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WIDELY TUNABLE LWIR PARAMETRIC SOURCE BASED ON PUMP WAVELENGTH TUNING

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ABSTRACT:

Long wave infrared (LWIR) coherent sources emitting between 8 and 12 μm can be used for standoff detection of many chemicals. Optical parametric sources are essential when peak power and wavelength tunability are both required. In particular, the nested cavity optical parametric oscillator (NesCOPO) based on orientation-patterned gallium arsenide (OP-GaAs) allows LWIR single longitudinal emission, by down conversion from 2 μm radiation. Using the recent development of a pulsed single longitudinal mode Tm:YAP laser tunable over 20 nm near 2 μm , we demonstrate broadband tuning over 830 nm in the LWIR with the NesCOPO architecture without tuning the non-linear crystal temperature. This result paves the way to fast, broadband wavelength tunable sources in the LWIR.

1. INTRODUCTION

Tunable long wave infrared (LWIR) coherent sources emitting between 8 and 12 μm can be used for remote detection of chemical warfare agents (CWA) and toxic industrial chemicals (TIC) thanks to the very distinctive absorption spectra of molecules and to the high transmission of the atmosphere in this spectral range.

At long wavelengths, solid-state materials suitable as active laser ion hosts are scarce, as they usually present strong multiphonon absorption. Only two types of laser technologies are available for direct emission in the LWIR: the CO₂ gas laser and the quantum cascade laser (QCL).

Until the advent of QCLs, the CO₂ laser has been the only coherent source available in the LWIR with a significant energy and has been extensively used in lidar emitters for standoff detection of chemicals. Several emitters delivering more than 100 mJ have been developed, mainly for detection of CWAs and TICs. Energies above 1 J have been demonstrated in operational lidars [1-2]. More recently, the CO₂ laser has been used for standoff detection of explosives. However, the restricted tunability still prevents addressing the strongest absorption bands

of most gases, and sometimes hinders detection of the species at low concentration levels, as for sulfur mustard for instance.

Quantum cascade lasers are now the workhorses of many spectroscopy and local gas sensing experiments. However due to their limited peak power, standoff detection with QCLs is currently limited to ranges of a few tens of meters.

To overcome these limitations, another solution is to use second-order nonlinear optics to achieve down-conversion to the LWIR. For instance, optical parametric oscillators are well suited for standoff detection of chemicals because they provide peak powers in the kilowatt range, greater wavelength tunability compared to QCLs and CO₂ lasers and good optical quantum efficiencies (typically around 30% with Gaussian beams). Among the available crystals for down-conversion to the LWIR, GaAs is one of the most interesting thanks to the following features: a broad transparency window ranging from 0.9 to 17 μm , a high second order nonlinear susceptibility ($d_{14} = 90 \text{ pm/V}$) [3], and excellent mechanical and thermal properties. GaAs is optically isotropic, precluding birefringent phase-matching, but it is free from spatial walk-off which usually limits the maximum usable length.

For a previous ANR/DGA project called MUSTARD [4] we implemented a doubly resonant nested cavity optical parametric oscillator (NesCOPO) using an orientation patterned gallium arsenide crystal (OP-GaAs) pumped by a Tm:YAP microlaser, in which broad LWIR tunability was achieved by temperature tuning of the crystal indices of refraction. This work directly led to the realization of preindustrial prototype #1 in 2020 in the DGA RAPID project called SPICE [5], shown in Fig. 1. This source demonstrated similar performances as the laboratory experiments in a packaged design. However, it suffers from the same tuning speed limitations due to the crystal temperature tuning method.

It is well known that a similar wavelength range can be addressed by tuning the pump wavelength rather than the crystal temperature [6]. In addition, pump tuning can be significantly faster than temperature tuning. Furthermore, we also need a single longitudinal mode (SLM) pump to control the

spectral output of the NesCOPO, which is based on Vernier spectral filtering in doubly-resonant cavities. We recently demonstrated a pulsed SLM Tm:YAP laser tunable between 1.94 and 1.96 μm using a transversally chirped volume Bragg grating [7].

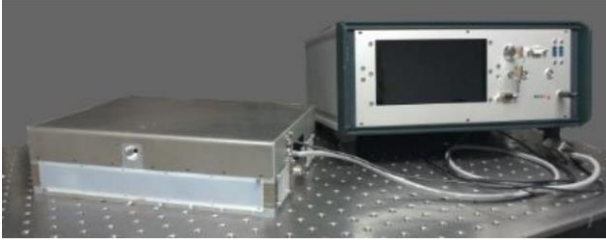


Figure 1. #1 LWIR prototype laser head and controller

Using this laser to pump the NesCOPO with an OP-GaAs crystal as non-linear medium, we demonstrate wideband tunability in the LWIR of this architecture through the mere tuning of the pump wavelength.

