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Letter

Tunable injection-seeded fan-out-PPLN optical parametric oscillator for high-sensitivity gas detection

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Abstract

We demonstrate the possibility to enhance spectroscopic and lidar capabilities of mid-infrared pulsed optical parametric oscillators (OPOs) based on fan-out periodically-poled lithium niobate (fan-out PPLN) by combining their own wavelength tunability with tunable continuous-wave injection seeding. To that effect, we have developed an original test-bed singly-resonant OPO configuration in which continuous wavelength tuning via intracavity translation of the fan-out PPLN is assisted by simultaneous tuning of a narrow-linewidth fiber-coupled seed diode laser. It is shown that such an approach provides strong (at least by one order of magnitude) spectral narrowing, wavelength stabilization and beam-quality improvement for the signal and idler radiations (tunable around 1.54 μm and 3.33 μm, respectively). The achieved spectral narrowing does not noticeably affect the OPO output pulse energy, but allows fine wavelength tuning and significantly increases the power spectral density which can be available at an analyzed gas absorption line. Thus, it leads to a noticeable increase in sensitivity of the photoacoustic gas sensing carried out with the developed OPO. We have achieved an almost double ($\sim$80%) increase in the photoacoustic response of a methane detector to the reference gas mixture with low concentration methane. The application of the method can be simply extended to many gas absorptions lines within the range 3.1–3.4 μm, due to the potentially wide tunability of the developed OPO. The demonstrated OPO features simplicity, reliability and energy efficiency. It can advance various LIDAR techniques due to the unique combination of spectral and energy characteristics.

Keywords: optical parametric oscillator, injection seeding, wavelength tuning, photoacoustic gas sensing

(Some figures may appear in colour only in the online journal)

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1. Introduction

Continuously tunable sources of coherent radiation at mid-infrared (mid-IR) wavelengths are required for many applications related to spectroscopy and gas analysis. Optical parametric oscillators (OPO) are universal solid-state coherent sources with possibility of wavelength tuning in the aforenamed spectral range [1]. However, conventional OPOs without special measures for spectral narrowing have rather broadband radiation spectra (up to dozens of nanometers) which are incompatible with high-resolution spectroscopy. Therefore, various techniques of spectral narrowing have been developed for OPOs.

Often, narrowband (even single-frequency) operation of OPO is achieved through the use of intracavity spectral selectors such as an intracavity etalon [2, 3], or a diffraction grating [4, 5] along with a special cavity configuration which allows for the spectral selector. A typical grazing-incidence grating-mirror combination in OPO resonators [4, 5] also enables wavelength tuning which makes OPO suitable for photoacoustic spectroscopy and trace gas analysis. Among more specific approaches is, for example, the use of a volume Bragg grating as the spectral narrowing element in a nonresonant OPO [6].

Another technique is the use of a narrow-band master oscillator, with an OPO being used as an amplifier. This technique is referred to as injection seeding, and quite often applied for OPO-based spectroscopic systems [7]. For instance, an injection-seeded OPO for remote sensing of CH_4 at 1645 nm was presented in [8], despite low sensitivity of detection at an overtone (1645 nm) of the absorption line. Also, suitability of pulsed injection-seeded OPOs for infrared differential absorption LIDAR measurements has been demonstrated by making range-resolved measurement of atmospheric methane and water vapor [9–11]. Configurations of the injection-seeded OPOs can be quite different [12, 13]. Most of the reported tunable configurations utilize bulk nonlinear crystals or regular multi-grating MgO:PPLN or periodically poled stoichiometric lithium tantalite structures. When bulk crystals are used, the OPO wavelength tuning is carried out by rotating the crystal. It has to be accompanied by readjustment of the OPO cavity. When OPOs employ multi-grating PPLN structures, discrete wavelength tuning is performed by switching between the PPLN gratings with different poling periods in combination with temperature tuning of the PPLN crystal. It also may require realignment of the OPO cavity.

In the context of the above, novel configurations of tunable injection-seeded OPOs with simpler, more reliable and efficient wavelength tuning mechanisms are still in demand. We believe that a quite promising approach to the above problem solving is the use of special PPLN structures, for example, fan-out [14] or slant-strip-type PPLNs [15].

