High-power, tunable difference frequency generation source for absorption spectroscopy based on a ridge waveguide periodically poled lithium niobate crystal

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Abstract: A novel waveguide for difference frequency generation in the mid-IR spectral region at 3.52 μm is characterized. High mid-IR power of 15 mW and an external conversion efficiency of up to 19 % W−1 have been obtained. An optical beam propagation factor M²=1.18 was determined using the second moment method. A simple 2-f absorption spectra demonstrates the potential of this mid-IR source for high precision trace gas sensing applications.

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OCIS codes: (190.2620) Frequency conversion; 300.6340 Spectroscopy, infrared

References and links
1. Introduction

The precise measurement of several key trace constituents present from the surface to the stratosphere may aid in answering several scientific questions related to atmospheric chemistry, affecting urban and global environments. For many atmospherically important molecules, tunable laser mid-IR absorption spectroscopy is an attractive direct measurement technique that is suitable for operation on ground, ship, and airborne measurement platforms. However, in most spectroscopic techniques, the limit of sensitivity largely depends on the performance and characteristics of tunable mid-IR laser sources. Lead-salt diode lasers, quantum-cascade lasers, and mid-IR laser sources based upon difference-frequency generation (DFG) have been successfully applied to numerous trace gas measurement applications [1]. In particular, advanced DFG based laser spectrometers have recently been developed. One such system was recently deployed during three consecutive airborne field studies, where it demonstrated reliable operation (300 flight hours) and provided fast, high measurement sensitivity for formaldehyde (<100 pptv, 1 second average) [2, 3]. This paper describes the characterization of an advanced, more efficient method for difference-frequency generation using a ridge waveguide periodically poled lithium niobate (WG-PPLN) crystal and discusses the important design characteristics that may improve the current performance and efficiency of bulk-PPLN crystal based DFG spectrometers that utilize multi-pass absorption cells. WG-PPLN crystals may also enable their application to other spectroscopic techniques such as cavity-enhanced absorption.

To achieve very high precision and absorption sensitivities of $I/I_0 \sim 10^{-7}$ or better, such as obtained using a fiber optic pumped bulk-PPLN based DFG source [3], it is important that the laser source provides all of the following characteristics: narrow linewidth (<5 MHz) and single longitudinal mode operation to couple all of the energy into the absorption line to maximize the absorption signal, high beam quality (near Gaussian) to minimize noise sources due to optical scattering and permit low optical losses through the spectrometer, high $f/#$ to provide a stable coupling with multi-pass absorption cells while minimizing mode matching optics, sufficient power to overcome the electronic noise floor of the detectors, and predictable tuning characteristics that enable stable response factors. For airborne atmospheric research applications it is also important that such a laser source operates without liquid cryogen, is as compact as possible and able to operate without degrading performance if subjected to severe vibration, ambient temperature variations and extremes, and changes in ambient pressure.

Bulk-PPLN based optical fiber pumped DFG sources typically require the use of rare-earth doped fiber amplifiers to increase the pump and signal powers to yield sufficient idler power levels of several tens to hundreds of W. Commercial fiber amplifiers, signal and pump diode and fiber laser sources achieve most of the required characteristics listed above. In particular, the overall rugged properties of optical telecom rated components make reliable, long-term operation an easy task to achieve. Another notably important characteristic of fiber optic pumped bulk-PPLN crystal DFG sources is the high beam quality, which also minimizes the number of required optical elements to collimate and match the typically high $f/#$ of multi-pass absorption cells while minimizing optical scattering. However, in order to obtain high spectroscopic stability, one also needs to achieve the utmost stability in the Wavelength Modulated Output Intensity (WMOI) of the laser source, which invariably is present in the output of such devices. For instance, any optical effect that changes the polarization, will lead to a change of the WMOI and add to the optical noise background. One successful approach that has been implemented in the airborne DFG spectrometer introduced by Wehring et al. [3] is to capture and subtract such noise before the idler beam is coupled into the multi-pass absorption cell. In addition, proper temperature control and opto-mechanical stability is necessary to minimize other effects that may lead to WMOI. While very long stability times of 900 s and absorption sensitivities of $I/I_0=3\times10^{-7}$ have been obtained, the complexity of such a system becomes challenging to
improve upon. The size, weight, power consumption, and overall efficiency of such a system may be significantly improved by using a WG-PPLN crystal. In addition, WG-PPLN based DFG sources have the potential to significantly reduce the optical noise generated and induced by the use of optical fiber amplifiers and thus enable one to further improve the measurement sensitivity. On the other hand, the continued use of optical fiber amplifiers in combination with a highly efficient WG-PPLN DFG source would permit its application to cavity enhanced absorption techniques [4] and potentially to open path absorption measurements, which require 10 mW of optical mid-IR power. Such a source would also complement the limited spectral coverage of Quantum Cascade laser sources in the 2 to 4.5 m spectral region.

