Widely tunable mid-IR difference-frequency generation based on fiber lasers

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A wide tuning technique for mid-IR difference-frequency generation (DFG) with uniform grating periodically poled $\mathrm{LiNbO_3}$ (PPLN) is presented. Based on the dispersion property of the PPLN, the quasi-phase matching (QPM) band for the pump can evolve to two separate bands, and the spacing between them can be increased with the decrease of the crystal temperature. Two such separate QPM bands can be used for increasing the idler tuning range when the crystal temperature is set to adapt the pump tuning. With the technique, an idler tuning range of 690 nm is experimentally achieved with fiber laser fundamental lights. © 2010 Optical Society of America

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The cw mid-IR difference frequency generation (DFG) laser source, based on the quasi-phase matching (QPM) technique, is very important for spectroscopy applications, because it is capable of precise wavelength resolution, narrow linewidth, wide and continuous wavelength tunability [1]. In the past decade, a lot of work has been focusing on how to obtain wide tuning for the mid-IR DFG source [2–8]. For normal uniform periodically poled crystals (PPCs), the DFG tuning curves usually have the sinc^2 function shape with a rather narrow QPM wavelength acceptance bandwidth (BW); the idler tuning range is only 1–10 cm^{-1}. For this reason, various PPC structures, such as chirped [3], apodized [4], and phase-modulated [5], have been designed to broaden the QPM BW for the wide tuning requirement. However, with these methods, the QPM BW could be increased to 100–200 nm, limited by the conversion efficiency. Tuning ranges of greater than 2 μm have also been achieved by rotating the PPC [2] or using the fan-out structure [6] to move the QPM band by varying the grating period. Unfortunately, these techniques lead to other issues, either in controlling precision or in the manufacture process. In fact, many nonlinear crystals exhibit strong temperature-dependent dispersion, and the QPM band could be moved by simply altering the crystal temperature, which can also be used for wide tuning [7]. For example, a tuning range of about 200 nm near 3 μm has been achieved using a uniform grating periodically poled $\mathrm{LiNbO_3}$ (PPLN) [8].

Most recently, we have broadened the QPM BW to about 170 nm around 3.4 μm by using the dispersion property of PPLN. With a multiwavelength ytterbium-doped fiber laser (YDFL) and an erbium-doped fiber laser (EDFL) as the fundamental lights, the DFG laser source can simultaneously emit 14 wavelengths, which can be synchronously tuned between 3.28 and 3.47 μm [9]. In this Letter, we report a DFG wide tuning technique that uses the two controllable separate QPM bands based on the dispersion property of PPLN. Our simulation results show that the DFG tuning range for the uniform grating PPLN can be increased to 1.3 μm. With fiber laser fundamental lights, a tuning range of about 690 nm is experimentally obtained.

The effect of the temperature dependent dispersion property of PPLN on the DFG output properties can be simulated with Eq. (1) in [10]. Considering that the QPM BW for the 1060 nm pump is much larger than that for the 1550 nm signal [9], we first simulate the QPM properties for different temperatures when the signal wavelength is fixed at 1.58 μm. Figure 1 shows the results when Λ and L are, respectively, 30 μm and 50 mm. As shown, when the crystal temperature is set at 132.2 °C, the QPM BW around 3.4 μm is about 120 nm, indicating that, when the pump wavelength changes in a wide range, $\Delta k \approx 0$, $\partial \Delta k / \partial \lambda \approx 0$ can always be satisfied due to the temperature-dependent dispersion property of PPLN [9,10]. When the temperature is decreased to 130.2 °C, the QPM BW for the idler reaches a maximum of about 175 nm with a dip in the central part of the QPM band. Thus, at such a specific temperature, a tuning range of 175 nm can be achieved by simply varying the pump wavelength. As the temperature decreases from 130.2 °C, the QPM band gradually evolves to two separate narrower bands, and the

