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Continuous-wave 2.9–3.8 μm random lasing via temperature-tunning free difference-frequency generation of random fiber lasers in PPLN crystal

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Continuous-wave (CW) tunable mid-infrared (MIR) laser sources are necessary for laser spectroscopy, remote sensing, and infrared imaging applications [1]. Generally, quantum cascaded lasers (QCLs) are mature MIR radiation sources with decent power. However, the tunning range of QCLs is limited to ten of cm^{-1}. In contrast, difference-frequency generation (DFG) sources based on nonlinear optical crystals have advantages in broad wavelength tunability. In particular, for the DFG sources with wavelength below 5 μm, commercial available periodically poled lithium niobate (PPLN) has been widely used to generate CW tunable DFG sources pumped by fiber lasers by tuning the wavelength of pump/signal sources and adjusting the crystal temperature and/or grating period [2, 3]. Among them, compared to the temperature-based tuning method, tunable dual wavelength-tunable fiber lasers can potentially shorten the time required by the wavelength-tuning process, which can meet the requirement of high measurement rates in some applications [3]. However, the tuning range of fiber-laser-based DFG source in PPLN is still limited by the wavelength range of the commonly used ytterbium-doped fiber laser (1–1.1 μm) and erbium-doped fiber laser (1.5–1.6 μm).

Unlike rare-earth-doped fiber lasers, Raman fiber lasers are available at arbitrary wavelength across the transparency window of the fiber material. Furthermore, random Raman fiber lasers based on distributed Rayleigh scattering and Raman gain in passive fibers with no resonant cavity have been extensively studied in recent years [4]. In particular, cascaded random Raman fiber lasers (CRRFLs) have been shown to generate tunable random lasing, covering 1.1–2 μm wavelength range with high output power [5, 6], and could be promising candidates as the CW seed sources for DFG [7].

In this study, we experimentally demonstrate the feasibility of using a tunable CRRFL as a signal source and a tunable ytterbium-doped random fiber laser (YRFL) as a pump source for MIR random lasing generation with ultrabroad tuning range and milliwatt-level output power via single-pass DFG in PPLN, without needing temperature tuning. By tuning the wavelengths of YRFL and CRRFL, gap-free wavelength tuning from 2.9 to 3.8 μm is realized at a fixed crystal temperature 40°C with two PPLN grating periods.

Experimental setup. The experimental setup is depicted in Figure 1(a). The setup is mainly composed of three parts: the DFG pump source (the tunable YRFL), the DFG signal source (the tunable CRRFL), and a PPLN crystal containing two separate, poled gratings with the periods of 30.10 and 31.15 μm. A more detailed statement of experimental setup is shown in Appendix A.

Characterization of tunable YRFL and CRRFL. The output spectra of proposed DFG pump, i.e., tunable YRFL are shown in Figure 1(b). The wavelength of YRFL could be continuously tuned from 1045 to 1090 nm, and the −3 dB bandwidths of the YRFL are approximately 0.2 nm in the entire tuning range. A more detailed depiction of spectra and other related output characteristics are shown in Appendix B.

To fulfill the quasi-phase-matching condition in PPLN with the grating periods of 30.10 and 31.15 μm, we use the 5th- and 6th-order random Raman lasing of CRRFL at wavelength near 1.5 and 1.6 μm, respectively, as the DFG signal source. The output spectra of the 5th (ranging from 1495 to 1535 nm)- and 6th (spanning from 1595 to 1642 nm)-order random Raman lasing of CRRFL are shown in Figures 1(c) and (d), respectively, with the tunable pump in the range of 1065–1090 nm. A more detailed description of the output characteristics of the 5th- and 6th-order random Raman lasing of the CRRFL is shown in Appendix B.

Difference-frequency generation. We firstly characterize the output properties of MIR random lasing generated via DFG at fixed wavelengths of pump and signal sources. The output characteristics are shown in Appendix C. The wavelengths of YRFL and CRRFL are fixed at 1055.3 and 1609.8 nm, respectively, and the grating period is chosen as 31.15 μm. The generated idler radiation is located near 3064 nm with 16 nm of −3 dB bandwidth that is mainly