In this work we present an original fan-out-PPLN-based configuration of a narrowband, continuously tunable, high-energy pulsed injection-seeded OPO which is intended for high-sensitivity gas analysis in the mid-IR spectral region, around 3.3 μm. In this simple OPO configuration we have combined, for the first time, advantages of the injection seeding technique with the tuning capability of the fan-out periodically-poled lithium niobate (fan-out PPLN) structure. The tunable seed diode laser with a narrow linewidth and a high-quality beam (shaped by a single-mode optical fiber) provides strong spectral narrowing and wavelength stabilization of the OPO radiation, while the fan-out PPLN allows easy wavelength tuning in the compact two-mirrors OPO cavity. It is revealed that the spectral narrowing does not affect the OPO output pulse energy and increases the power spectral density which can be available at an analyzed gas absorption line. Thus, it leads to increased sensitivity of the gas analysis carried out with the developed OPO.

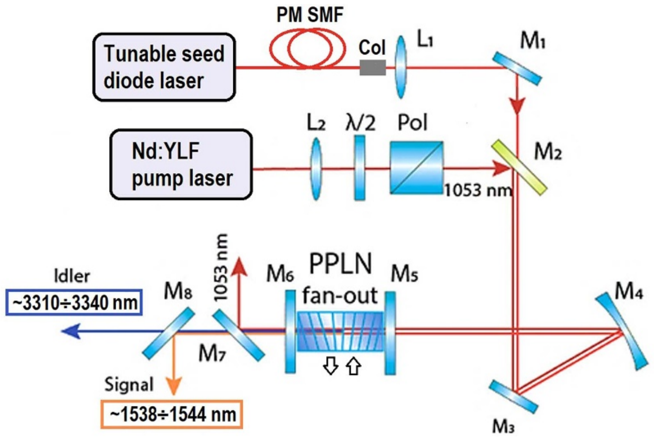

Figure 1. Schematic of the developed injection-seeded fan-out-PPLN OPO with fine wavelength tuning: PM SMF—polarization-maintaining single-mode fiber; Col—collimator; L_1, L_2—lenses; $\lambda/2$—phase plate; Pol—polarization cube; M_1 – M_8—mirrors.

2. Experimental setup

Layout of the developed OPO is shown in figure 1. A pulsed Nd:YLF laser (TECH-1053 Advanced, Laser-export LLC) with a wavelength of 1.053 μm was used as the OPO pump source. Its pulse repetition rate can be varied from 0.02 kHz to 4 kHz. The maximum pulse energy is about 1 mJ. The energy level of the pump radiation was adjusted using an attenuator consisting of a half-wave plate ($\lambda/2$) and a polarizer (Pol). The intensity spatial profile of the pump laser beam is close to the Gaussian distribution, and the M^2 factor is $\sim$1.2, the pump laser linewidth is 1 cm^{-1}.

A fan-out MgO:PPLN was used as the OPO nonlinear medium. It was prepared at Ural Federal University (Russia) by using an original technique of periodical poling with multi-pulse electric field application at elevated temperatures [16]. The grating period of the structure is smoothly varied from 27.9 to 32.2 μm. The dimensions of structure are $3 \times 20 \times 50$ mm. It was mounted on a high-precision translation stage which allows continuous adjustment of the effective grating period by lateral displacement of the fan-out structure, thereby providing wavelength tunability of the OPO.

The pumping radiation beam was matched with the OPO cavity by using a CaF_2 lens L_2 with a focal length of 300 mm. The diameter of the pump beam at the mirror M_4 was 1.2 mm.