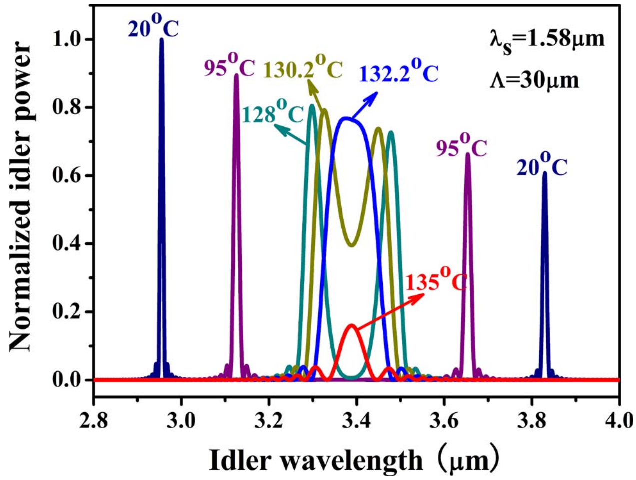

Fig. 1. (Color online) Normalized DFG output power for different temperatures when λ_s is fixed at 1.58 μm.

spacing between them increases with the decrease in the temperature. When the temperature is 128 °C, 95 °C, and 20 °C, the two QPM bands are moved to be at 3.30 and 3.48, 3.13 and 3.65, and 2.96 and 3.83 μm, giving wavelength spacing of 180, 520, and 870 nm, respectively. Although the BWs of the two QPM bands are decreased with the temperature, they are still 7.7 and 10 nm for the idler even when the temperature is 20 °C, corresponding to the QPM BW of 0.94 and 0.86 nm for the pump, which are still much larger than the linewidth of normal fundamental lights. This suggests that the DFG tuning range could be greatly broadened by extending the pump tuning in the two separate QPM bands while the crystal temperature is set to adapt the pump wavelength change.

Figure 1 also shows that the DFG output amplitude drops sharply when the temperature is above 132.2 °C, indicating that the allowable temperature range for the 1.58 μm signal wavelength may be between 20 °C–132.2 °C, if the 20 °C–250 °C reliable temperature range for the Sellmeier fit [11] used was taken into account. Figure 2 shows calculation results of the allowable temperature ranges for different signal wavelengths. As seen, the maximum allowable temperature (MAT) for the 1.58 μm signal wavelength is 132.2 °C, and the maximum idler tuning range is 870 nm. When the signal wavelength is 1.55 μm, the MAT is only 41 °C, giving a maximum tuning range of 400 nm. When the signal wavelength is 1.63 μm, however, the MAT could be 246 °C, and the idler can be tuned from 2.72 to 4.02 μm, i.e., a tuning range of 1.3 μm. This indicates that longer wavelength signals can be used to increase the DFG tuning range.

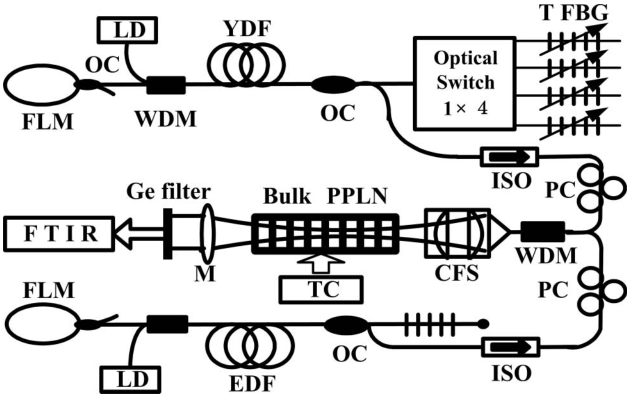

Fig. 3. DFG laser source based on fiber lasers. FLM, fiber loop mirror; LD, laser diode; YDF, ytterbium-doped fiber; EDF, erbium-doped fiber; OC, optical coupler; TFBG, tunable fiber Bragg grating; ISO, isolator; PC, polarization controller; WDM, wavelength division multiplexer; M, collimating lens; CFS, coupling focusing system.

