110GHz rapid, continuous tuning from an optical parametric oscillator pumped by a fiber-amplified DBR diode laser

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Abstract: A singly-resonant continuous-wave optical parametric oscillator (cw-OPO) pumped by a fiber-amplified diode laser is described. Tuning of the pump source allowed the OPO output to be tuned continuously, without mode-hops, over 110 GHz in 29 ms. Discontinuous pump tuning over 20 nm in the region of 3.4 µm was also obtained. The rapid and continuous idler tuning was demonstrated by the measurement of a methane absorption spectrum. We believe this to be the first example of a singly-resonant OPO pumped by a fiber-amplified diode laser and the mode-hop free tuning range to be the highest reported for a cw-OPO.

OCIS codes: (190.4970) Parametric oscillators and amplifiers; (140.3510) Lasers, fiber; (140.3600) Lasers, tunable

References and links

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1. Introduction

Real-time spectroscopic analysis of multi-component gas mixtures has many potential applications such as breath analysis for medical diagnostics, environmental monitoring and industrial process control. Sources of tunable radiation for use in such applications must meet a stringent set of performance criteria. To address the most prominent absorption features of a wide range of molecular species broad spectral coverage must be possible, ideally in a wavelength region, such as 3-5 μm, containing fundamental molecular ro-vibrational bands. To distinguish individual features in complex, possibly overlapping, spectra a resolution better than the typical atmospheric-pressure-broadened width of such molecular absorption features should be achievable. For real-time analysis applications, tuning should be rapid while remaining accurate and reproducible. Finally, sufficient power should be available to allow measurements to be made rapidly with a high signal-to-noise ratio.

Singly-resonant optical parametric oscillators (SROs) are able to meet many of the above requirements. SROs are capable of producing output powers in the mid-infrared (MIR) considerably greater than typically required for direct absorption measurements and sufficient to achieve high sensitivity with power-dependent techniques such as photo-acoustic spectroscopy [1]. The output wavelengths of an SRO can be coarsely tuned over wide ranges through the adjustment of the nonlinear crystal temperature, phase-matching angle or, in the case of quasi-phase-matched (QPM) materials, the QPM grating period. All these tuning methods are, however, relatively slow.

The combination of SROs with tunable pump lasers has allowed the development of a flexible and rapidly tunable class of MIR source. Typically, the SRO signal wave is resonated in a static cavity and maintains fixed, single-mode operation while the pump laser is tuned. The tuning performance of the pump is thus transferred directly to the MIR idler output of the SRO. In this way a source can be realized in the MIR which duplicates the tuning rate, range and accuracy of the pump laser operating in the near-infrared (NIR), where a variety of established and emerging tunable laser technologies exist. This approach has been successfully used to demonstrate precise, mode-hop free tuning over 56GHz from an SRO pumped by an external-cavity diode laser combined with a semiconductor amplifier [2], and also to achieve extremely rapid tuning over a wide spectral range when pumping with an acousto-optically tuned fiber laser [3]. While meeting some of the requirements of a source for real-time gas analysis mentioned above, these systems were limited in certain important respects. The mechanical tuning method of the external-cavity diode laser of [2] does not lend itself to rapid tuning or frequency-agile operation, while the limited spectral selectivity of the acousto-optic tuning element used in [3] resulted in an output bandwidth considerably larger than the resolution required for absorption measurements at atmospheric pressure.

In this paper we describe the operation of an SRO pumped by a fiber-amplified distributed Bragg reflector (DBR) diode laser. By combining the narrow linewidth and rapid, electronic tuning of the DBR laser with the high output power achievable from the fiber amplifier, a pump source is realized which allows the MIR output of the SRO to be rapidly tuned across mode-hop free ranges of up to 110GHz with sufficient resolution and precision to acquire accurate absorption spectra at atmospheric pressure. We believe this to be the first demonstration of an OPO pumped by a fiber-amplified diode laser and the mode-hop-free tuning range achieved to be the largest reported for a continuous-wave OPO.

