Mid-IR dual-wavelength difference frequency generation in uniform grating PPLN using index dispersion control*

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A novel widely tunable dual-wavelength mid-IR difference frequency generation (DFG) scheme with uniform grating periodically poled lithium niobate (PPLN) is presented in this paper. By using the temperature-dependent dispersion property of PPLN, the quasi-phase matching (QPM) peak for the pump may evolve into two separate ones and the wavelength spacing between them increases with the decrease of the crystal temperature. Such two pump QPM peaks may allow simultaneous dual-wavelength mid-IR laser radiations while properly setting the two fundamental pump wavelengths. With this scheme, mid-IR dual-wavelength laser radiations at around 3.228 and 3.548, 3.114 and 3.661, and 3.019 and 3.76 μm, are experimentally achieved for the crystal temperatures of 90, 65, and 30 °C, respectively, based on the fiber laser fundamental lights.

Keywords: mid-IR, difference frequency generation, quasi-phase matching, dual-wavelength

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1. Introduction

Mid-IR laser sources in 3 μm–5 μm wavelength band are essential for many applications, such as optical measurement, remote sensing and spectrum analysis.[1–3] Among the existing commercially available mid-IR lasers, the difference frequency generation (DFG) laser source, based on the quasi-phase matching (QPM) technique, is very attractive due to its superior features of narrow line width, wide and continuous wavelength tunability, and no need for extra liquid nitrogen cooling.[4–6] In the past few years, a lot of work has been focused on the multiwavelength mid-IR DFG laser radiations to satisfy the requirements for the detection of multiple species or multiple absorption lines synchronously. However, for normal uniform periodically poled crystals, the DFG tuning curves each usually have only one QPM peak with a rather narrow wavelength acceptance bandwidth (BW). Methods capable of achieving a DFG tuning curve with multiple QPM peaks are still a challenge. By introducing a periodical π-phase shift into the periodically poling domain structure, Liu *et al.*[7] have obtained a DFG tuning curve with equally spaced QPM peaks. Furthermore, by adopting a phase modulation technique, Asobe *et al.*[8,9] could achieve a DFG tuning curve with both equally and unequally spaced QPM peaks and then demonstrated the simultaneous detection of multiple hydrocarbon gases. In addition, chirped QPM grating[10] and the aperiodic optical superlattice (AOS) were also proposed to realize the multiwavelength conversion.[11] However, although multiple mid-IR laser radiations can be obtained with such a specially designed device, the demands for the device fabrication techniques and experimentally controlling precisions become more stringent. Particularly, an irregularly engineered QPM grating can only perform the fixed function, i.e., the designed function. Recently, by using the dispersion property of the periodically poled niobate (PPLN), Jiang *et al.*[12] presented a novel dual-wavelength mid-IR DFG laser source based on a near-IR multiwavelength erbium-doped fiber laser (EDFL) and an ytterbium-doped fiber laser (YDFL). Two stable mid-IR radiation lines with a spacing of about 5.4 nm were simultaneously achieved, which may also be synchronously tuned between 3295 nm and 3356.3 nm. Nonetheless, the wavelength spacing between the two mid-IR radiation lines is very small and difficult to change due to the configuration of the fundamental multiwavelength EDFL and the limited QPM BW for the signal.

In this paper, we propose a novel scheme for simultaneously generating dual-wavelength mid-IR laser line radiations by using the two controllable separate pump QPM bands based on the dispersion property of PPLN. With two tunable YDFLs and an EDFL as the fundamental light sources, the wavelength spacing between the two mid-IR laser lines can be varied in a wide range by tuning the pump wavelength to adapt to the change of the crystal temperature.

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2. Theoretical analysis

As is well known, the DFG laser source extracted with Gaussian beams can be fitted to 'sinc$^2(\Delta kL/2)$' function. According to the QPM technique, both energy and momentum conservation can be easily fulfilled simultaneously, and written as follows:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda_p} - \frac{1}{\lambda_s}, \tag{1}$$

$$\Delta k = 2\pi \left(\frac{n_p}{\lambda_p} - \frac{n_s}{\lambda_s} - \frac{n_i}{\lambda_i} - \frac{1}{\Lambda} \right), \tag{2}$$

where Δk is the phase-mismatch and λ_p, λ_s, and λ_i are the pump, signal, and idler wavelengths, respectively. When $\Delta k = 0$, the momentum conservation law is satisfied. Λ is the QPM grating period. The extraordinary refractive indices in PPLN at the pump, signal and idler wavelengths are n_p, n_s, and n_i respectively, which are functions of both temperature and wavelength and can be obtained numerically from published Sellmeier fits for PPLN.[13] When the fundamental light beams are the Gaussian beams, the DFG output power may be expressed as[14]

