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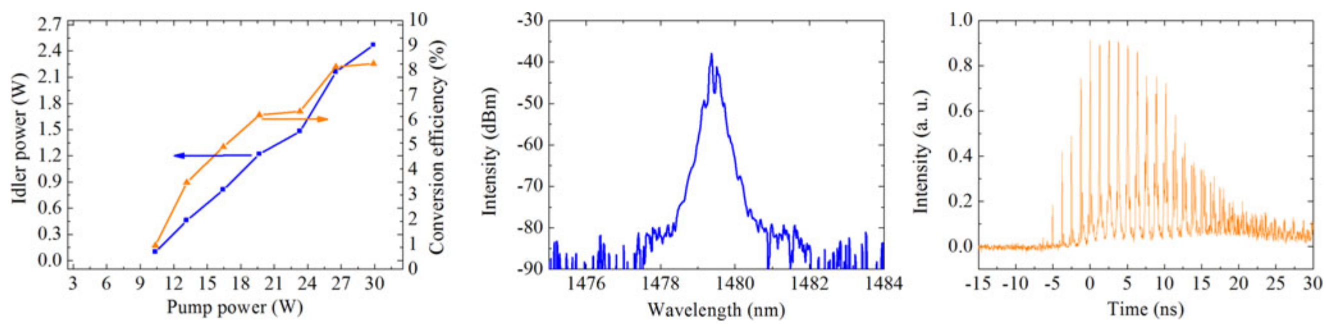

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3.8-μm Mid-Infrared Laser Quasi-Synchronously Pumped by a MOPA Structured Picosecond Yb Fiber Amplifier With Multi-pulse Operation

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Abstract: A picosecond pulsed mid-infrared laser with multi-pulse operation is experimentally demonstrated. This mid-infrared laser was composed of a fiber laser pumped optical parametric oscillator (OPO). The pump source of this OPO was a master oscillator power amplification-structured picosecond fiber amplifier with pulse bunch output, which was further used to quasi-synchronously pump a periodically poled magnesium-oxide doped lithium niobate crystal based OPO to obtain 3.8-μm wavelength output with picosecond multi-pulse operation. The pump-idler conversion efficiency, the signal spectrum, and the signal pulse bunch are presented, respectively.

Index Terms: Fiber amplifier, mid-infrared, multi-pulse operation, picosecond

1. Introduction

Mid-infrared laser sources that are around 3 to 5 μm wavelengths are of practical interest for a variety of applications, including environmental monitoring, medical diagnostics, free-space communication, and infrared countermeasures [1]–[4]. Quantum cascade lasers (QCLs) have become the ideal sources to achieve mid-infrared output owing to their compact cavity configuration and broad wavelength tunable range [5]–[7]. However, the QCLs have the difficulty of emitting the mid-infrared wavelengths less than 4 μm at room temperature due to their material limitations. Furthermore, 3.8 μm wavelength located in atmospheric window is especially important in the fields of optical communications and infrared countermeasures. Unfortunately, it is difficult to obtain the 3.8 μm laser directly from the QCLs.

Optical parametric oscillators (OPOs) are available to radiate the whole mid-infrared region from 3 μm to 5 μm through selecting appropriate nonlinear crystal [8]–[10]. The output properties from an OPO, to a great extent, depend on the parameters of the pump source. Picosecond pulsed fiber lasers are perfect source for pumping OPO, considering their excellent beam quality, high optical-optical conversion efficiency, simple thermal management, and high peak power [11]–[13].

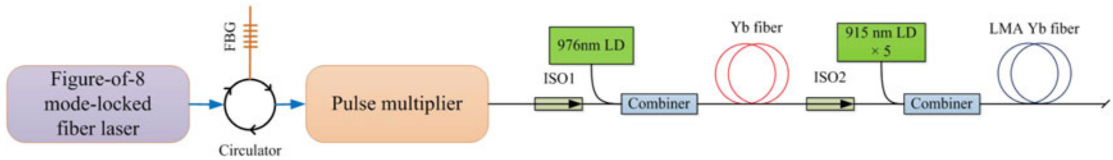

Fig. 1. Schematic diagram of the MOPA structured Yb fiber amplifier with multi-pulse operation.