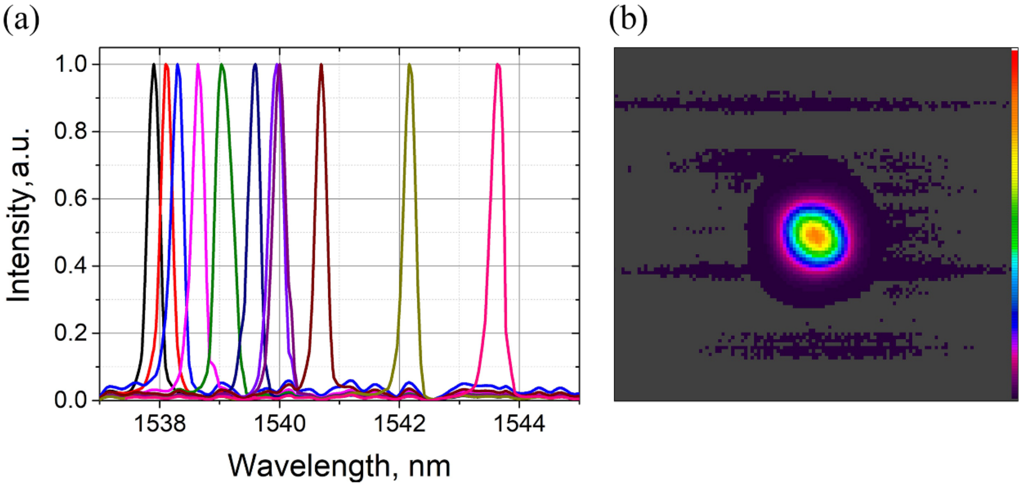

Figure 2. (a) Series of optical spectra which illustrates wavelength tuning of the seed diode laser (measured by using *High Finesse LSA IR-II* spectrometer with resolution 50 pm), (b) 2D beam profile of the seed diode laser (measured by using *Pirocam IV* system).

The OPO resonator is formed by two flat dichroic mirrors, M5 and M6, with high transparency at 1053 nm and high reflectivity around 1500 nm; the cavity length is 60 mm. Thus, the OPO configuration was singly-resonant for the signal wave. The seed diode laser beam was combined and matched with the pumping beam by using a CaF_2 lens L_1 with a focal length of 500 mm, and an arrangement of metallic (M1) and dichroic (M2) mirrors.

The combined beams of the pump and seed lasers were focused by using a spherical metallic mirror M_4 ($f = 500$ mm) to diameters of 0.72 mm and 0.87 mm, respectively, which ensured mode matching in the OPO cavity. Since the OPO cavity is designed to be resonant for the signal wave at around 1.54 μm, the idler wave can be obtained at around 3.33 μm which allows for matching with an absorption line of methane. Lateral translation of the fan-out PPLN changes its effective period, thereby providing continuous tuning of the OPO wavelengths, even with a fixed temperature of the PPLN chip. Without injection seeding, tuning range of the idler wave can be in principle as wide as 1778 cm^{-1} (2.5–4.5 μm) [17].

A fiber-coupled distributed-feedback diode laser (Optilab DFB-1550-DM-4) with 5 MHz linewidth (according to its specs) was used as a CW seed laser for our experiments with the tunable injection-seeded OPO. Output power of the diode laser was 12.8 mW (at an injection current of 200 mA). A commercial current driver combined with temperature controller (Thorlabs ITC 515) was used to provide operation of the laser diode. Adjustment of the laser diode temperature allowed continuous tuning of the lasing wavelength within the range ~1538–1544 nm as illustrated in figure 2(a). This range was determined by the exploited temperature range of the laser diode (from ~12 °C to ~40 °C). It can be further extended since these temperature values are far from absolute maximum rating specified for the laser diode. In our experiments we exploited the limited tuning range which was considered to be sufficient for the gas sensing test.

The polarization-maintaining single-mode output fiber of the seed diode laser ensured high quality of the seed laser beam as testified by the measured 2D beam intensity distribution shown in figure 2(b).

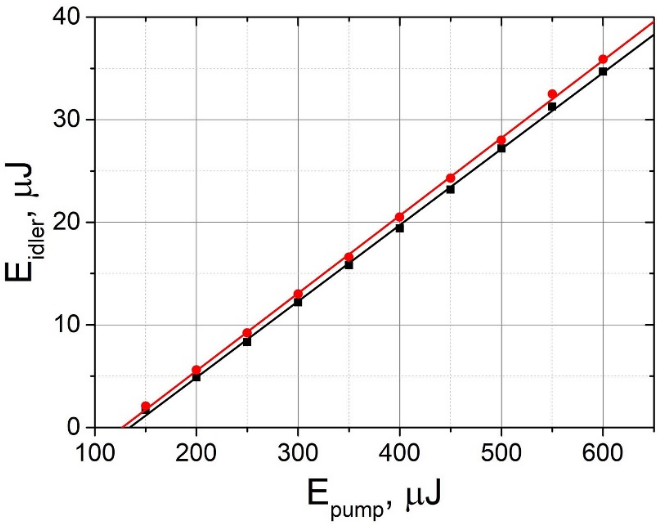

Figure 3. Dependences of the idler pulse energy on the pump pulse energy, measured in the free-running (black curve) and injection-seeded (red curve) OPO regimes.

