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2009 Chinese Phys. Lett. 26 124214

(http://iopscience.iop.org/0256-307X/26/12/124214)

CHIN. PHYS. LETT. Vol. 26, No. 12 (2009) 124214

Mid-IR Dual-Wavelength Difference Frequency Generation Using Fiber Lasers as Pump and Signal Light Sources [*]

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(Received 28 July 2009)

A continuous-wave mid-IR difference frequency laser source, which respectively uses an ytterbium-doped fiber laser as the pump source and a multiwavelength erbium-doped fiber laser cascaded with an erbium-doped fiber amplifier as the signal source, is demonstrated. Our experimental results show that two stable mid-IR radiation lines with a spacing of about 5.4 nm may be simultaneously emitted by a suitable setting the pump and signal polarization orientations. The number of the mid-IR radiation lines is limited by the quasi-phase-matching acceptance bandwidth. By changing the PPMgLN temperature the two mid-IR radiation lines may be synchronously tuned in the mid-IR range between 3295 and 3356.3 nm.

PACS: 42. 55. Wd, 42. 60. −v, 42. 65. Ky, 42. 72. Ai

Continuous-wave 3-5 μm mid-infrared (mid-IR) laser sources are very useful for applications in high-resolution trace-gas detections,[1,2] medical diagnosis,[3] biological and chemical analysis[4] since many gas molecules exhibit fundamental rotation and vibration absorptions in this mid-IR region, which are stronger than those of their overtones in the near-infrared region by 2-3 orders of magnitude.[5] However, most of the mid-IR laser sources can only emit one wavelength and cannot meet the requirements for real-time multiple species detections. Although some mid-IR laser sources, for instance, the quantum cascaded laser (QCL),[6] may operate in multiple wavelength oscillation, their wavelength spacing is too large for multiple species detection applications. On the other hand, the mid-IR difference frequency generation (DFG) laser sources based on the quasi-phase-matching (QPM) technique are capable of cw operation with a narrow line-width at room temperature and ease of tuning.[7−9] Recently, with the development of new nonlinear crystal, quasi-phase-matching technique and near infrared laser, the conversion efficient and output power of DFG mid-IR laser have been improved rapidly.[10,11] Moreover, the operation properties of a DFG laser source are mainly determined by its pump and signal beams used. Since near-infrared multiwavelength oscillations have been obtained with rare-earth doped fiber lasers,[12−14] it may be possible to achieve mid-IR multiwavelength laser radiations with the DFG/QPM technique when multiwavelength fiber lasers are used as the pump or signal sources. Such multiwavelength mid-IR DFG/QPM laser sources may find their applications in multiple species detection systems in the future.

In this Letter, we demonstrate a dual-wavelength mid-IR DFG/QPM laser source with periodically poled MgO-doped LiNbO$_3$ (PPMgLN), which uses an ytterbium-doped fiber laser (YDFL) as the pump source and a multiwavelength erbium-doped fiber laser (EDFL) cascaded with an erbium-doped fiber amplifier (EDFA) as the signal source, respectively. Our experiments show that the two mid-IR radiation lines may be simultaneously emitted by a suitable setting of the pump and signal polarization orientations, which may then be synchronously tuned by changing the crystal temperature.

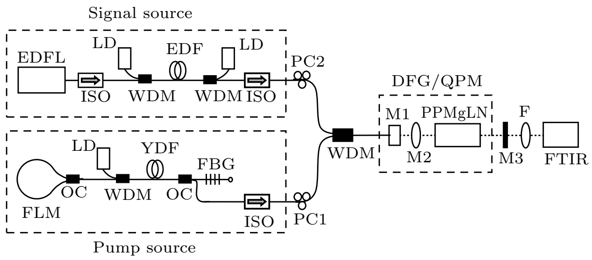

Fig. 1. Schematic diagram of the mid-IR DFG/QPM laser source. FLM: fiber loop mirror; WDM: wavelength division multiplexing coupler; OC: optical fiber coupler; ISO: isolator; M1: grin-lens; M2: lens; M3: CaF2 lens; F: Ge-filter.

Figure 1 shows the schematic diagram of the mid-IR laser source, which consists of three parts: the pump, the signal and the DFG/QPM unit. The three parts are connected with single-mode fibers. The pump source is a YDFL pumped with a 980 nm LD. Its cavity is formed by a Sagnac fiber loop based on a 3 dB optical fiber coupler and a fiber Bragg grating (FBG). The central wavelength, FWHM and the reflectivity of the FBG are 1064.9 nm, 0.1 nm and of

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[*] Supported by the National Natural Science Foundation of China under Grant No 60677050, and the National Basic Research Program of China under Grant No 2007CB936603.

