Ultra-compact mid-IR spectroscopic source based on frequency converted Yb - Er/Yb fiber amplified cw diode lasers

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Abstract: A novel narrow-linewidth mid-IR source based on difference frequency generation of fiber coupled diode laser seed sources at 1.08 μm and 1.56 μm mixed in periodically poled LiNbO₃ is reported. Both seed pump wavelengths are amplified by a cascaded Yb and Er/Yb amplifier combination to generate coherent radiation of up to 0.1 mW at 3.5 μm. Furthermore, PPLN crystals of 0.5 mm and 1 mm thickness of 20 mm and 50 mm length have been compared in terms of their respective conversion efficiencies. Up to 1 mW at 3.5 μm of stable, tunable mid-infrared light was generated using separate Yb and Er/Yb amplifiers and a 50 mm long PPLN crystal.

OCIS Codes: (060.2320) Fiber optics amplifiers and oscillators; (190.2620) Frequency conversion

The availability of tunable, spectrally narrow mid-infrared light sources permits selective and sensitive detection of trace gas species based on absorption spectroscopy (direct, dual-beam, 2f, photo-acoustic or cavity-ring-down) at fundamental vibration – rotational absorption bands. Important applications include industrial and environmental emission monitoring. For certain field applications, demanding operating conditions must be considered in the design of a reliable, sensitive gas detection system to minimize performance limiting effects such as vibration, humidity, and temperature cycling. In this work, we report the design, implementation and validation of a compact modular mid-infrared source that is based on the use of telecommunication fiber optical pump sources and recent advances in non-linear optical materials.

Fig.1: Schematic and photograph of a compact DFG based mid-infrared source with outer dimensions of 13” × 8.5” × 4.5” (including all electronics).

Two fiber amplified near infrared diode lasers operating at 1083nm (DBR, 50 mW) and 1563 nm (DFB, 10mW) respectively are difference frequency converted to the mid-IR using a 50 mm long...
periodically poled lithium niobate (PPLN) crystal. The use of fiber optics provides diffraction limited Gaussian pump beams and inherent spatial beam overlap, which is crucial for an effective and robust difference frequency mixing process. Its novel design is reflected in the use of only one active 30 dBm Yb fiber amplifier (gain at 1 μm) fusion spliced to a 6.8 m long Er/Yb co-doped single mode fiber that provides amplification at 1.5 μm (Fig.1) [1]. The Er/Yb silica glass fiber is co-doped with phosphorous for efficient energy transfer from the Yb$^{3+}$, $^{2}F_{5/2}$ level to Er$^{3+}$, $^{4}I_{11/2}$ level to provide gain at 1.5 μm [2]. The Er/Yb fiber with a N.A. of 0.16 and core diameter of 5.1 μm has an absorption coefficient of 0.6 dB/m at 1083 nm and is pigtailed to a Lucent “truewave” fiber and terminated with an 8° angle fiber connector (FC-APC). An f=10 mm achromat is used to image (M=11) the amplified pump beams with estimated respective mode field diameters 8.8 μm (1563 nm) and 5.9 μm (1083 nm) into the PPLN crystal. The generated mid-IR radiation is collimated by a CaF$_2$ lens (f=5 cm) and can be directed to either an open path or an extractive optical multi-pass absorption cell module.

Fig. 2: a) Yb amplifier output power as a function of pump diode laser current. b) Yb - Er/Yb fiber amplifier output power as a function of Yb fiber amplifier pump current. Seed powers were 10 mW (1083 nm) and 13 mW (1563), respectively.

The fiber amplifier pumping scheme was initially optimized to provide a balanced pumping power product $P_{1083\,\text{nm}} \times P_{1563\,\text{nm}}$ that is directly proportional to the generated difference frequency mid-IR power. The Yb fiber amplifier (IPG Photonics) is pumped by three parallel 970 nm broadband diode pump sources with an efficiency of 1024 mW/A and an operating bandwidth from 1060 nm to 1090 nm with the maximum gain at 1083 nm. The output of the Yb-amplifier is spliced to a 2x1 WDM and combined with a 15 mW DFB diode laser operating at 1563 nm. Fig. 2a shows the output power of the Yb fiber amplifier as a function of diode laser pump current with a fiber coupled seed power of ~10 mW at 1083nm. Fig.2b depicts the maximum power of the Er/Yb fiber amplifier with 581 mW at 1083 nm and 232 mW at 1563 nm just prior to the achromat. These powers correspond to an effective Er/Yb fiber amplifier slope efficiency of 46%.