3. Results and discussion

First, energy characteristics of the developed OPO were investigated with the pump pulse repetition rate set to 1.7 kHz (i.e. the operating rate of photo-acoustics measurements). Figure 3 shows measured dependence of the idler pulse energy (at 3320 nm) on the pump pulse energy (at 1053 nm). It was revealed that efficiency of the pump energy conversion into the idler wave energy in the free-running OPO configuration (without injection seeding) was 5.80%, the differential efficiency was 7.16%, and the quantum efficiency was 18.28%. When using the seed laser, the OPO efficiency slightly increased: the conversion efficiency was 6.15%, the

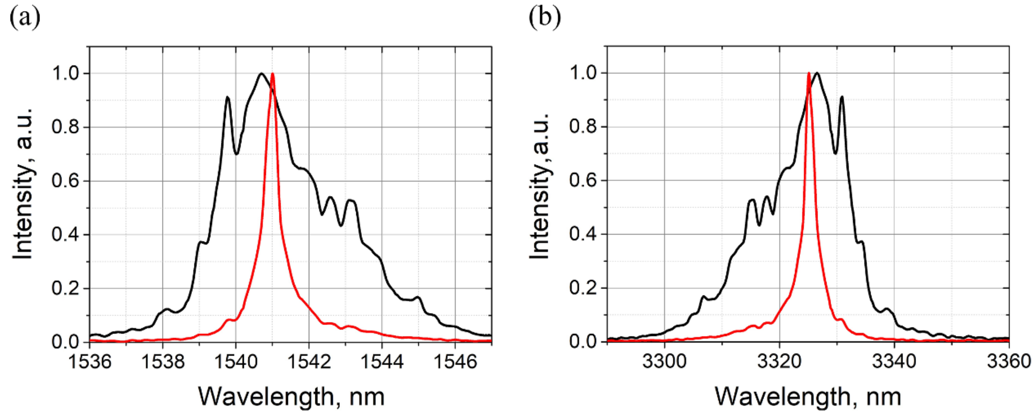

Figure 4. Optical spectra of the signal (a) and idler (b) radiation obtained from the free-running (black curves) and injection-seeded (red curves) OPO.

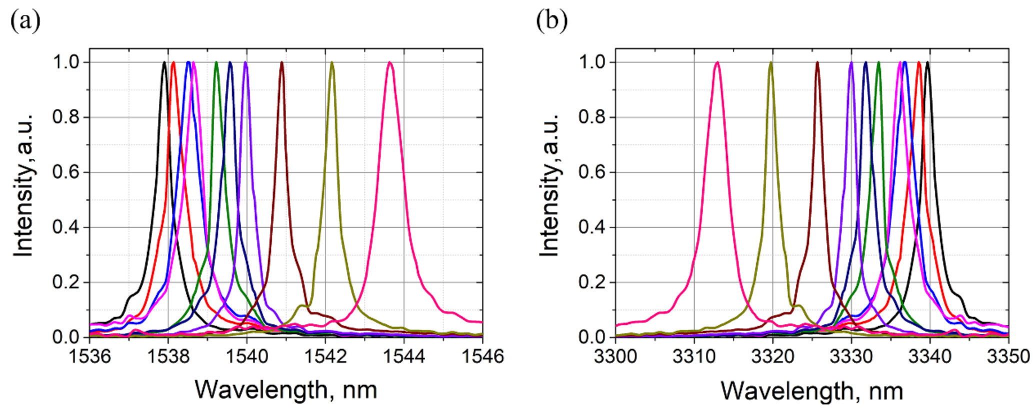

Figure 5. Series of optical spectra which illustrates continuous wavelength tunability of the injection-seeded fan-out PPLN OPO system: mutually dependent tuning of the signal (a) and idler (b) waves.

differential efficiency was 7.54%, and the quantum efficiency was 19.39%. The threshold pump energy density also differed: it was 0.038 J cm^{-2} and 0.035 J cm^{-2} in the free-running and injection-seeded regimes, respectively. The energy characteristics were not noticeably affected by the OPO wavelength tuning within the limited range which was explored in this study for the purpose of methane detection.

Due to limited stability of the OPO cavity and pump source, the free-running OPO radiation features relatively wide, fluctuating optical spectra (nearly-20 nm wide at the idler wavelength) as seen in figures 4(a) and (b). This impedes adjustment of the idler wavelength for efficient interaction with the absorption line of methane. To overcome this, we made injection of narrow-linewidth continuous-wave low-power seed radiation (from the above-described fiber-coupled diode laser) into the OPO. Figure 4 shows the spectral linewidth narrowing of signal (a) and idler (b) waves, achieved with the injection seeding. The spectral narrowing barely affects the total pulse energy of the idler radiation as seen in figure 3, but it significantly increases the power spectral density available at the gas absorption line.

