Broadly tunable single-frequency cw mid-infrared source with milliwatt-level output based on difference-frequency generation in orientation-patterned GaAs

Sergey Vasilyev,[1,*] Stephan Schiller,[1] Alexander Nevsky,[1] Arnaud Grisard,[2] David Faye,[2] Eric Lallier,[2] Z. Zhang,[3] A. J. Boyland,[3] J. K. Sahu,[3] M. Ibsen,[3] and W. A. Clarkson[3]

[1]*Institut für Experimentalphysik, Universitätsstraße 1, 40225 Düsseldorf, Germany*
[2]*Thales Research and Technology, RD 128, 91767 Palaiseau cedex, France*
[3]*Optoelectronics Research Centre University of Southampton Highfield, Southampton, SO17 1BJ United Kingdom*
Corresponding author: Sergey.Vasilyev@uni-duesseldorf.de

Received March 28, 2008; accepted April 30, 2008;
posted May 23, 2008 (Doc. ID 94403); published June 19, 2008

A narrow-linewidth mid-IR source based on difference-frequency generation of an amplified 1.5 μm diode laser and a cw Tm-doped fiber laser in orientation-patterned (OP) GaAs has been developed and evaluated for spectroscopic applications. The source can be tuned to any frequency in the 7.6–8.2 μm range with an output power of 0.5 mW. The measured characteristics of the OP-GaAs sample demonstrate a high quality of the material. © 2008 Optical Society of America

OCIS codes: 190.2620, 190.4360, 190.4400, 300.6350.

Spectroscopy and monitoring of molecular gases in the mid-IR range (5–15 μm) attract a growing interest for a number of scientific and commercial applications. In cw mode, this range can be addressed, e.g., by quantum-cascade lasers. However, an attractive alternative approach is nonlinear downconversion of near-IR laser radiation using difference-frequency generation (DFG). The advantages of this method are wide and fast tunability, potential complete coverage of the mid-IR range, and spectral properties determined by those of the near-IR waves, for which narrow-linewidth sources are available.

Single frequency cw-DFG (and cw–optical-parametric-oscillator) sources are now well established in the 3–4.5 μm spectral region [1] thanks to quasi-phase-matched (QPM) oxide nonlinear materials. However, the use of standard QPM materials for the mid-IR is restricted owing to their intrinsic absorption at wavelengths longer than ~5 μm. GaAs is a suitable material for the generation of longer wavelengths. Important features of the GaAs crystal are its high nonlinear coefficient (100 pm/V), wide transparency range (0.9–17 μm), and high thermal conductivity (50 W $K^{-1} \cdot m^{-1}$). However, for lack of birefringence, one must use the QPM technique for efficient nonlinear conversion. As the electric field poling technique cannot be employed for GaAs, the crystal must be grown with the optical axis periodically reversed (orientation patterning, OP). Recently, methods were developed for fabrication of wafer-size OP-GaAs structures. These methods rely on a specific epitaxial growth step based on hydride vapor phase epitaxy (HVPE) carried out on a prepatterned substrate [2].

As pump sources for OP-GaAs, fiber lasers are an obvious option, since, e.g., cw Er-doped fiber lasers and amplifiers (EDFA) with up to 100 W output at 1.5 μm wavelength and very good spectral properties are turnkey commercial products. More recently, high-power cw single-frequency Tm-doped fiber lasers operating in the 2 μm wavelength range have been demonstrated [3]. Their wide emission range (1.75–2.1 μm) makes Tm-doped fiber lasers especially attractive for realization of a broadly tunable mid-IR source based on a OP-GaAs crystal. Another advantage of the long-wavelength Tm-laser pump is large offset of the photon energy from the GaAs bandgap. This translates into lower linear absorption, two-photon absorption, and linear dispersion, which are favorable for high-power pumping and for QPM.

The first mid-IR cw-DFG sources based on OP-GaAs were demonstrated a few years ago. Weak (40 nW) mid-IR output was obtained by mixing 1.3 μm (3 mW) and 1.55 μm (800 mW) telecom lasers [4]. More recently, tunable 1.3 μm (80 mW) and 1.55 μm (2 W) lasers were mixed, resulting in several microwatts of output, tunable in the 7–9 μm range [5]. This source was evaluated for cavity ring-down spectroscopy. In this Letter we report on a broadly tunable mid-IR DFG source with submilliwatt output. The source is based on DFG between a telecom laser amplified by a commercial EDFA and a custom Tm-doped fiber laser. The DFG output wavelength was tunable from 7.6 to 8.2 μm by simultaneous tuning of the diode laser wavelength and of the OP-GaAs crystal temperature. The spectroscopic capabilities of the mid-IR source were tested by measuring CH_4 absorption spectra.