2. Experimental configuration

The experimental configuration of the OPO and its pump source is shown schematically in Fig. 1. The DBR diode laser (Eagleyard Photonics GmbH, Berlin, Germany) was a multi-section device giving up to 80 mW of output in the region of 1082 nm. Three separate sections provided gain, phase control and DBR feedback. The phase and DBR sections could

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be thermally tuned by passing current through small resistive elements fabricated onto their upper surfaces. The device could be discontinuously tuned by up to 560 GHz (2.2 nm) via the DBR section alone while synchronous control of the phase and DBR sections allowed over 100 GHz of mode-hop-free tuning. The linewidth of the DBR laser was measured, using a Fabry-Perot interferometer, to be around 40MHz. After two-stage (60dB) isolation, up to 50mW of the DBR laser output was available to seed the 30 m long double-clad Yb-doped fiber amplifier (Institut für Physikalische Hochtechnologie, Jena, Germany). This amplifier had a 10 μm core, with a numerical aperture (NA) of 0.07 and a Yb_2O_3 doping concentration of 1000 mol-ppm, pumped via a 400 μm D-shaped inner cladding (NA 0.38). The amplifier was pumped from the output end with up to 25 W from a fiber-coupled 976 nm diode laser. Following isolation and polarization control, up to 6.9 W of amplified output were available to pump the OPO.

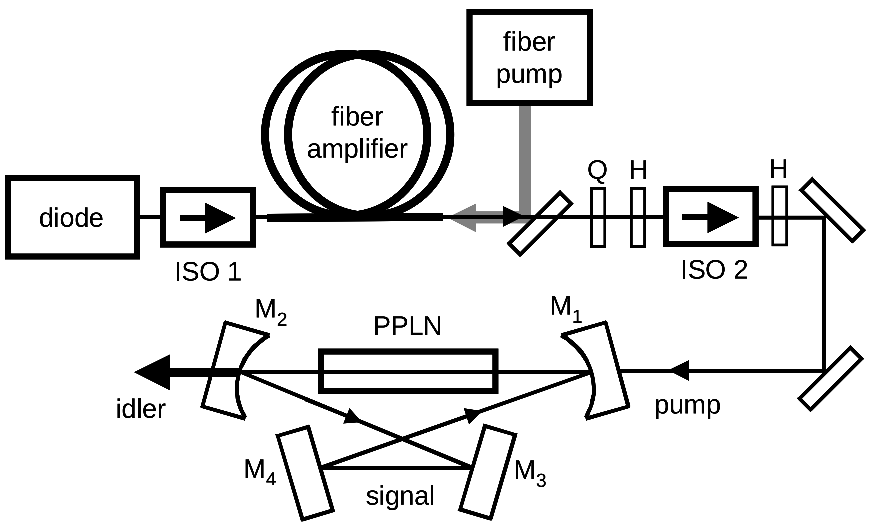

Fig. 1. Schematic of experimental arrangement. diode: 3-section DBR diode laser, fiber pump: 25W fiber-coupled 976nm diode bar, ISO 1: 60dB optical isolator, ISO 2: 30dB optical isolator, Q: quarter wave plate, H: half wave plates, M_1-M_4: OPO cavity mirrors, PPLN: 40mm PPLN crystal in oven.

When seeded with narrow-band sources, high-power fiber amplifiers can exhibit excessive intensity noise and self-pulsing behavior. Such effects were observed, in our case, for amplifier output powers greater than approximately 2W when operating the DBR laser with its normal spectral width of 40MHz. Stimulated Brillouin scattering (SBS) plays a major role in these instabilities, and has been shown to limit the achievable output power from double-clad amplifiers similar to that used here [4]. Suppression of SBS by the use of shorter fiber amplifiers having larger core diameters has enabled high power, narrow-band operation [5], although seed powers considerably greater than those available from the DBR diode laser used in this work were required. The alternative SBS suppression technique of spectral broadening via modulation is widely used in long-haul telecom fibers [6], although it has found only limited use with high-power fiber amplifiers [7]. By applying sinusoidal modulation at a frequency of 2 MHz to the gain section of the DBR laser we broadened the averaged output spectrum to 100 – 200 MHz. This was found to effectively suppress pulsation in the fiber amplifier when operating up to its pump-limited maximum output power of 6.9W, measured before the OPO.

