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Abstract: We demonstrate a broadly and continuously tunable optical parametric oscillator (OPO) based on orientation-patterned GaAs (OP-GaAs) operating at 2 kHz repetition rate. With the choice of the pump wavelength near λ = 3 μm, we were able to achieve tunable output in the whole range of 4-14.2 μm with a linewidth between 2 and 6 cm^{-1}, using a single OP-GaAs structure with a domain reversal period of 150 μm. The OPO output was tuned using (i) an intracavity diffraction grating, and (ii) fine adjustment of the pump wavelength near 3 μm. In certain portions of the spectrum this system potentially allows fast (sub-millisecond scale) wavelength tuning over > 2500 nm by fast steering the diffraction grating at a fixed pump wavelength.

OCIS codes: (190.2620) Harmonic generation and mixing; (190.4970) Parametric oscillators and amplifiers; (190.4400) Nonlinear optics, materials; (160.6000) Semiconductor materials.

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1. Introduction

Because of its wide infrared transparency (0.9-17 µm), large second-order nonlinear optical coefficient d_{14} = 94 pm/V [1] and excellent mechanical and thermal properties, quasi-phase-matched (QPM) orientation-patterned GaAs is among the most attractive nonlinear optical materials for reaching the long wavelength portion, λ>5 µm, of the mid-IR spectrum. After the first demonstration of the OP-GaAs OPO (nanosecond pump at 1.8-2 µm) [2], optical parametric devices operating in different time formats were implemented, including high-average-power nanosecond [3, 4], picosecond [5], femtosecond [6, 7] and continuous wave [8] regimes. As for the long-wavelength operation, the idler wave tuning range of 5.8-9.1 µm was obtained in Ref. 2 and was later extended the same authors to 11.1 µm [9]. Longwave infrared OPO output (at 8.8, 10.7, and 11.5 µm) was produced in [10] with the 2.05-µm pump and three OP-GaAs crystals with different QPM periods. Also, tunable narrow-linewidth and high brightness continuous-wave output tunable in the range 7.6–8.2 µm was generated via difference frequency generation [11].

One of the main motivations for this work was to create a broadly and continuously tunable compact source for spectroscopic applications, including infrared spectroscopy at the nanoscale using an atomic force microscope [12–14], in the range of vibrational resonances of condensed matter, typically between 2.5 and 15 µm. Here we demonstrate a compact narrow-linewidth GaAs-based OPO that is uninterruptedly tunable over a broad mid-IR range.

2. Setup

An anomalously broad tuning (or wide instantaneous spectrum if there is no spectral selection) of an optical parametric device can be achieved near degeneracy, when the group velocity dispersion of the nonlinear crystal is close to zero at the degeneracy point [5,15,16]. Here we fulfill such a condition by choosing a pump near 3-µm wavelength, to achieve broadly-tunable narrow-linewidth output.