2. Experimental system and description

Recently, high-efficiency direct-bonded PPLN ridge waveguides in the 3 m band were developed at NTT Photonics Laboratories using z-cut non-doped LN wafers and z-cut LiTaO$_3$ (LT) as waveguide and substrate layer, respectively [5]. Ridge waveguide type PPLN crystals are orders of magnitude more efficient than waveguides based on annealed proton exchange [6]. The WG-PPLN chip used in this work was 50 mm long, with a waveguide cross-section of 14.0 m wide x 11.7 m thick, and had a nominal grating period of 28.35 m. The WG-PPLN chip was temperature controlled using a Peltier element and operated at ~ 40 °C. The experimental set-up is shown in Fig. 1. A single mode, narrow-linewidth DFB fiber ($P_{pump}$=25 mW, $\lambda_{pump}$=1083 nm) and diode laser ($P_{signal}$=80 mW, $\lambda_{signal}$=1562 nm) served as pump and signal wave, respectively. In addition, high-power Yb and Er doped fiber amplifiers were added to investigate the response of the WG-PPLN at high pump power levels, and to explore the viability of high power (tens of mW) DFG-based mid-IR sources. The pump and signal beams were combined using a Wavelength Division Multiplexer (WDM) coupler. The polarization state of the pump and signal beams were controlled by inline manual polarization controllers. The single mode output fiber (1060 Flexcore) following the WDM was cleaved at 0° and aligned to the waveguide using high-resolution translation stages and aided by the use of a microscope. Both fiber optic amplifier outputs were protected using in-line optical isolators. The experimental set-up was assembled on a Class 100 horizontal flow bench to avoid dust contamination of the WG-PPLN chip and coupling fiber optic.

![Fig. 1. Optical set-up of WG-PPLN based DFG laser source](image_url)

3. Characterization of the WG-PPLN based DFG source

To efficiently couple and excite the fundamental mode for the pump and signal beams, the fiber was positioned 5 to 10 m from the input facet of the WG-PPLN and translated in the x-y direction, while the pump and signal intensity was monitored with an IR monitoring card,
as well as a near-IR CCD beam profiler. Typically, good single mode coupling was achieved for the signal laser but not for the pump laser, which largely remained multimode. The WG-PPLN chip had no anti-reflection coating and was cleaved at $0^\circ$, which created a rather large optical fringe ($\sim 40\%$) corresponding to the length of the WG-PPLN crystal. Environmental vibrations were picked up by the set-up, resulting in high-frequency intensity noise, which was exacerbated by the limited stability of the translation stages and fiber coupling. The use of a damped optical bench minimized the noise during the evaluation; however, a packaged module with locked components similar to a butterfly DFB diode laser, and angle cut anti-reflection coated WG-PPLN chip would likely preclude such noise [7].

3.1. Optical fiber coupling to the WG-PPLN crystal

Using a $f=20$ mm plano-convex CaF$_2$ lens, the idler output was collimated and imaged onto an InSb array. Figure 2 shows the recorded idler beam intensity profile while translating the input fiber back and forth in sequential horizontal and vertical directions, as well as moving it along the optical propagation axis. The vertical and horizontal translation of a few microns shows an intensity change of the idler beam, but not its absolute position.

![Image](image.jpg)

Fig. 2. Movie showing the idler beam cross section as a function of input fiber translation with respect to the WG-PPLN input facet. The movie was recorded using a 320x256 Sterling-cooled InSb array (30 $\times$ 30 m pixel size).

Translating the fiber in the direction of the optical axis causes notably less intensity modulation. For a fixed alignment, this would minimize a change of conversion efficiency for small changes in the WG-PPLN length if temperature tuned and may accommodate lower intensity losses across the phase-matching range.