$$P_i = \frac{P_p P_s}{\pi w^2} \frac{4 d_{eff}^2 \omega_i^2 L^2 \left(\sin c^2 \left(|\Delta K| L/2 \right) \right)}{\varepsilon_0 n_i n_p n_s c^3}, \tag{3}$$

where L is the length of PPLN; ε_0 and c are the dielectric permittivity and light speed in a vacuum; ω_i is the idler frequency; d_{eff} is the effective nonlinear coefficient of the nonlinear crystal; P_p, P_s, and P_i are the pump, signal, and idler power, respectively; the radii of pump, signal, and idler beams are assumed to be identical: they are all denoted as w. For all calculations, we assume that the wavelength of the signal is fixed; considering the two fundamental lasers are operating in 1060 nm and 1550 nm wavebands, respectively, the period of PPLN is chosen to be 30 μm; the crystal temperature variation scope is limited to 30 °C–200 °C.

Figure 1 shows the plots of phase mismatch versus pump wavelength for different crystal temperatures when the signal wavelength is fixed at 1.57 μm. It is clearly seen that when the crystal temperature is set at 30 °C, there are two pump wavelengths located, respectively, at 1.032 μm and 1.107 μm (points A_1 and A_2), simultaneously satisfying the perfect phase-matching condition. As crystal temperature increases, the two phase-matching pump wavelengths both gradually move close to each other. As shown in the figure, when the crystal temperature increases to 65 °C and 90 °C, the corresponding phase-matching pump wavelengths change to 1.042 μm and 1.097 μm, and 1.053 μm and 1.085 μm, which are marked as B_1 and B_2, and C_1 and C_2 correspondingly. When the crystal temperature rises to 102.6 °C, the two phase-matching points are completely overlapped at the wavelength of 1.068 μm (point D), at which the dashed line is exactly tangent to the QPM tuning curve. Obviously, if the crystal temperature is increased further, the phase-matching wavelengths will not exist in the pump wavelength range any more.

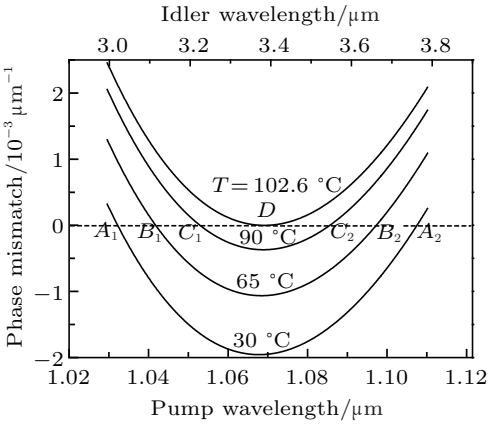


Fig. 1. Plots of phase mismatch versus pump wavelength with a signal wavelength of 1.57 μm for different crystal temperatures.

The DFG output characteristics are then evaluated by substituting the phase mismatching conditions into Eq. (3). Figure 2 shows the normalized idler output spectra for different crystal temperatures. As seen from this figure, for the crystal temperatures of 30, 65, and 90 °C, there exist two idler QPM peaks at each crystal temperature, which are located at around 3.012 and 3.754, 3.098 and 3.641, and 3.198 and 3.512 μm, respectively. As the crystal temperature increases, the wavelength spacing between the two QPM peaks becomes smaller and smaller. When the crystal temperature increases to 102.6 °C, the two peaks overlap each other and form a broadband QPM peak, which implies that the minimum wavelength spacing between the generated dual-wavelength laser lines may be as small as zero. Thus, by using the two temperature controllable QPM peaks, the proposed dual-wavelength mid-IR laser radiations may cover the range of 3.012 μm–3.754 μm while tuning the fundamental pump wavelengths to adapt to the change of the crystal temperature.

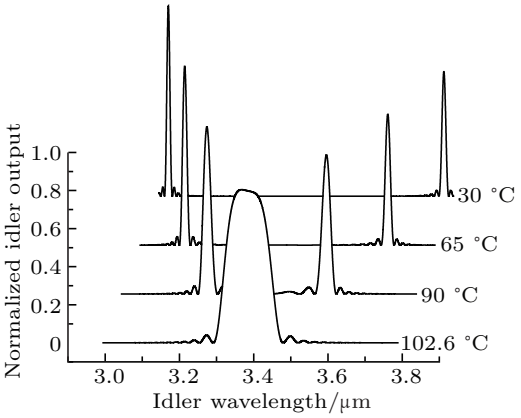


Fig. 2. Normalized DFG outputs versus idler wavelength at different crystal temperatures.