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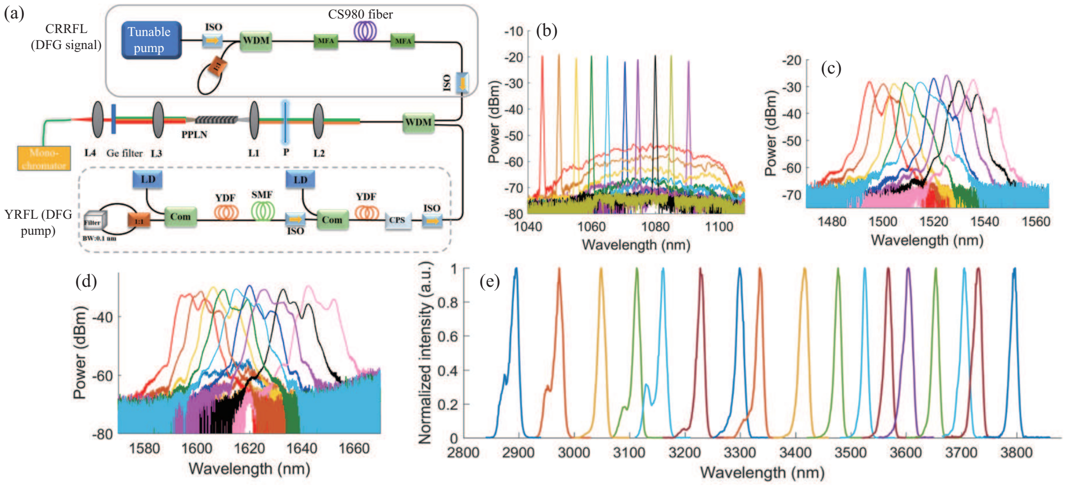

Figure 1 (Color online) (a) Experimental setup; (b) the spectra of YRFL; (c) and (d) the output spectra of the 5th- and 6th-order CRRFL; (e) the spectra of DFG sources.

determined by the bandwidth of the 1609.8 nm signal laser in our system. The DFG power grows linearly with the increase of pump power and reaches the maximum value of 1.26 mW at 4.5 W of the pump power when the signal power is fixed at 1.15 W. The conversion efficiency is calculated as $\eta = 0.24$ mW/W^2, with η defined as $\eta = P_{\rm i}/P_{\rm s} \times P_{\rm p}$, where $P_{\rm i}$, $P_{\rm s}$, $P_{\rm p}$ are the power of idler, signal and pump, respectively. Notably, the conversion efficiency is relatively low compared to that of the reported CW DFG laser source [7] because of the low temporal coherence (broad linewidth) of the used random fiber lasers, seeing Appendix B, and the imperfect beam overlap.

In the next step, to generate a broadly tunable MIR laser, by tuning the pump wavelength from 1045 to 1090 nm, the phase-matching condition shown in Appendix C can be satisfied to generate idler radiation from 3.4 to 3.8 μm by simultaneously tuning the signal wavelength from 1500 to 1530 nm, which is within the tuning range of the 5th-order random Raman lasing of CRRFL. Similarly, the required signal wavelength-tuning range is 1595–1635 nm to realize an idler emission from 2.9 to 3.4 μm in PPLN with 31.15 μm grating period, which can be satisfied by using the 6th-order random Raman lasing of CRRFL. Figure 1(e) presents the experimentally measured spectra of the MIR DFG random laser, with the wavelength continuously tuning from 2.9 to 3.8 μm, by varying the wavelength pairs of YRFL and CRRFL and shifting between the two different grating periods. The output power of idler radiation as a function of idler wavelength is shown in Appendix C. More than 1 mW MIR of output power is achieved for a 2.9–3.3 μm idler wave. The idler power beyond 3.4 μm is lower because of the lower power of the 5th-order random Raman lasing than that of the 6th-order one, which can be clearly seen in Appendix B.

Discussion. Considering that the CRRFL can emit random lasing with a tunable wavelength range covering 1.1–2 μm, the idler wavelength covering the entire transparency window of PPLN can be tuned with the proposed DFG system. An example is shown in Appendix D, with the phase-matching conditions in PPLN with grating periods of 29.13 and 28.30 μm to confirm further extension of tuning range of DFG source to 4.4 μm.

Conclusion. In this study, an ultrabroad tunable MIR random lasing spanning from 2.9 to 3.8 μm via DFG in PPLN without changing the crystal temperature is experimentally demonstrated using a tunable CRRFL in the range of 1495–1535 and 1595–1642 nm as the signal source and a tunable YRFL covering from 1045 to 1090 nm as the pump source. This study significantly broadens wavelength-tuning range of DFG source in PPLN with fiber lasers, and the generated MIR random lasing could inherit the low temporal and/or spatial coherence of random fiber lasers, extending the applications that require low-coherence light sources into MIR wavelength region [8].

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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