2. LONG WAVE INFRARED SOURCE

2.1. Overview

The architecture of #2 LWIR source is presented in Fig. 2. The source is composed of three parts: a tunable 2 μm pump microlaser source; a nested cavity OPO; and a sum frequency generation (SFG) module for wavelength measurements.

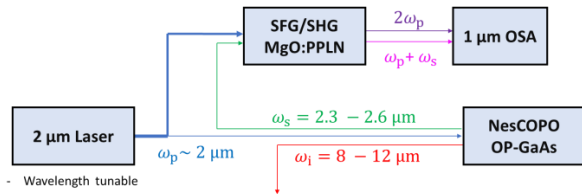


Figure 2. #2 LWIR source architecture

2.2. Tunable pump laser

The pump laser, shown in Fig. 3, is a slightly modified version of a Tm:YAP laser tunable from 1.94 to 1.96 μm thanks to a transversally chirped volume Bragg grating (TC-VBG), especially designed to pump the NesCOPO [7]. The front mirror is a highly reflective ($R > 98\%$) TC-VBG tunable from 1.94 to 1.96 μm made by OptiGrate Inc. Tuning of the output wavelength is obtained by translating the TC-VBG transversally with respect to the cavity axis using a micrometric screw and a high-resolution motor. The gain medium is a 4 mm long yttrium aluminium perovskite (YAP) crystal doped with 3 at.% of thulium, anti-reflective coated at 0.8 and 2 μm on its facets. It was chosen for its relatively high gain and thermal conductivity, its long excited-state lifetime, its birefringence leading to naturally polarized emission, and its ability for broadband wavelength tuning. Pulsed operation is obtained with a tellurium dioxide acousto-optic modulator from Gooch & Housego. A 4 mm thick

undoped YAG etalon is used to ensure single longitudinal mode operation in combination with the VBG. The output coupler is a concave dielectric mirror with an 88 % reflectivity and a 38 mm radius of curvature. The overall cavity is approximately 50 mm long. We pump the gain medium through the TC-VBG with a 4 W, 793 nm fibered laser diode imaged with a lens doublet to obtain a 100 μm pump beam radius into the gain medium. Residual pump is then filtered out with a dichroic mirror highly reflective near 2 μm and highly transmissive near 0.8 μm . The laser emits 60 to 80 ns pulses with an energy of 250 μJ , delivered at 1 kHz repetition rate. The laser beam has a fundamental Gaussian profile with an M^2 factor below 1.05.

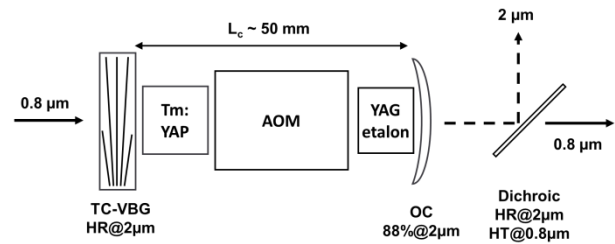


Figure 3. Schematic of the tunable pump laser

2.3. Nested cavity optical parametric oscillator

The NesCOPO, presented in Fig. 4, consists of a dual-cavity doubly resonant OPO where the signal and the idler cavity lengths are controlled separately. In this architecture the two wavelengths produced by the nonlinear crystal oscillate in separated cavities ($M_2 - M_3$ for the signal wave and $M_1 - M_3$ for the idler wave). This approach leads to single-longitudinal-mode operation for an adequate differentiation of the cavity lengths because only a single exact coincidence of signal and idler modes can be obtained within all the parametric gain bandwidth via Vernier filtering, as illustrated in Fig. 5.