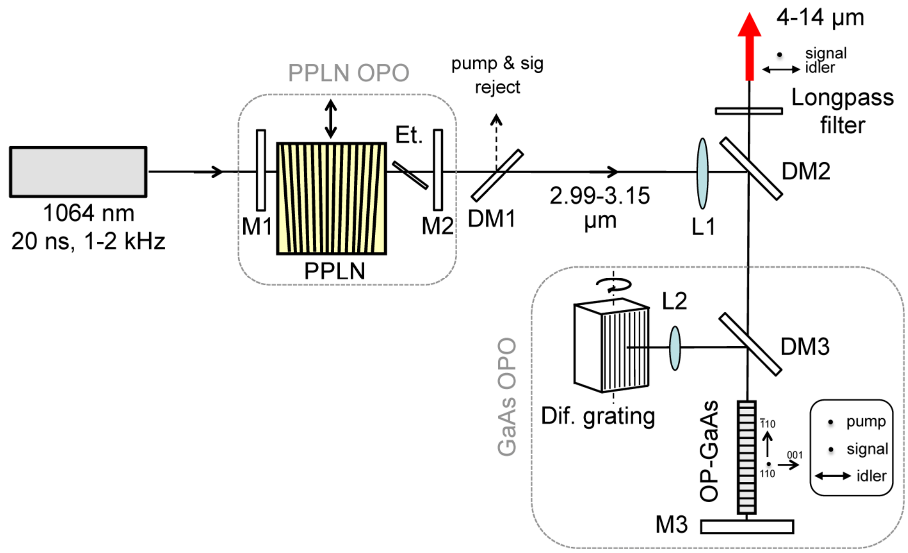

Fig. 1. Schematic of the OP-GaAs OPO. Tunable 2.99 - 3.15 µm pump pulses from the PPLN OPO were focused by a lens L1 into the GaAs crystal. A dichroic mirror DM2 reflects the 3-µm pump and transmits the GaAs OPO output (4-14 µm). The L-shaped GaAs OPO cavity is formed by: (i) diffraction grating, (ii) dichroic mirror DM3 that highly reflects (R>98%) the signal at 4-6 µm and transmits the 3-µm pump and the idler at 6-14 µm, and (iii) metallic mirror M3. The lens L2 is introduced to make a stable cavity.

The pump source was a periodically poled lithium niobate (PPLN) OPO pumped by a Nd:YAG laser (1.064 nm, 20 ns, 1-2 kHz 1.4 mJ). The OPO was formed by two flat mirrors M1 and M2 that were highly reflective at the signal wave, Fig. 1. A 20-mm-long PPLN crystal (t = 160°C) had a 'fanned' grating with a QPM period that varied from 29 to 30.6 µm across the width of the crystal and tuning of the wavelength was achieved by linear motion of the crystal across the beam. To reduce the linewidth, we used a 60-µm-thick undoped YAG intracavity etalon (*Et.* in Fig. 1) so that the spectral width was < 5 cm^{-1}, that is within the pump acceptance bandwidth of the GaAs OPO (13-42 cm^{-1}, depending on the wavelength). A 45-degree dichroic mirror (DM1 in Fig. 1) was used to reject the 1064-nm pump and signal wave, and transmit the idler at $\lambda \approx 3$ µm.

The OP-GaAs crystal was grown at BAE Systems using the all-epitaxial processing technique developed at Stanford [17]. First polar-on-non-polar molecular beam epitaxy was used to grow a 1200Å-thick inverted GaAs layer on a 3-inch diameter, 4°-offcut (toward <111B>) semi-insulating substrate. Photo-lithography, wet-etching, and MBE regrowth were then used to produce a 2-µm-thick QPM "orientation-patterned" GaAs template with the desired grating periods. Finally, low-pressure hydride vapor phase epitaxy (LP-HVPE) was performed in a commercial reactor to produce a low-loss, 1.3-mm-thick QPM layer in a single uninterrupted 10-hour growth run resulting in excellent vertical domain propagation to maintain the 50:50 grating duty cycle. (Sequential 10-hr growth runs have since yielded OP-GaAs samples with QPM layers up to 3.5-mm thick [18].) An OP-GaAs device crystal measuring 20-mm-long, 5-mm-wide, and >1-mm-thick (along [001], Fig. 1) was cut from the multi-grating wafer without 'streets' between gratings to eliminate overgrowth. A QPM grating period of 150 µm was selected for broadband operation with a 3-µm pump. The optical faces were polished and anti-reflection coated for minimal reflection losses at $\lambda \approx 3$ µm and 4 – 6 µm.

The OPO schematic is shown in Fig. 1. Pump pulses from the PPLN OPO (100-120 µJ, 20 ns, $M^2 \approx 1.5$), were focused by a lens L1 (focal distance f = 100 mm) to the spot size $w_0 \approx 135$ µm ($1/e^2$ intensity radius) inside the OP-GaAs. A dichroic mirror DM2 reflects (>98%) the 3-

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μm pump and transmits (>70%) the GaAs OPO output at 4-14 μm. The L-shaped OP-GaAs OPO cavity was formed by: (i) a diffraction grating in the Littrow configuration, (ii) a dichroic mirror DM3 that highly reflects (R>98%) the signal wave at 4-6 μm and transmits (>90%) the pump and the idler at 6-14 μm, and (iii) a gold-coated flat mirror M3.