Further studies show that the wavelength coverage of the dual-wavelength mid-IR DFG laser source is significantly affected by the fixed signal wavelength. Figure 3 gives the plots of QPM crystal temperature versus the idler wavelength for different signal wavelengths. As shown in the figure, when the signal wavelength is increased to 1.61 μm, the dual-wavelength DFG may cover the range of 2.805 μm–3.955 μm. However, when the signal is fixed at 1.545 μm, the wavelength coverage for the dual-wavelength DFG decreases to 3.329 μm–3.465 μm. Figure 4 shows the plots of maximum achievable wavelength spacing (MAWS) and the maximum allowable temperature (MAT) versus signal wavelength. As seen in the figure, both the MAWS and the corresponding MAT increase with the augment of the signal wavelength. According to the above simulation results, we can conclude that for the two fundamental lights respectively operating in 1060 nm and 1550 nm wave bands, the fixed signal wavelength should exceed 1.54 μm, and the longer the signal wavelength, the larger mid-IR wavelength coverage could be accessible for the dual-wavelength DFG.

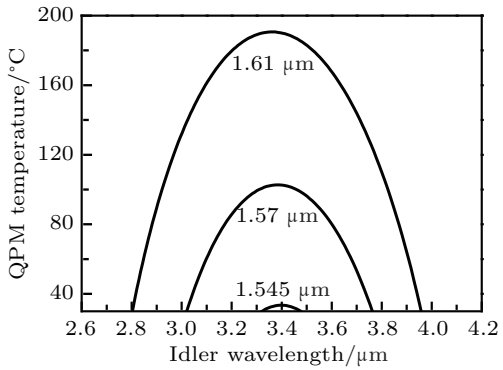


Fig. 3. QPM crystal temperatures versus idler wavelength for different fixed signal wavelengths.

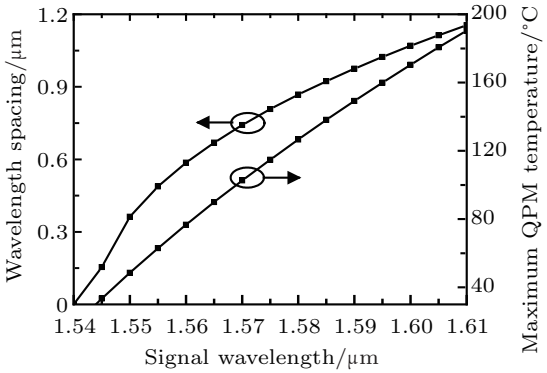


Fig. 4. Maximum approachable wavelength spacing between the output mid-IR dual-wavelength radiations and the allowable maximum QPM crystal temperature versus signal wavelength.

3. Experimental results and discussion

Figure 5 illustrates the experimental schematic diagram of the dual-wavelength mid-IR laser source. The fundamental light sources consist of a signal wavelength EDFL and two tunable YDFLs which can be tuned to adapt the movable pump QPM peaks. Each fiber laser is followed by a fiber-type polarization controller to guarantee the polarization orientations of the laser beams being parallel to the principal axis of PPLN so as to utilize the maximum nonlinear coefficient of d_{33}. After that, the fundamental light beams are combined by a broadband 1060 nm/1550 nm wavelength division multiplexer (WDM), which has a collimating lens on the facet of the output fiber pigtail. Through a CaF_2 converging lens, the combined laser beams are incident into PPLN, which is placed in an oven controllable in a temperature scope of 30 °C–200 °C within a precision of ±0.1 °C. The oven is located on a multi-dimensional stage allowing delicate adjustment to the position of PPLN to ensure that the laser beams are completely contained in the crystal. After the nonlinear interaction, the output from PPLN is collimated by a CaF_2 lens and then filtered by a germanium slide to remove the residual fundamental light. Finally, the generated mid-IR emissions are detected by a Fourier transform infrared spectroscopy (FTIR).

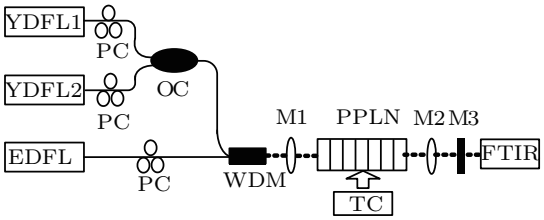


Fig. 5. Configuration of the dual-wavelength mid-IR DFG/QPM laser source. YDFL: ytterbium-doped fiber laser; PC: polarization controller; OC: optical coupler; WDM: wavelength division multiplexer; M1, M2: CaF_2 converging lens; TC: temperature controller; M3: Ge filter. FTIR: Fourier transform infrared spectroscopy.