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93%, respectively. The YDF has the absorption of 199 dB/m at 975 nm and the length of 5 m. A 70:30 optical fiber coupler is used for the laser output and the maximum output power is 50 mW. The signal source is a multiwavelength EDFL cascaded with an EDFA. The EDFL is also pumped by a 980 nm LD and has the same configuration as that in Ref. [12]. The multiwavelength EDFL can simultaneously emit 15 wavelengths with the spacing of about 1.2 nm in the spectral range between 1558 and 1576 nm, as shown in Fig. 2(a). The EDFA is bi-directionally pumped with a 980 nm LD and a 1480 nm LD respectively, for obtaining both low noise figure and high output power.[15] All the EDF used has the absorption of 7.2 dB/m at 1532 nm, with lengths of 20 and 48 m for EDFL and EDFA respectively. The total power of the signal source after having been amplified by the EDFA is about 100 mW, and the spectrum is shown in Fig. 2(b). With two PCs to adjust the polarization states, the pump and the signal beams are combined with a 1060/1550 WDM fiber coupler, which has 3 dB bandwidth of ±20 nm, and the insertion losses of 0.5 and 0.7 dB at 1060 and 1550 nm, respectively. The combined beams are then collimated with a grin-lens at the fiber facet, and then launched into the DFG/QPM unit with a 100 mm focal length plano-convex lens. The PPMgLN has seven optional grating periods, ranging from 28.5 to 31.5 µm in increment of 0.5 µm, with each having the same length, width and thickness of 50, 1 and 1 mm, respectively. The crystal is mounted in a temperature controlled oven, which can be adjusted between 20°C and 200°C with controlling precision of ±0.1°C. The residual pump and signal beams are blocked by a long-wave pass Ge filter with cut-off wavelength of 2500 nm and being perpendicular to the propagation direction of output laser. The mid-IR radiation is delivered to a Fourier transform Infrared spectroscopy (FTIR) with a CaF_2 lens for measurements.

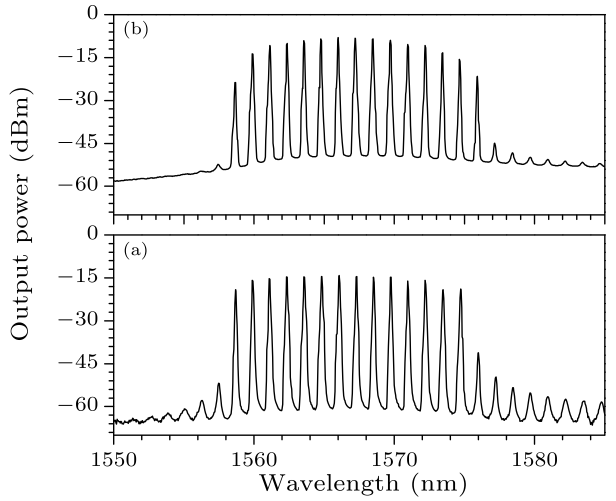

Fig. 2. Measured output spectrum of the multiwavelength signal source, (a) before and (b) after the EDFA.

In the experiment the period of PPMgLN is chosen to be 30 µm according to the spectral regions of the pump and the signal lights. By suitably adjusting the PCs and controlling the crystal temperature two mid-IR radiation lines are obtained simultaneously with our DFG/QPM laser source. Figure 3 shows the measured output spectrum when the crystal temperature is controlled at 89.7°C. As seen, the wave numbers of the two mid-IR lines are 3000.1 and 3004.9 cm^{-1}, i.e., 3333.3 nm and 3327.9 nm, giving the wavelength spacing of 5.4 nm, which respectively correspond to the incident signal wavelengths of 1564.8 and 1566 nm. The two mid-IR lines are almost uniform and very stable in both the magnitude and the wavelength, with an amplitude fluctuation less than 5%.

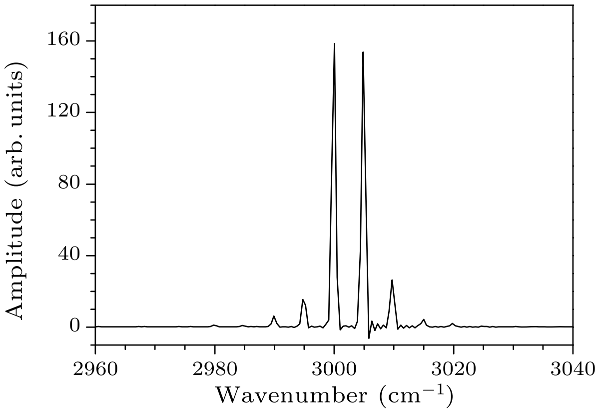

Fig. 3. Measured output spectrum of the DFG/QPM laser source for the crystal temperature of 89.7°C.

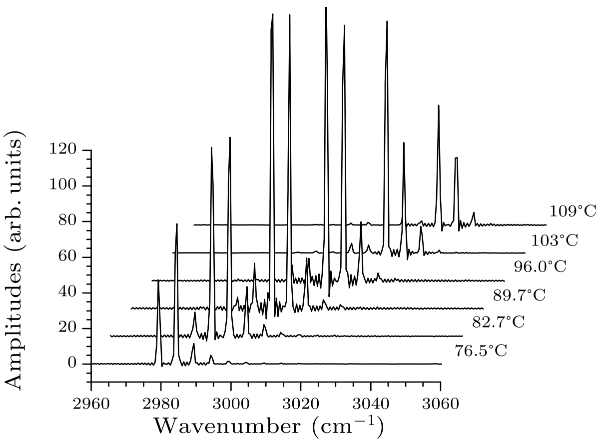

Fig. 4. Measured output spectra of the DFG/QPM laser source for different crystal temperatures.