The singly-resonant OPO was similar to that described previously [8], consisting of a 40 mm long crystal of periodically-poled $LiNbO_3$ (PPLN), poled with a single grating of

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29.75 μm period, placed in a symmetric bow-tie ring resonator formed by two 50 mm radius mirrors (M_1, M_2) and two plane mirrors (M_3, M_4). The crystal faces were anti-reflection coated for the pump (R < 1.5% 1050 – 1100 nm), signal (R < 1.2% 1580 – 1600 nm) and idler (R < 2% 3100 – 3600 nm) while the mirrors were coated for high reflectivity at the signal wavelength (R > 99.2%, 1520 – 1650 nm) and high transmission at the pump ($M_{1,3,4}$: T > 97%, M_2: T = 85 - 95%, 1060 – 1090 nm) and idler (T ≈ 90%, 2900 – 3600 nm). A CaF_2 substrate was used for the idler output mirror, M_2. The rear surfaces of the mirrors were anti-reflection coated for the pump, signal and idler, except for M_2 which was uncoated. The curved mirrors, M_1 and M_2, were separated by 80mm while the plane mirrors M_3 and M_4 were separated by 20 mm. The angle of incidence at all the mirrors was 13°. This geometry resulted in a non-astigmatic focus at the centre of the PPLN crystal with a focussing parameter of $\xi \approx 1$ [9], and a free spectral range for the resonant signal wave of 1.2GHz. The temperature of the PPLN crystal could be maintained at up to 200°C, both to tune the OPO output wavelengths and to avoid photo-refractive effects.

3. Tuning performance

To achieve coarse wavelength selection the pump wavelength was tuned discontinuously, using only the DBR section of the seed laser, resulting in tuning of the OPO idler output over 20 nm, as shown in Fig. 2. It can be seen that an idler output power of around 1 W was maintained over this entire tuning range. The idler output of the OPO could also be tuned over a range of 300nm by varying the temperature of the PPLN crystal, as previously reported [8].

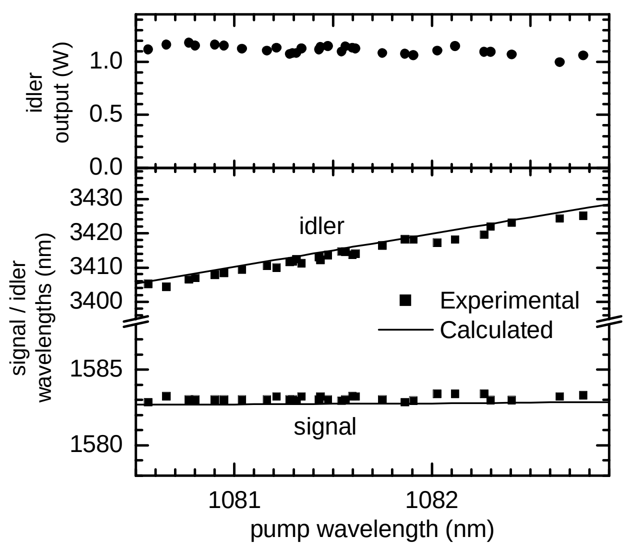

Fig. 2. Variation of OPO output wavelengths (lower plot), and corresponding idler output power (upper plot), during pump tuning by seed laser DBR section alone. PPLN grating period was 29.75 μm and temperature was 180.5°C. Calculated tuning data was derived using the Sellmeier equations of Jundt [10].