3.2. Conversion efficiency and tuning characteristics

With a signal frequency of 6405.3 cm$^{-1}$ and pump frequency of 9234.10 cm$^{-1}$ and a nominal WG-PPLN temperature at 42 $^\circ$C, the measured quasi-phase matching temperature bandwidth (FWHM) was 4 $^\circ$C. The conversion efficiency of the WG-PPLN was evaluated for a range of pump powers. The WG-PPLN exhibited a higher conversion efficiency for pump power products of less than 0.02 W$^2$, as shown in Fig. 3. As much as 15 mW of output power was measured with an pump power product of 0.16 W$^2$. For high and low pump power products, the measured external conversion efficiency was 60$\times$ to 90$\times$ higher than typically obtained...
with bulk PPLN crystals. The decrease in conversion efficiency in the high input power region is likely caused by optical damage of the WG-PPLN. The optical damage can, however, be reduced considerably by using ZnO-doped LN as the core layer of the WG-PPLN [8]. An optimal fiber coupling alignment, phase matching temperature, and pump/signal wavelength to minimize reduction of measured intensity due to optical fringes yielded up to 19 %W⁻¹. Due to the opto-mechanical and temperature stability of the set-up, this conversion efficiency was not sustainable over a longer time period. However, the slightly lower conversion efficiencies plotted in Fig. 3 were sustainable and easily repeatable. All reported conversion efficiencies are exclusive of residual optical losses sustained by the collimation lens and A/R coated Ge-window.

![Graph](image)

Fig. 3. Idler power and conversion efficiency as a function of signal and pump power product. The applied pump and signal power ranges are marked. The idler power was measured using a calibrated thermopile power meter. All measurements were taken without change of alignment.

3.3. Beam quality

To further investigate the beam quality, the idler output beam was imaged with a f=10 mm plano-convex sapphire lens, and the beam cross sections were recorded over a ~1 m propagation length using a mid-IR InSb array. Using the second moment method (ISO 11146), the beam radii were measured and fitted to the gaussian beam equation to yield a M² propagation factor of 1.18 (Fig. 4). Also shown in Fig. 4 are the beam cross sections before, at, and past the beam waist. The movie in Fig. 5 shows the imaged idler output as the collimating lens is translated away from the WG-PPLN output facet, and essentially shows the cross sections through the idler beam waist. Several Airy like rings can be seen and disappear past the beam waist. A possible cause for these Airy like rings could be the presence of wavefront aberration. The low M² value compares well with the beam quality obtained with fiber optic pumped bulk
Fig. 4. Measured beam radius using the second moment method (ISO11146) and selected beam intensity cross sections measured before, at, and past the beam waist. The data is fitted to the gaussian beam equation to yield a propagation factor $M^2=1.18$.

$\omega = \omega_0 \left[ 1 + (M^2 \frac{\lambda}{\pi} \frac{1}{\omega_0^2}) \right]$

$M^2=1.18$

$\lambda=3.53 \, \mu m$

$\omega_0=565 \, \mu m$

Fig. 5. Images of the idler beam cross section while translating the collimating lens away from the WG-PPLN output facet.
PPLN crystal DFG sources, however, the presence of Airy like rings may add additional time dependent optical noise to the spectroscopic background.

3.4. Absorption spectra

The large optical background due to fringes from the 0° cleaved WG-PPLN facets did not permit a thorough spectroscopic characterization of the presence of additional embedded noise caused by the Airy like fringes and its potential effect on the spectroscopic background stability. Nevertheless, a series of simple 2-f absorption spectra were collected using a reference cell filled with CH₂O (7.62 cm long, p_{cell}=10 torr), that demonstrate the spectral fidelity of the WG-PPLN DFG laser source. Figure 6 shows the absorption signal obtained using 2-f modulation spectroscopy. The signal DFB diode laser was scanned and modulated with triangular waveforms at 25 Hz and at 50 kHz, respectively, and the signal was demodulated using a lock-in amplifier at 100 kHz. Figure 6 shows the 2-f signal with and without the reference gas absorption cell in the beam path. The large spectroscopic background caused by the WG-PPLN crystal noticeably distorts the 2-f absorption profile.

4. Summary and Conclusion

The optical and spectroscopic characteristics of a WG-PPLN crystal based tunable mid-IR DFG source were evaluated. As much as 15 mW of tunable, narrow-linewidth mid-IR radiation was measured and typical conversion efficiencies of 10 to 15 %W⁻¹ for high and low pump and signal power products were obtained. The optical beam quality of the WG-PPLN yielded a M² value of 1.18. The idler beam intensity cross section showed Airy like rings of unknown origin. The overall efficiency and initial characterization of the WG-PPLN shows good potential for its application in high precision mid-IR trace gas sensing applications.

Fig. 6. 2-f signals as a function of time (displayed as acquisition channel). Shown are a CH₂O absorption line as well as the spectroscopic background without the reference gas cell in the beam path.
Acknowledgments

The authors would like to thank Dr. Scott Spuler (NCAR) for helpful discussions. The National Center for Atmospheric Research is sponsored by the National Science Foundation. This work was also supported by a NCAR directors opportunity.