In the experiment, the period of PPLN is chosen to be 30 μm according to the spectral regions of the pump and the signal light. In order to testify the existence of the broadband QPM peak, the mid-IR output property is first investigated by tuning the YDFLs when the crystal temperature is set at 102.6 °C. Figure 6 shows the measured idler tuning spectrum, which can be continuously tuned between 3.281 μm and 3.462 μm, corresponding to a pump wavelength range from 1.062 μm to 1.08 μm. It is easily found that the envelope shape of the idler tuning spectra accords well with the theoretical result for a temperature of 102.6 °C in Fig. 2, which indicates that the broadband idler QPM band at around 3.4 μm truly exists. It also suggests that within such a broadband idler QPM band, the generated dual-wavelength mid-IR laser lines can be located anywhere by properly choosing the fundamental pump wavelengths.

Next, widely tunable dual-wavelength mid-IR laser radiations are also observed while changing the crystal temperature. Figure 7 shows the measured idler output spectra for different crystal temperatures with the proper pump wavelengths. As discussed in the theoretical section, the broadband idler QPM

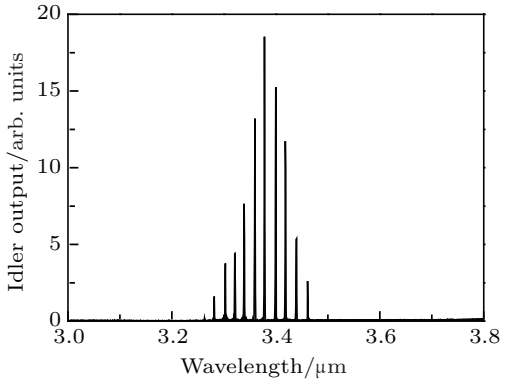


Fig. 6. Measured mid-IR idler output spectrum for a crystal temperature of 102.6 °C by tuning the pump wavelength.

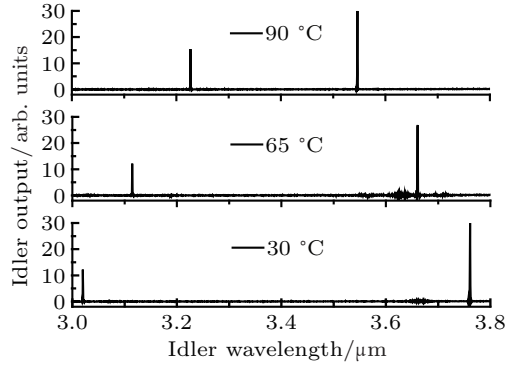


Fig. 7. Measured dual-wavelength mid-IR idler output spectra at different crystal temperatures.

peak may gradually evolve into two separate ones with crystal temperature decreasing. As shown in the figure, when the crystal temperatures are set at 90, 65, and 30 °C, high level mid-IR outputs can be achieved at around 3.228 and 3.548, 3.114 and 3.661, and 3.019 and 3.76 μm, where the two corresponding pump wavelengths are tuned near 1.056 and 1.088, 1.044 and 1.099, and 1.033 and 1.108 μm, respectively. The mid-IR wavelength spacing as large as 741 nm is obtained for the crystal temperature of 30 °C. Slight difference in wavelength between the experimental results and the theoretical expectations may be due to the inaccuracies of the used Sellmeier equation. If a longer signal wavelength is used, the mid-IR idler wavelength spacing may increase further. It should be noted that the measured idler output amplitudes in the shorter wavelength swing are lower than those in the longer wavelength region, which is in contradiction with the simulation prediction. The reason might lie in the fact that the overlapping factor between the fundamental light beams decreases due to the performance degradation of the collimating and focusing system.

4. Conclusions

In conclusion, we demonstrate a novel DFG scheme for generating dual-wavelength mid-IR laser radiations. For the fundamental light beams operating in 1060-nm and 1550-nm wavebands, respectively, the pump tuning curve has two QPM peaks and the wavelength spacing between them can be continuously varied by changing the crystal temperature. Such a property may be used for the tunable dual-wavelength mid-IR DFG laser sources by properly tuning the two pump wavelengths to adapt the temperature-controlled QPM peaks. In the experiment, a wavelength spacing between the two emitted mid-IR laser lines is achieved to be as large as 741 nm for the crystal temperature of 30 °C when the signal wavelength is fixed at 1.57 μm. Such a mid-IR laser source can be found to have applications in multiple species detections in the future.

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