Figure 1 shows the experimental setup. A high-power non-polarization-maintaining EDFA (Keopsys KPS-STD-BT-C-40-SLM) seeded by a single-frequency tunable external-cavity diode laser (Agilent 81642A), is used as pump source. The maximum EDFA output after the external isolator was about 9 W. The pump wavelength was tunable within the 1540–1570 nm range, with precision of 0.1 pm. The

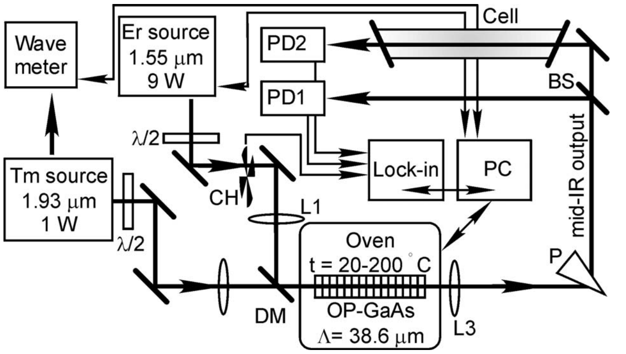

Fig. 1. Experimental setup: λ/2, retardation plates; CH, chopper wheel; PD, photodetectors; see description in the main text.

signal source is a Tm laser consisting of a DFB fiber laser followed by a Tm-fiber amplifier and generates 1 W output power at 1.945 μm. Its emission spectrum consists of two orthogonally and linearly polarized modes spaced by 600 MHz. Thus two 500 mW single-frequency output beams can be obtained using a polarizing beam splitter. A drawback of this regime of operation is considerable output power fluctuations for each mode (25%), on a subsecond time scale, although the total output power of the Tm laser was rather constant (within 3%). The Tm laser is piezotunable over a 15 GHz range. The Tm-laser wavelength was monitored with 80 MHz accuracy using a Burleigh WA-1000-IR wavemeter. Pump and signal beams were focused by lenses L1 and L2 (both with 100 mm focal length) and combined using a dichroic mirror (DM). The OP-GaAs crystal was 33 mm long and 0.45 mm thick and had a 38.6 μm period. Crystal faces were plane-parallel polished and cut at a small angle to its axis so as to prevent etalon effects. The crystal was uncoated, introducing 30% Fresnel reflection at all wavelengths for each surface. The losses in the HVPE layer at pump and signal wavelengths were measured as 0.03–0.05 cm^{-1}. The crystal's temperature was adjustable in the 20°C–60°C and 40°C–200°C ranges using two ovens with a thermoelectric heater and a resistive heater, respectively. The pump and signal beams were separated from the idler beam using a Ge prism (P), which efficiently transmitted the *p*-polarized idler wave. The mid-IR output was collimated and focused using antireflection-coated ZnSe lenses (L3).

The spectroscopy system consisted of a measurement channel, with a 1-m-long gas absorption cell and a reference channel. A CaF$_2$ wedge (BS) was used to split the mid-IR output between two channels. Both channels were equipped with pyroelectric detectors (InfraTec LME-353), and a standard lock-in amplifier technique was used to generate output signals. Data acquisition, pump wavelength tuning, and crystal temperature tuning were computer controlled using a LABVIEW program. The pump wavelength was step tuned at 2–5 steps per second and down to 0.1 pm (12 MHz) minimum step size, while the crystal temperature was tuned so as to maintain phase matching.

Figure 2 illustrates the dependence of DFG output power on the pump wavelength at fixed signal wavelength (1944.8 nm) and OP-GaAs crystal temperature (30°C). A theoretical conversion-efficiency curve was calculated in the plane-wave approximation, using data on GaAs dispersion from [6]. An empirical correction of the OP-GaAs temperature was made in order to take into account heating of the crystal by laser beams. As can be seen, the deviation of the measured curve from the sinc^2 behavior is small. The calculated and measured bandwidths as well as the positions of the secondary maxima almost coincide. This agreement indicates a high quality and uniformity of the HVPE layer patterning.