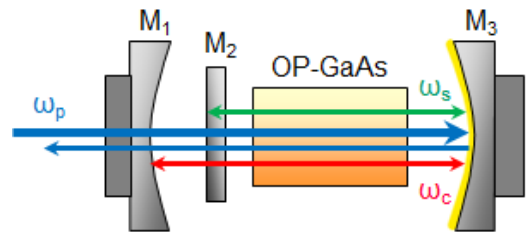


Figure 4. Illustration of the NesCOPO doubly resonant cavities

The NesCOPO is made of a 6 mm long OP-GaAs crystal with quasi-phase matching (QPM) periods of 64.8 and 66 μm , a concave dichroic mirror (M_1) highly transmissive near 2 μm and in the 2.3 – 2.6 μm range and with a 80 % reflectivity in the 8 – 12 μm range with a radius of curvature of 30 mm, a plano-plano dichroic mirror (M_2) highly transmissive near 2 μm and in the 8 – 12 μm range

and 98 % reflectivity in the 2.3 – 2.6 μm range and a concave gold mirror (M_3) with a radius of curvature of 50 mm. The M_1 and M_3 mirrors form the idler cavity and the M_2 and M_3 mirrors form the signal cavity. The overall cavity is ~ 10 mm long. The M_1 and M_3 mirrors are mounted on piezoelectric transducers to finely adjust the length of the idler and signal cavities.

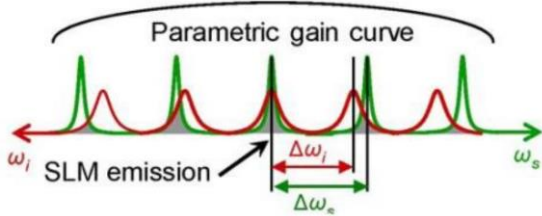


Figure 5. Giordmaine and Miller diagram. Illustration of mode selection in the NesCOPO. The signal and idler frequency axes are oriented in opposite directions to fulfil energy conservation.

We pumped this NesCOPO with the tunable 2 μm laser in the setup shown in Fig. 6. The pump laser was focused into the OP-GaAs crystal with a triplet of lenses ($F_1 = 75$ mm; $F_2 = -40$ mm; $F_3 = 100$ mm) to obtain a beam radius of 100 μm . Half-wave plate ($\lambda/2$) and polarising beam splitter (PBS) were used to adjust the injected pulse energy, and two dichroic mirrors (D_s and D_i) were used to extract signal and idler beams. An optical isolator was used to prevent back coupling of the residual pump into the laser cavity.

2.4. Orientation patterned gallium arsenide crystal

Orientation patterned gallium arsenide crystals are grown by hydride vapor phase epitaxy. The substrates obtained by bonding a layer of GaAs in crystallographic direction [00-1] on a [001] GaAs wafer. The quasi-phase matching pattern is defined with photolithography and etching processes. Then the crystal is grown from the patterned wafer [8]. Final crystals are diced and polished before their facets are antireflection coated.

We used a 6 mm long OP-GaAs crystal with three tracks with quasi-phase matching periods of 63.6, 64.8 and 66 μm as shown in Fig 7. Unfortunately, the 63.6 μm QPM period track was broken before we started the measurements; therefore, we only present results with the two other QPM periods.

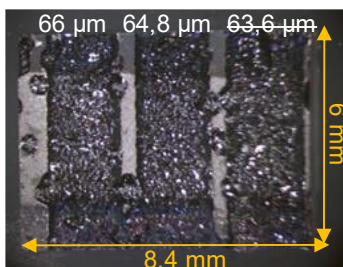


Figure 7. Annotated picture of the OP-GaAs crystal

The NesCOPO oven allows us to set the crystal temperature from 10 to 60 $^{\circ}\text{C}$ with thermoelectric modules. Table 1 sums up the crystal characteristics and gives the expected tuning ranges through pump wavelength tuning from 1.94 to 1.96 μm for the two available QPM periods at 20 and 60 $^{\circ}\text{C}$.

Table 1. Properties of the used OP-GaAs crystal

QPM period (μm)	64.8	66
Length (mm)	6	
Idler range at 20 $^{\circ}\text{C}$ (μm)	7.5 – 7.9	7.8 – 8.2
Idler range at 60 $^{\circ}\text{C}$ (μm)	7.8 – 8.2	8.1 – 8.5

2.5. Sum frequency generation for wavelength measurement

To check the pump wavelength, we chose second harmonic generation (SHG) near 1 μm and used a silicon-based spectrometer that present higher resolution and sensitivity than its InGaAs counterparts, at a lower cost. We can similarly measure the idler wavelength, thanks to sum frequency generation (SFG) of the pump and signal wavelengths, near 1.1 μm . The principle of the module is illustrated in Fig. 8.