To realize efficient parametric conversion using the picosecond fiber laser, the synchronous pumping scheme which usually requires a relatively high pulse repetition rate from pump source, should be adopted due to a short light-matter interaction duration in a picosecond pulsed OPO system [14]. However, in the conventional picosecond fiber laser systems, the high repetition rate generally brings about the relatively low peak power [15], [16], which leads to the increase of the OPO pumping threshold. In order to obtain the higher peak power, the burst-mode technique in picosecond pulsed fiber lasers have been employed to realize the multi-pulse output [17], [18], although the burst-mode operated fiber lasers have been seldom applied as the pump source of the OPOs so far. Based on the burst-mode technique, the quasi-synchronously pumping is proposed as a new approach, in which the multi-pulses from the burst-mode operated lasers are applied as the pump in an OPO system.

In this paper, we present a quasi-synchronously pumped OPO emitting 3.8 μm wavelength using a multi-pulse operated picosecond fiber laser system as pump source. This fiber laser system was composed of a master oscillator power amplification (MOPA) structured fiber amplifier with multi-pulse operation. The seed of this fiber amplifier was a home-made figure-of-8 cavity structured mode-locked fiber laser, which was followed by a spectral picker for obtaining narrow linewidth output. An all-fiber pulse multiplier was used to realize multi-pulse operation. The multi-pulse operated train was amplified to 43 W using large mode area (LMA) based polarization-maintaining (PM) Yb doped fiber. The high power output from this fiber amplifier was focused to pump a periodically poled magnesium-oxide doped lithium niobate (PPMgLN) crystal for realizing parametric conversion. The maximum average power at 3.8 μm obtained was 2.45 W.

2. Experimental Setup

The architecture of the MOPA structured Yb fiber amplifier with multi-pulse operation is illustrated in Fig. 1. The seed of the MOPA was a home-made all-fiberized figure-of-eight cavity structured mode-locked fiber laser based on the principle of nonlinear optical loop mirror (NOLM). The setup of the seed was identical to that in our previous work [18]. To realize efficient parametric conversion, a fiber Bragg grating (FBG) based spectrum filter was used to acquire narrow spectral bandwidth output. A fiber-pigtailed pulse multiplier module, which was composed of three cascaded fiber couplers, was applied to realize multi-pulse operation. A polarization-insensitive fiber isolator (ISO1) was spliced to the output fiber of the multiplier module.

The multiplied pulses were amplified to tens of watts using two-stage Yb fiber amplifier. The pulsed laser from ISO1 and a multi-mode fiber pigtailed 976 nm laser diode (LD) were together coupled to a home-made 3.5-m-long Yb doped double-cladding fiber (YDDCF) with a size of 7/125 μm and a cladding absorption of 3 dB/m at 976 nm through a multi-mode combiner. The pulses were further power-amplified using a large mode area (LMA) based 6-m-long polarization-maintaining (PM) YDDCF with a size of and 25/250 μm, a core numerical aperture (NA) of 0.07, and a cladding absorption of 1.8 dB/m at 915 nm (Nufern PLMA-YDF-25/250-M) respectively. The power-amplified laser passed through a high power PM isolator with an insertion loss of 1.5 dB to eliminate the influence of backward light.