For the OPO tuning and linewidth control we have used a first-order diffraction grating in the Littrow configuration [19]. The 300 grooves/mm grating from Optometrics had reflection efficiency of >85% for the signal wave at 4-6 μm. Through tuning the signal between 6 and 4 μm (grating angle of incidence between 66 and 37.5 degrees), the idler was tuned from 6 to 14 μm. The signal wave was resonant, while the pump and the idler made a double pass (via M3) through the OP-GaAs crystal and left the cavity. The total physical length of the L-shaped cavity was 41 mm; a CaF_2 lens L2 with f = 20 mm was introduced to form a stable cavity with the eigenmode spot sizes of 100 and 350 μm at M3 and at the diffraction grating correspondingly. Polarization directions for the pump, the OPO signal and idler are shown in Fig. 1.

3. Results

Figure 2 plots the OPO tuning curve, taken with a grating monochromator and a pyroelectric detector. There is a good agreement with the theoretical curve (solid line) based on GaAs dispersion data [20].

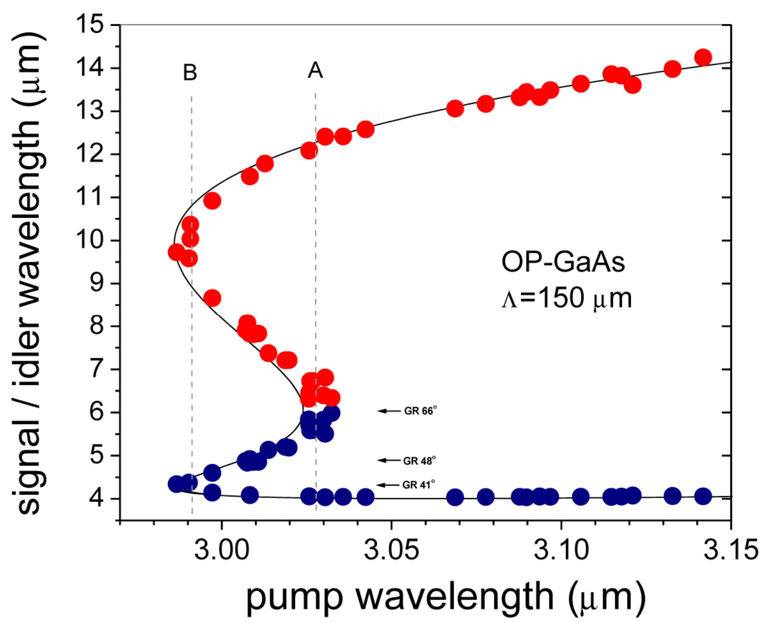

Fig. 2. The OPO pump tuning curve. The wavelength was tuned by (i) intracavity diffraction grating and by (ii) fine adjustment (within less than 160 nm) of the pump wavelength. Solid line is theoretical tuning curve. Also shown are diffraction grating angles for several resonating signal wavelengths.

A small mismatch can be accounted for by the fact that the theoretical curve was generated for the plane-wave interaction, while here we had focused beams. The OPO wavelength was tuned by (i) intracavity diffraction grating and by (ii) small adjustment of the pump wavelength within 2.99 - 3.15 μm. Overall, continuous tunability in the whole range of 4-14.2 μm was achieved with a linewidth between 2 and 6 cm^{-1}. Figure 3 plots the line shapes at different spectral regions.

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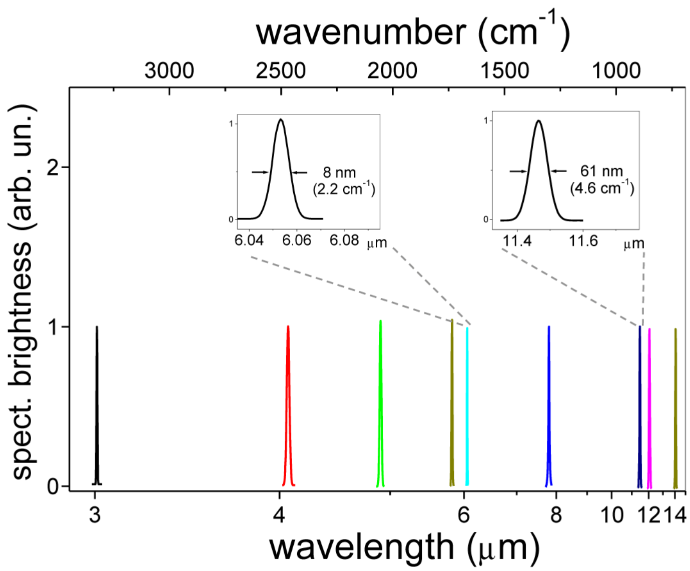