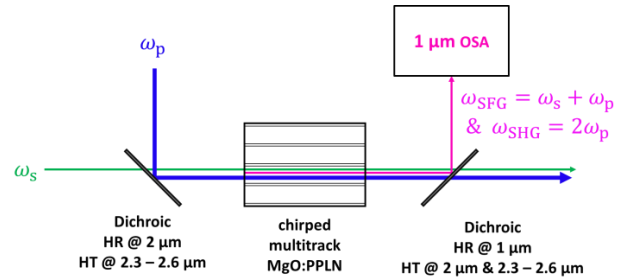


Figure 8. Principle of the SHG/SFG module for wavelength measurements.

Based on energy conservation (Eq. 1 – 3), we easily deduce Eq. 4, where ω_p , ω_s , ω_i , ω_{SHG} and ω_{SFG} are respectively the pump pulsation, the signal pulsation, the idler pulsation, the pump second harmonic pulsation and the pulsation of the sum frequency of pump and signal.

$$\text{Eq.1} \quad \omega_p = \omega_s + \omega_i$$

$$\text{Eq.2} \quad \omega_{\text{SHG}} = 2\omega_p$$

$$\text{Eq.3} \quad \omega_{\text{SFG}} = \omega_p + \omega_s$$

$$\text{Eq.4} \quad \omega_i = \omega_{\text{SHG}} - \omega_{\text{SFG}}$$

Sum frequency generation was obtained in a 20 mm long longitudinally chirped periodically poled lithium niobate crystal (APPLN) with multiple aperiodic quasi-phase matching period tracks. Here, we used a track with a QPM period chirp from 30.04 to 35.02 μm . The QPM period chirp broadens the spectral acceptance of the frequency conversion to 150 cm^{-1} allowing us to use only one crystal for all the measurements. Additionally, a measurable level of second harmonic generation was obtained as the

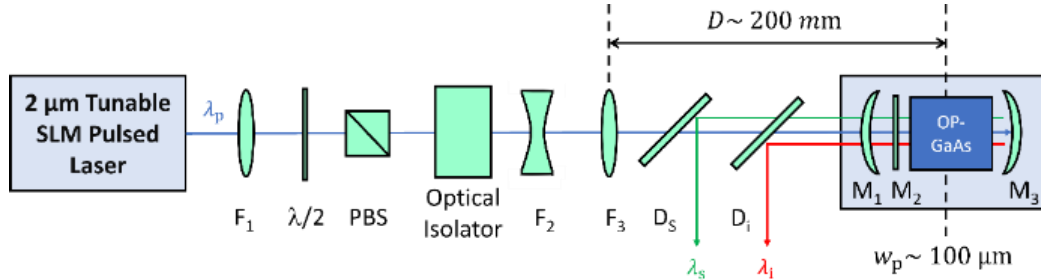


Figure 6. Experimental setup used to pump the NesCOPO with the tunable 2 μm pump laser. F_i with i from 1 to 3 are beam shaping lenses. $\lambda/2$ is a 2 μm halfwave plate, PBS a polarising beam splitter. D_i and D_s are dichroic mirrors to extract respectively the idler and signal waves.

consequence of off-phase-matched conversion in the crystal due to the high pump energy. The pump energy was $90 \pm 10 \mu\text{J}$ and the beam radii into the APPLN crystal were 100 μm for the pump and 110 $\pm 10 \mu\text{m}$ for the signal. The SFG and SHG beams are collimated with a 75 mm focal lens, separated from the pump and signal beams with a dichroic mirror and injected in a single mode fibre. We used an optical spectrum analyser ANDO AQ6317B to record the sum frequency and second harmonic spectra.

3. RESULTS

3.1. Operation of the NesCOPO

With a half waveplate and a polarizing cube, we injected 25 μJ of pump energy into the NesCOPO. We obtained up to 200 nJ of idler energy. As the pump laser operates at a 1 kHz repetition rate, it corresponds to a 200 μW average power. Figure 9 shows the temporal profile of the idler pulses in red compared to the pump pulses profile in blue while scanning M_3 position.

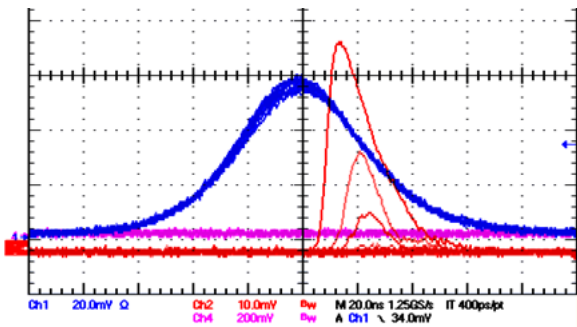


Figure 9. Pump (blue) and idler (red) pulses oscillogram.