The full width at half maximum of the idler radiation spectrum was as wide as $\sim$18 nm (16.2 cm^{-1}) in the free-running regime, and became as narrow as $\sim$2 nm (1.8 cm^{-1}) after injection of the seed laser radiation into the OPO, as seen in figure 4(b). Thus, the spectral narrowing at the spectroscopic idler wavelength reached almost one order of magnitude.

Series of measured optical spectra shown in figure 5 illustrate continuous wavelength tuning of the injection-seeded OPO system. The seed laser wavelength was tuned electronically by using its temperature controller, while the fan-out PPLN was slightly adjusted by using a single-axis translation stage for lateral displacement. The wavelength tuning procedure did not require any realignment of the OPO cavity or temperature readjustment of the PPLN.

Figure 6 demonstrates improved wavelength stability of the injection-seeded OPO as derived from long-term wavelength measurements of the OPO radiation. In the injection-seeded regime, standard deviation of the central wavelength was an order of magnitude less than in the free-running regime.

It is worth noting that high quality of the pumping and seeding radiation beams, along with proper adjustment of the OPO cavity, has provided relatively high beam quality for the OPO output radiation. Figure 7 illustrates 2D and 3D profiles of the idler radiation measured at the output of the injection-seeded

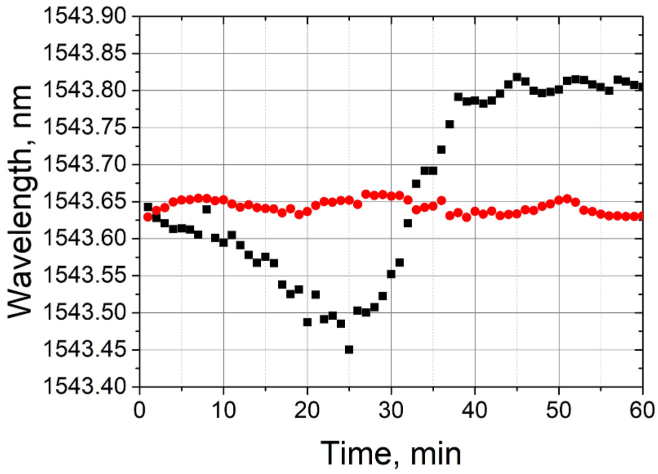

Figure 6. Central wavelength of signal radiation versus time, measured in the free-running (black squares) and injection-seeded (red circles) OPO regimes.

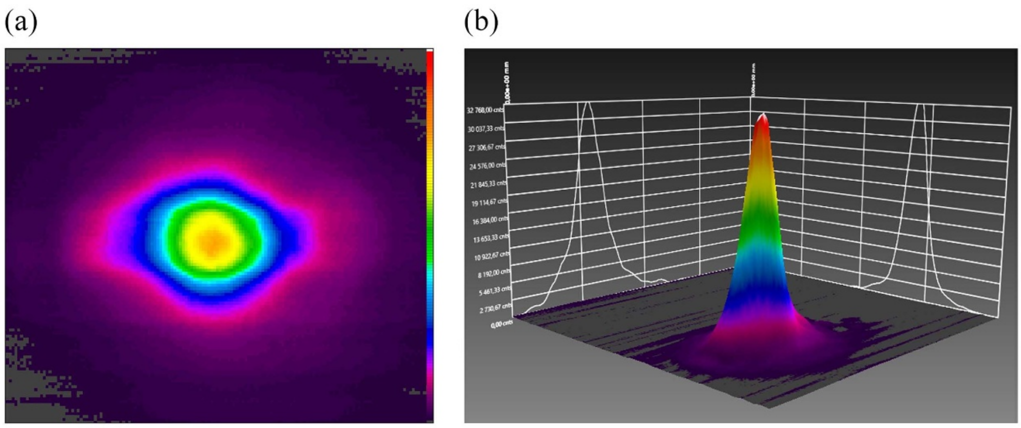

Figure 7. Measured 2D (a) and 3D (b) beam profiles of idler radiation from the injection-seeded fan-out PPLN OPO.

fan-out PPLN OPO. The idler beam quality factor was evaluated to be $M^2{}_x = 1.4$, $M^2{}_y = 1.35$. The measurement procedure corresponded to the ISO11146 standard.

Although the achieved strong spectral narrowing of the OPO radiation does not noticeably affect the pulse energy and peak power (over 5 kW), it significantly increases the power spectral density at the idler wavelength. This circumstance, along with improved wavelength stability and beam quality, allowed us to expect enhancement of spectroscopic capabilities of the OPO, in particular,—increased sensitivity of photoacoustic gas detection.