Fig. 3. Normalized line shapes of the pump and OPO output at different signal and idler wavelengths.

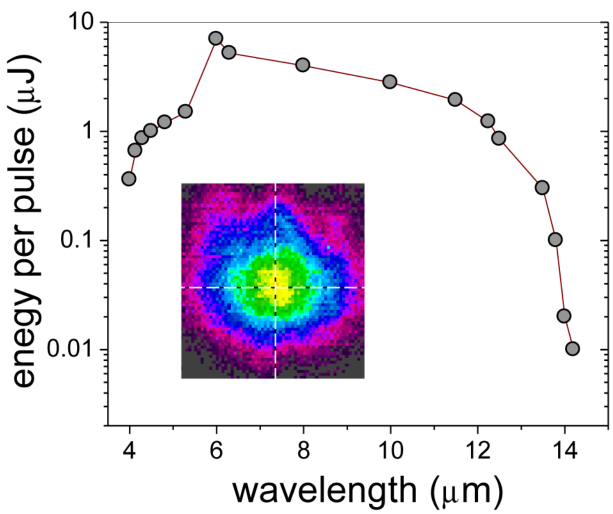

Fig. 4. OPO pulse energy as a function of wavelength. The inset shows a far-field beam profile of the idler wave at λ≈8 μm.

The OPO tuning curve shows a 'retracing' behavior, that is a single pump wavelength can generate two different signal-idler pairs. We have experimentally demonstrated that at the turning points (vertical dashed lines 'A' and 'B' in Fig. 2), the OPO tuning can be performed at a fixed pump wavelength, solely by the grating: within the range of 5.1-7.4 μm at 'A' and of 8.7 −11.2 μm (idler wave) at 'B'. This potentially allows very fast (<1 ms) OPO tuning by changing the grating angle via a fast steering piezo stage. The range of fast tuning can be extended to cover, for example, the whole 8-12 μm atmospheric window - by the proper choice of GaAs QPM period and pump wavelength.

The OPO threshold, in terms of pump pulse energy, was approximately 25 μJ. Figure 4 plots the OPO pulse energy vs. wavelength. On the longer wavelength side, the energy per pulse gradually drops from 7 μJ at 6-μm degeneracy (where the orthogonally polarized signal

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and idler waves are added together) to less than 1 μJ above 12.5 μm. The signal pulse energy vs. wavelength dependence mimics that of the idler; however the signal wave is less energetic because of the non-optimized signal outcoupling. The OPO pulse-to-pulse root mean square (*rms*) energy variation was measured to be 7.5% with *rms* variation for the 3-μm pump of 2.5%. The far-field of the GaAs OPO output was recorded using a Spiricon Pyrocam-III beam profiler. The inset to Fig. 4 shows the beam profile of the idler wave at $\lambda \approx 8$ μm (distance from OPO 20 cm, plotted area size 12x12 mm). The beam quality factor was found to be M^2 ~1.5.

4. Conclusion

We demonstrate a compact low-threshold GaAs OPO with an uninterrupted mid-IR tunability of 4-14.2 μm. In certain spectral ranges (near 6 and 10 μm) the OPO can be fast tuned over > 2500 nm by the grating with the pump wavelength fixed. Direct 3-μm sources such as fiber or solid-state lasers can be advantageous as a pump. Finally we note that by adding the tuning range of the PPLN OPO (2.5-4 μm), the whole spectral range from 2.5 to 14.2 μm can be accessed with the present setup without gaps.

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