Figure 3 shows the DFG laser source based on the fiber lasers used in our experiments. A YDFL with a tuning range from 1040 to 1110 nm, obtained by inserting an electronically controlled 1 × 4 channel optical switch into the cavity to choose one of four different tunable fiber Bragg gratings, is used as the pump source. The YDFL output power is 30 mW during the tuning process. An EDFL with a central wavelength of 1.58 μm and output power of 50 mW is used as the signal source. The measured linewidths of both fiber lasers are less than 0.06 nm, limited by the resolution of our optical spectral analyzer. With two polarization controllers (PCs) to adjust the polarization states, the pump and signal beams are combined with a broadband 1060/1550 nm wavelength division multiplexing fiber coupler, and then delivered into the crystal through a coupling focusing system (CFS) composed of a gradient-index lens collimator at the pigtail fiber facet and a plano–convex lens (Newport Model: CAPX013) with 100 mm focal length and 25.4 mm diameter. A 50 × 1 × 1 mm PPLN with the uniform poling period of 30 μm is used as the nonlinear crystal, which is placed in a controllable oven to adjust the temperature with the accuracy of ±0.1 °C. The generated idler is transmitted into a CaF$_2$ collimating lens, filtered by a Ge filter to block the residual fundamental lights, and finally, detected with an FTIR.

The tuning properties of the DFG laser source for fixed crystal temperatures are investigated as a first step. When the temperature is set at 128 °C, the idler can be tuned to any value between 3.277 and 3.453 μm by simply changing the pump wavelength. The measured results are given in Fig. 4. As shown, the QPM BW for the idler is about 176 nm with an obvious dip in the central part of the QPM band, which is in good agreement with the predicted results at 130.2 °C. When the temperature is actually set at 130.2 °C, however, the measured tuning range is only 140 nm, much smaller than the simulation

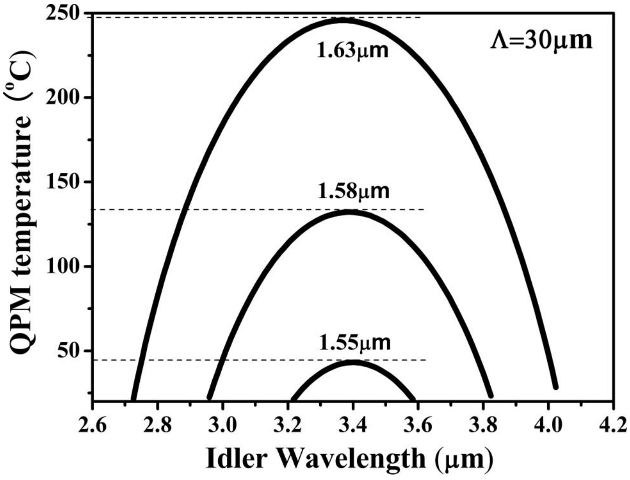

Fig. 2. Optimized QPM temperature as a function of idler wavelength for different signal wavelengths.

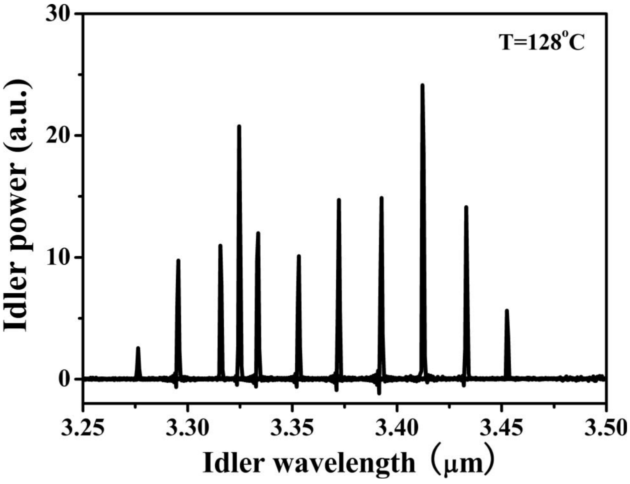

Fig. 4. Measured tuning properties of the DFG source for the crystal temperature of 128 °C when λ_s is fixed at 1.58 μm.