The experimental setup of the quasi-synchronously pumped OPO is shown in Fig. 2. The picosecond laser from the fiber amplifier was focused onto the PPMgLN crystal using a convergent lens with a focal length of 150 mm. A simple standing cavity configuration was adopted in our research to ensure compactness. The OPO resonator was composed of two coated mirrors

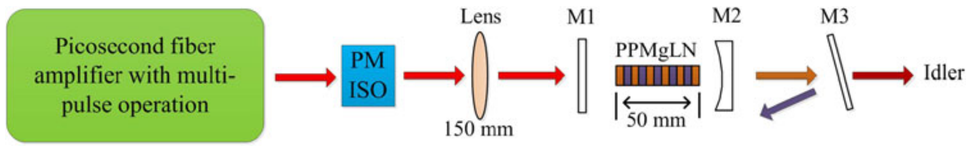

Fig. 2. Experimental setup of the quasi-synchronously pumped OPO.

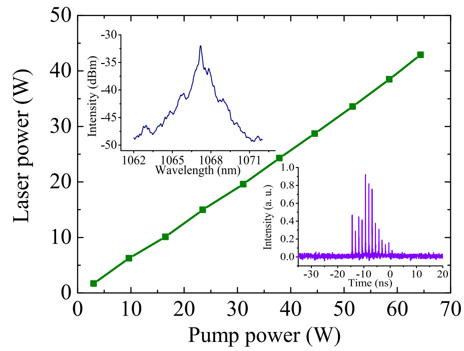

Fig. 3. Laser power as a function of the pump power in the power-amplifier. (Insets) Spectrum and the pulse bunch, respectively, at the maximum laser average power of 43 W.

and a PPMgLN crystal with a poled period of 29 μm. The input mirror (M1) was a plane mirror and was coated with high-reflection (HR) film for signal (R>99.7% over 1.4-1.7 μm) and idler band (3-4 μm), as well as a high transmission coating for pump (T>98%). The output coupler (M2) was a concave mirror with a radius of curvature 200 mm and was coated with HR for signal (R>99.7% over 1.4-1.7 μm) and high transmission for the pump and the idler (3-4 μm) (T>98%). The undepleted pump and the OPO signal were highly reflected by M3 (R>99.8%). The signal output was extracted through M2, while the idler power was measured after M3. To meet the requirement of quasi-synchronously pumping, the cavity length was chosen to be approximately 12 cm, corresponding to the round-trip time of 1.26 ns.

3. Results and Discussions

By slowly increasing the pump power, a stable mode-locked pulse train was obtained with a repetition rate of 2.67 MHz and a pulse duration of 700 ps. The full width at half maximum (FWHM) of the seed spectrum observed was 7.5 nm at the maximum seed laser of 38 mW. However, the spectrum was too broad to achieve an efficient parametric conversion in an OPO system. A FBG based circulator was applied to narrow the seed spectrum, meanwhile, the pulse duration became also much narrower owing to the chirp characteristics of the seed pulse. The FWHMs of the seed spectrum and pulse via this circulator were 0.15 nm and 50 ps, respectively, while the laser power was reduced from 38 mW to 0.7 mW. To build quasi-synchronously pumped OPO in our subsequent experiment, a home-made pulse multiplier was used to form the pulse bunch, in which the time intervals between neighbouring sub-pulses were equal to be 1.26 ns corresponding to the repetition rate of 794 MHz.

The multiplied pulses were firstly pre-amplified to 1.6 W using a multi-mode LD pumped YDDCF. Then, the pre-amplified laser passed through a high power PM isolator to obtain linearly polarized output, meanwhile the laser power was reduced to 0.7 W, which was further amplified to 43 W using a LMA based PM YDDCF. The laser power with respect to the pump power is illustrated in Fig. 3, in which the insets show the spectrum and the pulse bunch respectively at the maximum laser average power of 43 W. The slope efficiency estimated was 67%.