To achieve rapid, mode-hop-free tuning, the DBR and phase section tuning currents of the seed laser were swept synchronously and their amplitudes and dc offsets were adjusted to maximize the mode-hop free tuning range of the DBR laser. A static, low-finesse Fabry-Perot interferometer (FPI), having a free spectral range of 7.1GHz, was used both to measure the tuning range of the seed laser and to detect mode hops. The OPO signal frequency was monitored using a scanning Michelson wavemeter, which had an absolute precision of

600MHz at the signal wavelength. To observe the resulting idler tuning, part of the idler output was passed through a 90 cm gas cell containing 15 mbar of methane buffered to 0.52 bar in air and the transmission monitored using an InAs/InAsSbP photodiode. A similar measurement with the gas cell removed from the beam path was made to allow the cancellation of wavelength-dependent power variations in the idler.

Figure 3 shows the resulting seed laser FPI transmission (upper plot) and gas cell transmission at the idler (lower plot) as a function of time (bottom axis). It can be seen that the seed laser tuned continuously over 110 GHz with a high degree of linearity. The signal frequency indicated in Fig. 3 remained constant within the resolution of the wavemeter on time scales of tens of seconds, thus over many tuning cycles of the pump. From this, it can be inferred that the idler tuning reflected that of the pump, having a continuous range of 110 GHz in the MIR. Mode-hop free tuning of the idler is confirmed by the absence of discontinuities in the measured methane absorption spectrum. The 29 ms time interval indicated in Fig. 3 represents one half of a single period of the 17 Hz tuning function. The absorption spectrum shown in Fig. 3 was thus updated at a rate of 34 Hz, demonstrating the suitability of the source for real-time measurements.