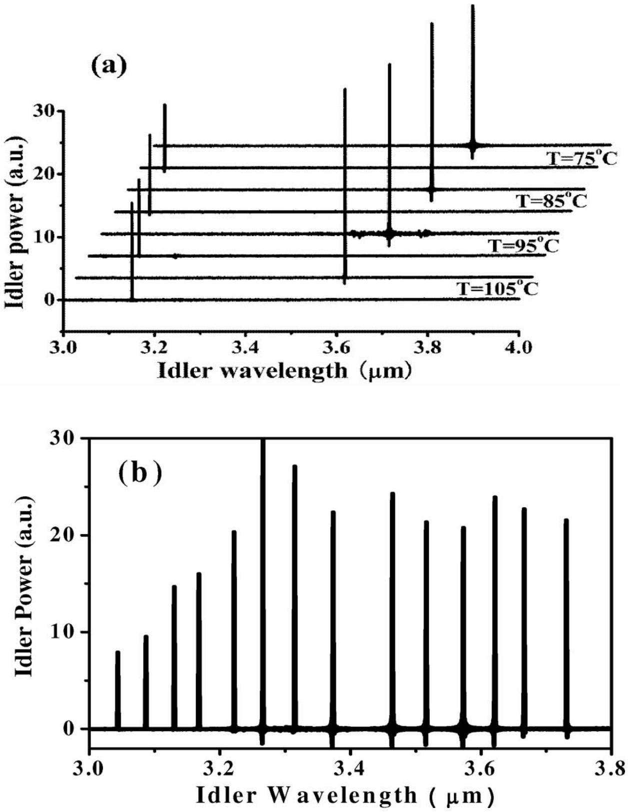

Fig. 5. Measured tuning output spectra of the DFG source for λ_s fixed at 1.58 μm. (a) tuning operation using the two QPM bands, (b) whole tuning output property.

result of 175 nm. This 2 °C discrepancy between the experimental and simulated results may be caused by the imprecision of the Sellmeier equation.

Next, the effect on the output properties of the DFG laser source when the crystal temperature is set below 128 °C are investigated. Figure 5(a) shows the measured idler output spectra for different temperatures. At 105 °C, a high level of DFG output can only be achieved near 3.15 and 3.59 μm, where the pump is tuned at around 1052.3 and 1097.1 nm, respectively, indicating that the two QPM bands truly exist. Moreover, the two QPM bands can always be observed for any temperature below 128 °C. However, the positions of the two QPM bands and the spacing between them are different for different temperatures. When the temperatures are 95 °C, 85 °C, and 75 °C, the two QPM bands are located at 3.11 and 3.63, 3.08 and 3.67, and 3.05 and 3.70 μm, corresponding to the spacing of 520, 590, and 650 nm, respectively. Similarly, the measured wavelengths (or temperatures) are slightly different from the simulated results, again caused by the imprecision of the Sellmeier equation. Therefore, wide DFG tuning can be achieved by tuning the pump wavelength when the crystal temperature is changed to adjust the positions of the two QPM bands for the pump tuning. Figure 5(b) gives the DFG output spectra. It shows that the entire tuning range covers 3.043–3.732 μm, nearly 690 nm, with the measured maximum conversion efficiency of about 0.09%/W at 3.267 μm. The tuning range is limited by our pump source tunability; if a longer wavelength L-band EDFL and a wider tuning range YDFL were used, the DFG tuning range might be increased further. It is also worthwhile to point out that the measured idler output amplitudes in the shorter wavelength swing were lower than those near the longer wavelength swing, which contradicts the simulation prediction. The reason may be that the overlapping factor between the pump and the signal beams decreases owing to the performance degradation of the CFS as the wavelength spacing between the pump and signal increases with the shortening of the pump wavelength, because the measured idler wavelength with the maximum output amplitude moves to the shorter wavelength swing when the signal wavelength is decreased to 1560 nm.

In conclusion, we have demonstrated a wide tuning technique for mid-IR DFG laser sources. When the fundamental lights are in the 1060 nm and 1550 nm wavebands, the pump tuning curve may have two separate QPM bands, and the positions of the two QPM bands and the spacing between them may be continuously tuned by changing the temperature. Such a property may be used for the widely tunable DFG laser sources, i.e., with the crystal temperature being changed to adjust the positions of the two QPM bands for the pump tuning. Our simulation results show that a tuning range of nearly 1.3 μm may be obtained for the signal wavelength fixed at 1.63 μm. With a DFG source based on fiber lasers, a 690 nm mid-IR tuning range has been demonstrated for the signal wavelength of 1.58 μm.

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