Using this high power fiber amplifier as the pump source of the OPO system, the linearly polarized picosecond laser was focused onto the middle of the PPMgLN crystal to obtain mid-infrared laser

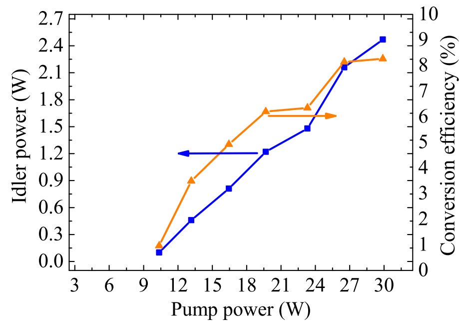

Fig. 4. Idler power with respect to the pump power.

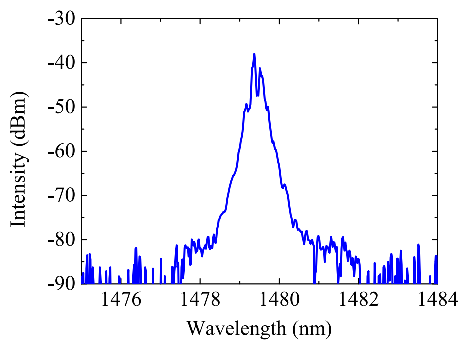

Fig. 5. Signal spectrum from OPO at the maximum pump power of 30 W.

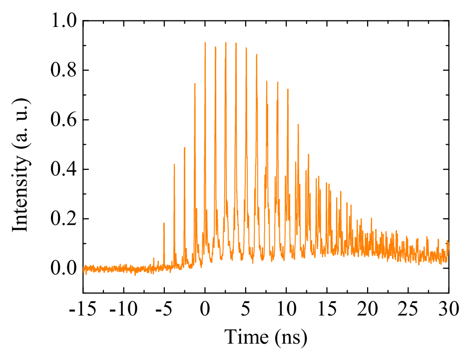

Fig. 6. Pulse bunch of the signal at the maximum pump power of 30 W.

output. The focused pump laser had a beam waist of 100 mm. By increasing the pump power and adjusting the cavity length at the same time, the red light was observed, as was the spectrum of the signal laser displayed in optical spectrum analyzer (OSA). With the increase of the pump power, the idler power was nearly promoted linearly, as shown in Fig. 4. The maximum pump power was limited at 30 W because of the 1.5 dB insertion loss of ISO2. As seen from Fig. 4, the OPO threshold was 10.4 W, and the maximum idler power of 2.45 W with the maximum optical-optical conversion efficiency of 8.2% was obtained at the maximum pump power of 30 W. The slope efficiency of this OPO was about 12%. The higher idler power could be obtained through optimizing the parameters of the pump source.

The signal spectrum at the maximum pump power of 30 W was measured as shown in Fig. 5. Two peak wavelength observed was located at 1479.2 nm and 1479.3 nm, respectively, corresponding to the idler wavelength of approximately 3.8 μm. The spectral FWHMs of these two peaks were same to be 0.1 nm.

As the pump power was promoted to 30 W, a stable signal pulse bunch train was obtained, and the shape of the individual pulse bunch was shown in Fig. 6. The envelope of this bunch had the Gauss-like pulse shape with a duration of approximately 20 ns. The rising edge was composed of six shape-similar sub-pulses, corresponding to a relatively short time span of 6.3 ns, while the long trailing edge of approximately 12 ns was obtained. The rising time mainly depended on the number of the sub-pulses in a pump bunch; however, the trailing time depended on the cavity losses induced by the cavity mirror, material loss, as well as feedback coupling.

4. Conclusions

In summary, we experimentally demonstrate a quasi-synchronously pumped OPO which emitted the mid-infrared wavelength of 3.8 μm. The pump source of this OPO system was a MOPA-structured Yb fiber amplifier with multi-pulse operation. An individual picosecond pulse from the mode-locked seed was multiplied to form a pulse bunch, in which multi-pulse operation was obtained. The amplified picosecond pulse bunches were used to quasi-synchronously pump OPO to achieve mid-infrared laser output. A multi-pulse operated mid-infrared laser was obtained with a maximum average power of 2.45 W at 3.8 μm wavelength.

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