs) as resonator output couplers to narrow the linewidth of the OPO and improve spectral purity was demonstrated.
- Pulse energies greater than 5 mJ were achieved from the OPO, meeting the requirements envisioned for a fielded DIAL system.
- Demonstrated 20% pump to OPO conversion efficiency, providing a practical transmitter overall operating efficiency.
- Demonstrated tuning of the OPO both with VBGs and seed laser near the on- and off-resonance wavelengths of interest for methane DIAL.
- Demonstrated line narrowing in the seeded OPO to levels compatible with the required spectral purity.
- Identified a pump laser and OPO architecture that is scalable to both near and long-term methane DIAL system requirements.
- The proposed design is based on component hardware developed under this and other NASA SBIR programs and will advance the technology readiness level from TRL 3 to TRL 5 with a clear path to TRL-6 flight ready hardware.

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