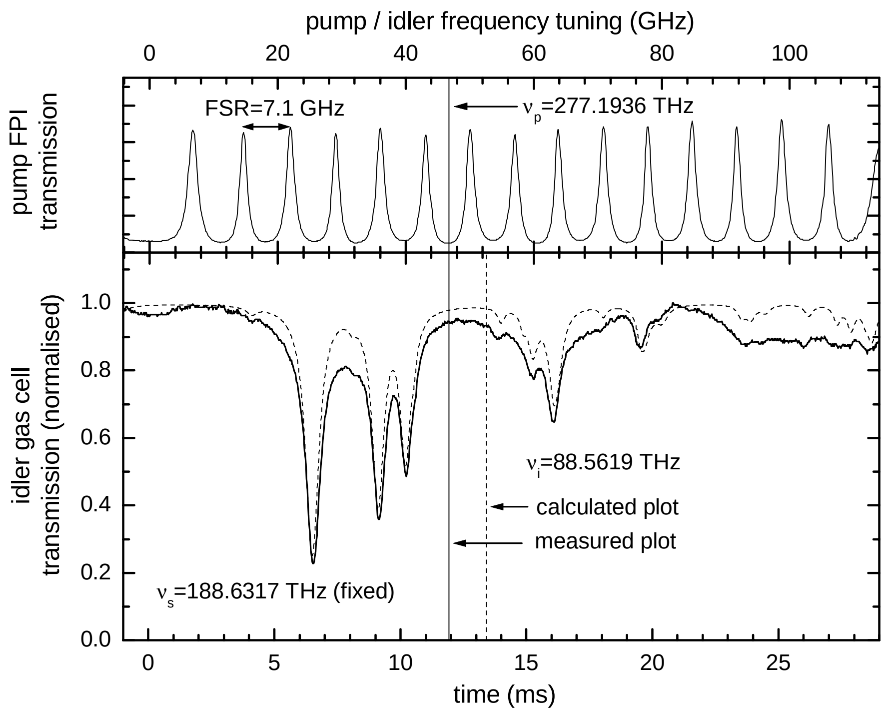

Fig. 3. Upper trace: Rapid, mode-hop free tuning of the seed laser over 110 GHz observed in the transmission of a Fabry-Perot interferometer with 7.1GHz FSR. Lower trace: corresponding OPO idler tuning observed in the transmission through a 90 cm cell containing 15 mbar CH_4 buffered to 0.52 bar in air (solid line), calculated cell transmission derived from HITRAN data (dashed line). Pump tuning axis was calibrated from the Fabry-Perot transmission and an absolute frequency reference, measured under static conditions, is indicated. A corresponding idler frequency reference is indicated for the measured and calculated plots. The signal frequency remained constant throughout the measurement. The total time scale represents one half of a single period of the 17 Hz tuning function.

To verify the linearity, continuity and accuracy of the idler tuning, an absolute frequency calibration of the measured methane absorption spectrum was made and the measured data compared to an absorption profile calculated from the HITRAN 2000 database [11]. The transmission of the interferometer was used to calibrate a relative frequency scale for the pump and, by inference, the idler as indicated in the upper horizontal axis of Fig. 3. To provide an absolute pump frequency calibration, the DBR laser was manually tuned to a reference point in the tuning cycle and its frequency measured using the wavemeter which had an absolute precision of 800MHz at the pump wavelength. The resulting frequency calibration point is indicated in the upper trace of Fig. 3. From this reference pump frequency and the fixed signal frequency, measured as the tuning data was acquired, an absolute frequency marker for the idler scale was calculated. This is indicated in the lower plot of Fig. 3. Having derived an absolute frequency calibration for the measured absorption spectrum, the corresponding simulated absorption profile was calculated from HITRAN data [11], and plotted on the same axes. Initially, a frequency offset of 5.8 GHz was observed between the positions of corresponding calculated and measured spectral features. To cancel this offset, the calculated data was shifted as indicated by the relative positions of the reference frequency markers for the measured and calculated data in Fig. 3. We attribute this calibration offset to the fact that the reference frequency for the pump was measured with the DBR laser in a steady state while the absorption spectrum was acquired under dynamic conditions.

Once corrected for this offset, the positions of spectral features in the calculated and measured data show excellent correlation across the entire tuning range. This result confirms that the idler tuned linearly and without mode-hops over 110 GHz. It can also be seen from Fig. 3 that the spectral width of the measured absorption features shows good correspondence with the calculated pressure-broadened widths of ≈ 2 GHz. This implies that the bandwidth of the OPO idler was considerably less than this value. While not measured directly, it is expected that the idler bandwidth reflected the 100 – 200 MHz bandwidth of the modulated pump. It is clear from Fig. 3 that this was sufficient to allow multiple overlapping spectral features to be easily resolved under pressure-broadened conditions.

4. Conclusions

In summary, we have demonstrated a continuous-wave, singly-resonant optical parametric oscillator pumped by a fibre-amplified DBR diode laser and producing over 1 W of output in the region of 3.4 μm. Rapid, continuous tuning of the pump allowed the idler output of the OPO to be tuned by 110 GHz in 29 ms without mode hops, while discontinuous tuning of the pump allowed the idler output of the OPO to be tuned with mode-hops over 20 nm. The spectral width of the OPO idler output was sufficiently narrow to easily resolve pressure-broadened features in the absorption spectrum of methane. The high accuracy and linearity of the tuning allowed the simple correlation of the observed spectral features with those recorded in the Hitran database across the entire rapid tuning range. The 34 Hz update rate of the targeted spectral window demonstrates the suitability of this source for real-time spectral measurements. The tuning method of the DBR laser is well suited to frequency-agile operation and it is anticipated that more complex tuning functions would allow a number of different spectral windows, within the total idler tuning range indicated in Fig. 2, to be rapidly addressed. We believe this to be the first reported example of a singly-resonant OPO pumped by a fibre-amplified diode laser and the 110 GHz mode-hop-free tuning range to be the highest reported for a continuous-wave OPO.

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