Recent improvements in electric field poling of lithium niobate led to the development of 1 mm thick PPLN crystals and consequently allow the use of longer crystals without experiencing aperture clipping of the pump and DFG beams. To determine the impact of poling quality
differences, length and thickness, the conversion efficiencies of four PPLN crystals were compared.

<table>
<thead>
<tr>
<th>PPLN Sample</th>
<th>A</th>
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<th>C</th>
<th>D</th>
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<td>Conversion Efficiency</td>
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<td>174</td>
<td>181</td>
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</table>

Table 1: Conversion efficiency of various PPLN crystals

Fig. 3: DFG power at 3.5 μm measured with a calibrated InSb detector as a function of incident pump power product for PPLN samples listed in Table 1. Also shown are microscope photographs of 1 mm and 0.5 mm thick PPLN crystals.

PPLN samples A, B and C were fabricated from the same wafer run and polished. All PPLN crystals were anti-reflection coated for pump, signal and idler wavelengths. The four samples were placed consecutively in the fixed fiber-to-crystal imaging stage. The conversion efficiency was found to be independent of crystal thickness as is evident from Table 1. With the maximum generated pump power product of 0.135 W² (Fig. 2b) a DFG power of ~0.1 mW (as measured with a calibrated thermopile detector) of stable narrow linewidth radiation is generated using the 50 mm long, 1 mm thick PPLN crystal.

The observed conversion efficiency of ~ 200 μW × W² × cm⁻¹ is about half the value obtained with a comparable DFG pump architecture reported in Ref. 3. Differences in the poling quality of 0.5 mm and 1 mm length PPLN crystals do not account for the lower conversion efficiency from the PPLN comparison listed in Table 1. For comparison, the 50 mm long, 1 mm thick PPLN crystal was implemented in a DFG pump architecture [4], shown in Fig. 4.
incident pump powers of 1.25 W (1083 nm) and 0.46 W (1563 nm) respectively, a mid-IR power of 1.1 mW was measured. Using the same magnification (M=11) for pump beam imaging, the conversion efficiency was determined to be 356 µW × W² × cm⁻¹, about a factor of two higher than measured with the ultra-compact architecture depicted in Fig.1. The slope efficiency measurement is shown in Fig. 4, where the apparent polynomial function is due to the characteristic nonlinear response (>100µW) of the photo-conductive MCT detector used in this work.

![Diagram](image)

**Fig. 4:** Schematic and slope efficiency of a 1 mW DFG source based on highly saturated Yb and Er/Yb high power fiber amplifiers.

The difference in conversion efficiency of the two DFG architectures can be explained by the use of different fiber types for pump beam delivery. Another contributing factor to the lower conversion efficiency in the Er/Yb – “truewave” fiber pigtail architecture was the observed power drop of ~30% beyond the achromat at 1563 nm (~10% at 1083 nm). This power drop was not observed using a pair of off-axis parabolic mirrors to simulate pump beam imaging into the PPLN crystal. Despite the use of an FC-APC fiber termination and an angled imaging objective, the residual backscattered light from the microscope objective first flat surface depleted the gain at 1563 nm. This did not affect stable output power and narrow linewidth operation, as confirmed by monitoring a mid-IR reference absorption spectrum of H₂CO.

Although the highest conversion efficiency was obtained using a “flexcore” 1060 fiber (NA=0.11) with the architecture depicted in Fig.4, this fiber type was not suitable for fiber pig tailing to the Er/Yb doped fiber. The substantial difference in core diameter and numerical aperture with respect to the Er/Yb fiber led to an increased bending sensitivity (loss >80% at 1 in. bending radius), and severe optical feedback that produced power fluctuations. For the different FC/APC fiber pigtail combinations tested, the “truewave” fiber offered the lowest splice loss and highest DFG conversion efficiency in a cascade fiber amplified pump architecture.

In summary, an ultra-compact difference-frequency based mid-IR source at the 0.1mW-level was demonstrated. The use of longer (50mm) nonlinear optical PPLN crystals and optimized fiber optic pump delivery resulted in the generation of more than 1 mW of tunable cw mid-IR
radiation at 3.5 μm. This enhanced DFG power now makes it possible to achieve a minimum detectable absorbance of $10^{-5}$[4].

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References:

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