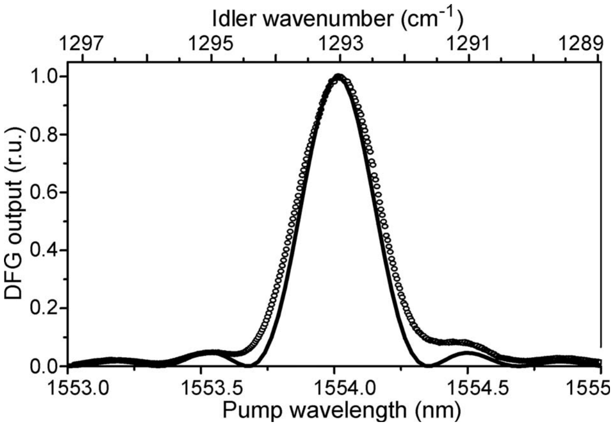

Fig. 2. Measured (°) and calculated (solid curve) DFG output versus signal wavelength.

The output power of the DFG source was measured at fixed Tm-laser power (500 mW), whereas the EDFA power was varied. The measurements were carried out using a highly sensitive thermal head (OPHIR 3A). Solid circles in Fig. 3 show the DFG output power versus pump power, and hollow circles show respective EDFA wavelengths, which correspond to the maximum DFG output. As can be seen, the DFG output increases in direct proportion to the pump power, in good agreement with the theory. The optimal pump wavelength increases with increase of the pump power. The obvious reason is the heating of the crystal region traversed by the high-power 1.5 μm pump laser, above the average temperature inside the oven (25°C). The measured value of the wavelength shift corresponds to a temperature in-

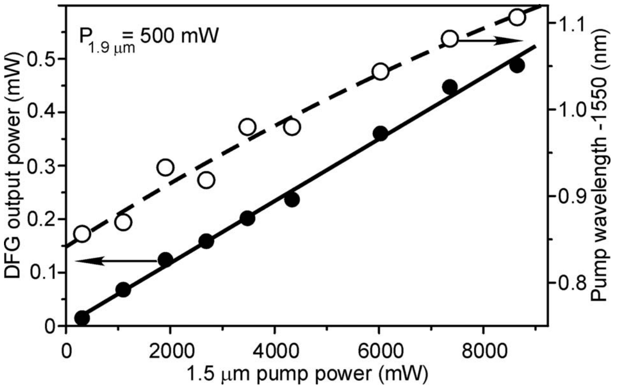

Fig. 3. DFG output power (•) and optimal pump (°) wavelength versus pump power.

crease of 2.5 °C. No visible degradation of the crystal has been observed during long-term operation of the setup at the highest pump power. A maximum mid-IR output power of 0.5 mW for single-frequency output was measured at 9 W pumping (correcting for the crystal output facet reflection, this is 0.7 mW). The theoretical estimate for DFG between optimally focused beams [4] is 1.8 times higher. This difference may be explained by nonideal beam focusing and some losses introduced during beam separation and collimation.

To characterize the spectroscopic capability of the source, absorption spectra of CH_4 were measured using the setup described above. Maximum spans of fully automated measurement runs (7.6–7.8 μm and 7.7–8.2 μm) were limited by the temperature-tuning range of the crystal's ovens. The limited power stability of the signal wave was a main factor degrading the signal-to-noise ratio. Consequently, a tuning rate of two points per second was selected in order to average the noise. In addition, fast tuning of the DFG source over a 0.5 cm^{-1} range was realized by piezotuning the signal (Tm-laser) wavelength at fixed pump wavelength and crystal temperature.

Figure 4 compares three spectra: (a) part of the spectrum measured by tuning of the pump wavelength and the crystal temperature, (b) a spectrum measured by piezotuning the Tm laser, and (c) a reference CH_4 absorption spectrum, generated using the HITRAN database. The gas cell was filled with 0.2 torr of CH_4. Spectrum (b) was acquired during the single-tuning cycle of the Tm laser (0.25 s), using a fast dc-coupled semiconductor detector (VIGO PVI-2TE-8). An empirically derived formula for the voltage-to-frequency offset conversion was applied to compensate the Tm laser's piezoactuator nonlinearity. Within the 80 MHz inaccuracy of wavelength measurements, line positions on spectra (a) and (c) coincide. The absorption line shapes on the slowly measured spectrum (a) and "quick" spectrum (b) are very similar.