However, only two significant mid-IR radiation lines are observed in our experiment though the incident signal light is from the multiwavelength EDFL which emits 15 lasing lines simultaneously. Considering that the polarization states of the incident 15 lasing lines may not be all controlled in the same direction that is parallel to the optical axis of the crystal with the result that the signal intensities are low for some lines, this ultimately results in a low DFG output for the corresponding signal lines, thus, the output spectrum of the DFG/QPM system is monitored while PC2 is being adjusted to vary the polarization states of incident signal lines. However, no new mid-IR idler lines are generated in our experiment, only amplitude variations for the same two mid-IR lines are observed during the adjusting process. This indicates that the other incident signal lines may not locate in the QPM acceptance bandwidth, in particular, by considering the fact that the incident multiwavelength signal lines are almost flattened near the center region (see Fig. 2).

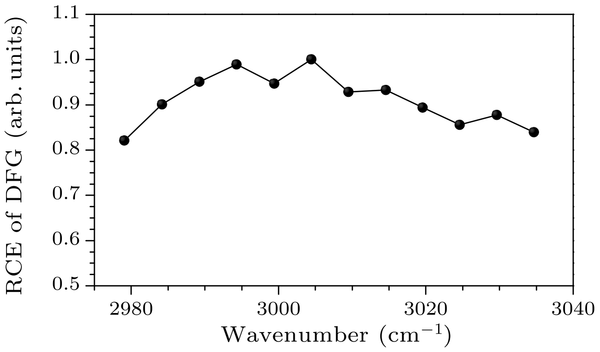

Fig. 5. Measured the relative conversion efficiency (RCE) for the 12 incident signal lines when they are respectively under their own perfect QPM conditions.

Figure 4 shows the measured output spectra of our DFG/QPM laser source for different controlling temperatures. As shown, the two mid-IR lines can be achieved when the controlling temperature is set at any value between 76.5 and 109°C. For different temperatures, the wave-numbers of the two mid-IR lines are different. When the temperature is 76.5°C, the frequencies of the two radiation lines are 2979.5 and 2984.4 cm^{-1}, corresponding to the incident signal wavelengths of 1559.8 and 1561 nm. As the temperature increases, the frequencies of the two mid-IR lines become larger. This shows that two signal lines participated in the DFG/QPM process gradually and successively switch to the longer wavelength wing of the incident signal lines. When the temperature is increased to 109°C, the frequencies of the two mid-IR lines are 3030 cm^{-1} and 3034.9 cm^{-1}, corresponding to the two incident signal wavelengths of 1572.2 and 1573.4 nm. We find in the experiment that two mid-IR lines corresponding to any two neighboring lines of the central 12 incident lines may be obtained by changing the temperature, i.e., the two mid-IR lines may be synchronously tuned by changing the crystal temperature. This means that by changing the crystal temperature the incident signal wavelength under the perfect QPM condition may be moved while the QPM acceptance bandwidth is unchanged. From Fig. 4, the QPM acceptance bandwidth with respect to the idler may be inferred to be about 10 nm, and thus about 2 nm for the signal, for the pump wavelength of 1064.9 nm.

When the two mid-IR lines are synchronously tuned, as shown in Fig. 4, they have different amplitudes because the incident signal lines are not uniform. For this reason, only the mid-IR radiation for the central 12 signal lines are obtained since the powers on the edge of the 15 signal wavelengths are lower than those in the center by about 15 dB (see Fig. 2). However, when each of the center 12 lines is under its own perfect QPM condition by controlling the crystal temperature, the measured amplitudes of the idlers for the given pump power are approximately proportional to the power of the corresponding signal lines. Figure 5 shows the relative conversion efficiency (RCE) for the 12 incident signal lines when they are respectively under their own perfect QPM conditions, which clearly shows that the RCEs for the 12 idlers vary between the 0.82 and 1, with the fluctuation less than 10%.

In summary, we have demonstrated a dual-wavelength mid-IR DFG/QPM laser source by using a YDFL as the pump and a multiwavelength EDFL cascaded with an EDFA as the signal sources, respectively. When the pump and signal polarization orientations are suitably controlled, the DFG/QPM laser source may emit two mid-IR radiation lines simultaneously. The number of the mid-IR radiation wavelengths is limited by the QPM acceptance bandwidth, which is inferred to be about 10 nm with respect to the idler for the pump at 1064.9 nm and the signal around 1565 nm. Moreover, the two mid-IR lines may be synchronously tuned by changing the PPMgLN temperature.

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