We also obtained a few hundreds of microwatts of power on the signal wave.

3.2. Sum frequency generation

The APPLN crystal temperature was set to 50 $^\circ\text{C}$ by optimizing the SFG yield for a signal and pump wavelengths pair. Even though the yield varies with the pump and signal wavelengths, we were able to estimate that it was at least 5 % after injection in the single mode fibre with respect to signal energy.

3.3. Pump tuning results

Fig. 10 shows the measured idler wavelength as a function of the measured pump wavelength with 64.8 and 66 μm QPM periods, superimposed with the theoretical gain bandwidth of 20 cm^{-1} (dashed lines).

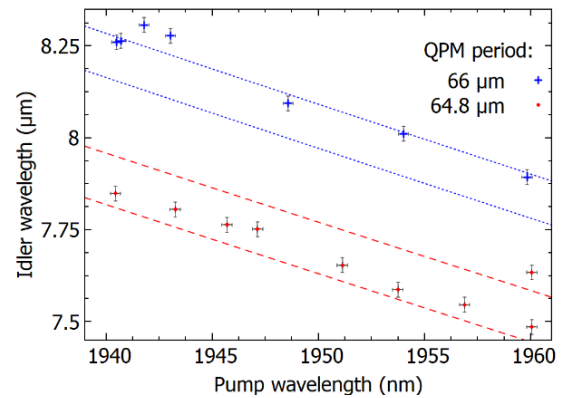


Figure 10. Idler wavelength emitted by the NesCOPO depending on the pump wavelength for QPM periods of 64.8 μm and 66 μm and crystal temperature of 21.7 $^\circ\text{C}$.

As shown in Fig. 10, tuning the pump wavelength from 1.94 to 1.96 μm with the OP-GaAs crystal at 21.7 $^\circ\text{C}$, we tuned the idler wavelength from 8.31 to 7.89 μm (64 cm^{-1}) with the 66 μm QPM period, and from 7.85 to 7.48 μm (63 cm^{-1}) with the 64.8 μm period. The same tuning of the idler wavelength through crystal temperature tuning would require scanning more than 60 $^\circ\text{C}$. The tuning slopes are 21 and 18.5 nm/nm respectively with the 66 μm and the 64.8 μm QPM periods.

We notice on Fig. 10 that with the 64.8 μm QPM period, 1.96 μm pump wavelength leads to multiple possible idler wavelength and that with the 66 μm QPM period, there is a slight slope reversal near 1.94 μm pump wavelength. These elements are linked to signal/idler longitudinal mode coincidence selection within the parametric gain bandwidth, that was not actively controlled when acquiring this set of measurements.

Tuning the pump wavelength required a few seconds between measurements to translate the TC-VBG with a manual translation stage. This can be fastened with a motorised translation stage. Tuning the nonlinear crystal temperature to obtain similar idler wavelength tuning range would require

a few minutes to properly scan and stabilize the temperature.

4. PERSPECTIVES

These results open the way for broader and faster wavelength tuning of parametric sources.

The moderate output energy still limits the detection range below a few tens of meters in integrated path lidar setups with a topographic target. One way to overcome this limitation is to use this source as a master oscillator for a power amplifier.

We are currently making an upgraded version of the #1 LWIR source to include both pump wavelength tuning and an OP-GaAs based optical parametric amplifier suited to reach microjoule level idler pulses. A picture of the new laser head prototype (#2) is shown in Fig. 11.



Figure 11. Picture of the #2 LWIR laser head prototype.

Concurrently, automation of the wavelength control is being developed to benefit from faster tuning and ensure long term wavelength stabilisation. This automation is based on in-place wavelength measurements with the SHG/SFG module and a compact SWIFT based spectrometer such as MicroSpectra from Resolution Spectra Systems. Further developments will strive to increase the broadband wavelength tuning speed and to increase pulse energy.

5. CONCLUSION

Tuning of the pump laser over 20 nm translated to close to 400 nm tuning in the LWIR for the two QPM periods, leading to a total tuning span close to 1 μm in the LWIR. These results show that pump tuning of a NesCOPO is a promising way to achieve broadband tuning in the LWIR much faster than by using crystal temperature tuning. In addition, a preindustrial prototype of this LWIR source was manufactured and will be integrated in a lidar prototype to perform standoff measurements of gas concentration.

6. ACKNOWLEDGEMENT

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