The established fine tuning of the idler wavelength in the injection-seeded OPO regime covers the wavelength range $\sim$3310 – 3340 nm which includes the absorption line of methane at 3.3 μm [18, 19]. Therefore, the developed injection-seeded OPO was examined as the radiation source for photoacoustic detection of the low concentration methane in a gas mixture. During this experiment, the differential photoacoustic detector (Model OAD-90, ILP SB RAS) [19] was filled by turns with a dry nitrogen gas, room air, and a reference gas mixture based on the nitrogen with an admixture of methane (N_2 + 1000 ppm of CH_4). All methane detection measurements were made at atmospheric pressure and room temperature. The results (responses of the photoacoustic detector) are summarized in figure 8.

The above test measurements revealed almost double ($\sim$80%) increase in response of the photoacoustic methane detector to the reference gas mixture with low concentration methane when the injection seeding was applied. This effect is caused by the following features of the injection-seeded regime: increase of the power spectral density at the idler wavelength, improvement of its stability, and possibility of its finer tuning to the absorption line. We believe that stronger spectral narrowing and further improvement of detection response will be possible with fine optimization of the injection-seeded OPO cavity.

We also anticipate that the obtained unique combination of spectral and energy characteristics of the OPO radiation makes it particularly suitable for some specific long-range LIDAR techniques [20].

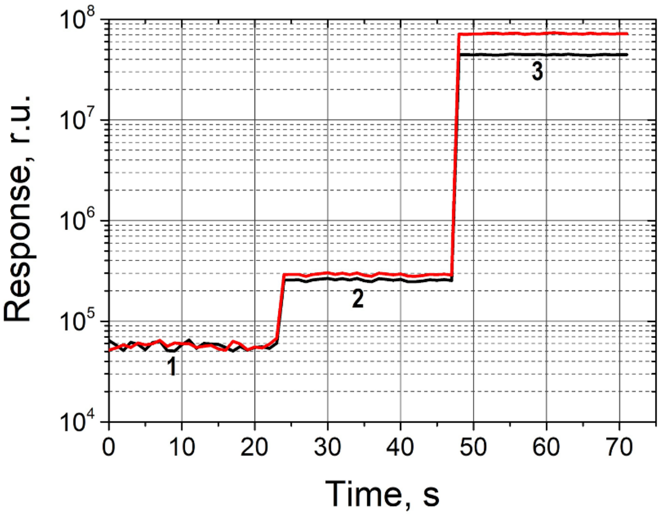

Figure 8. Experimental records of response from the photoacoustic methane detector employing the developed OPO in the free-running (black trace) and injection-seeded (red trace) regimes: 1—response to the dry nitrogen, 2—response to the room air (∼1.86 ppm of CH_4), 3—response to the reference gas mixture (N_2 + 1000 ppm of CH_4).

4. Conclusion

We have demonstrated that combination of a fan-out PPLN OPO (which has a very simple single-resonant pulsed configuration) with the tunable continuous-wave injection seeding (from a fiber-coupled narrow-linewidth diode laser) yields a simple and reliable continuously tunable mid-IR coherent source with the advanced spectroscopic capabilities. The applied injection seeding has provided strong (by a factor of 9) spectral narrowing, wavelength stabilization, beam-quality improvement, and possibility of fine wavelength tuning for the OPO idler radiation. The resulting increase in the power spectral density available at an analyzed gas absorption line has led to improved sensitivity of the gas detection. Thus, we have revealed an almost double (∼80%) increase in the photoacoustic response of a methane detector to the reference gas mixture with low concentration methane when the injection seeding was applied.

The application of the method can be easily extended to other gas absorptions lines within the range 3.1–3.4 μm, due to the potentially wide tunability of the developed OPO. To operate beyond the wavelength tuning limits of the seed diode laser, one can easily apply another fiber-coupled seed laser source with a wider tuning range, like an earlier demonstrated widely tunable Er-fiber laser [21]. Such substitution will not require any realignment of the OPO cavity.

The demonstrated approach to the fine management of the OPO spectral characteristics is simpler than many other techniques which require additional wavelength- or mode-selective elements to be used in the OPO cavity. It features remarkable simplicity, reliability and high energy efficiency. We believe that it can advance practical methods of photoacoustic spectroscopy and implementation of gas analyzers, as well as particular long-range LIDAR techniques.

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