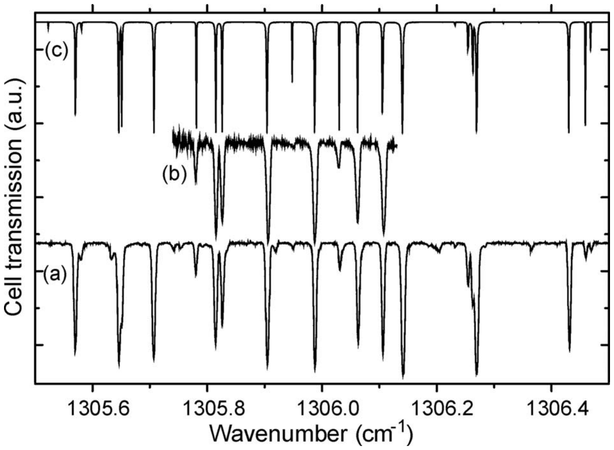

Fig. 4. Comparison of CH_4 spectra: (a) measured by slow pump wavelength tuning, (b) measured by fast signal wavelength tuning, (c) simulation based on HITRAN data.

In conclusion, we have developed a cw narrowband mid-IR source with 0.5 mW output power based on DFG between 1.5 and 2 μm fiber laser sources in OP-GaAs. The source was step tunable in 7.6–7.8 μm and 7.7–8.2 μm ranges with minimum step size of 12 MHz at up to five steps per second. It is well suited to spectroscopy, as was demonstrated by measuring methane absorption spectra using simple pyroelectric detectors. A straightforward improvement of the source is an increase of the mid-IR output power by a factor of 3 by antireflection coating the crystal facets. Moreover, the observed performance of the OP-GaAs crystal under high-power 1.5/2 μm laser irradiation indicates that the pump powers, and hence the generated power, can be further scaled up. The tuning speed of the mid-IR source can be increased to several cm^{-1} per minute by using pump lasers with fast mode-hop free tunability and the oven design allowing 10 °C–20 °C min^{-1} crystal's heating or cooling speed. Thus, cw OP-GaAs DFG sources are interesting alternatives to current cw quantum-cascade lasers.

We are grateful to Peter Geiser and Norsk Elektro Optikk for CH_4 spectra simulations and for lending us a mid-IR detector. This research is supported by the European Commission within the VILLAGE project (www.neo.no/village).

References

1. F. K. Tittel, D. Richter, and A. Fried, in *Solid-State Mid-Infrared Laser Sources*, I. T. Sorokina and K. L. Vodopyanov, eds., *Topics in Applied Physics* (Springer-Verlag, 2003), Vol. 89, pp. 445–516.
2. D. Faye, E. Lallier, A. Grisard, B. Gerard, and E. Gil-Lafon, presented at Materials Research Society Fall Meeting, December 1–5, 2003, Boston, Mass., Symposium Z2.2.
3. D. Gapontsev, N. Platonov, M. Meleshkevich, O. Mishechkin, O. Shkurikhin, S. Agger, P. Varming, and J. H. Povlsen, in *Conference on Lasers and Electro-Optics*, OSA Technical Digest Series (Optical Society of America, 2007).
4. O. Levi, T. J. Pinguet, T. Skauli, L. A. Eyres, K. R. Parameswaran, J. S. Harris, Jr., M. M. Fejer, T. J. Kulp, S. E. Bisson, B. Gerard, E. Lallier, and L. Becouarn, Opt. Lett. **27**, 2091 (2002).
5. S. E. Bisson, T. J. Kulp, O. Levi, J. S. Harris, and M. M. Fejer, Appl. Phys. B **85**, 199 (2006).
6. T. Skauli, P. S. Kuo, K. L. Vodopyanov, T. J. Pinguet, O. Levi, L. A. Eyres, J. S. Harris, M. M. Fejer, B. Gerard, L. Becouarn, and E. Lallier, J. Appl. Phys. **94**, 6447 (2003).