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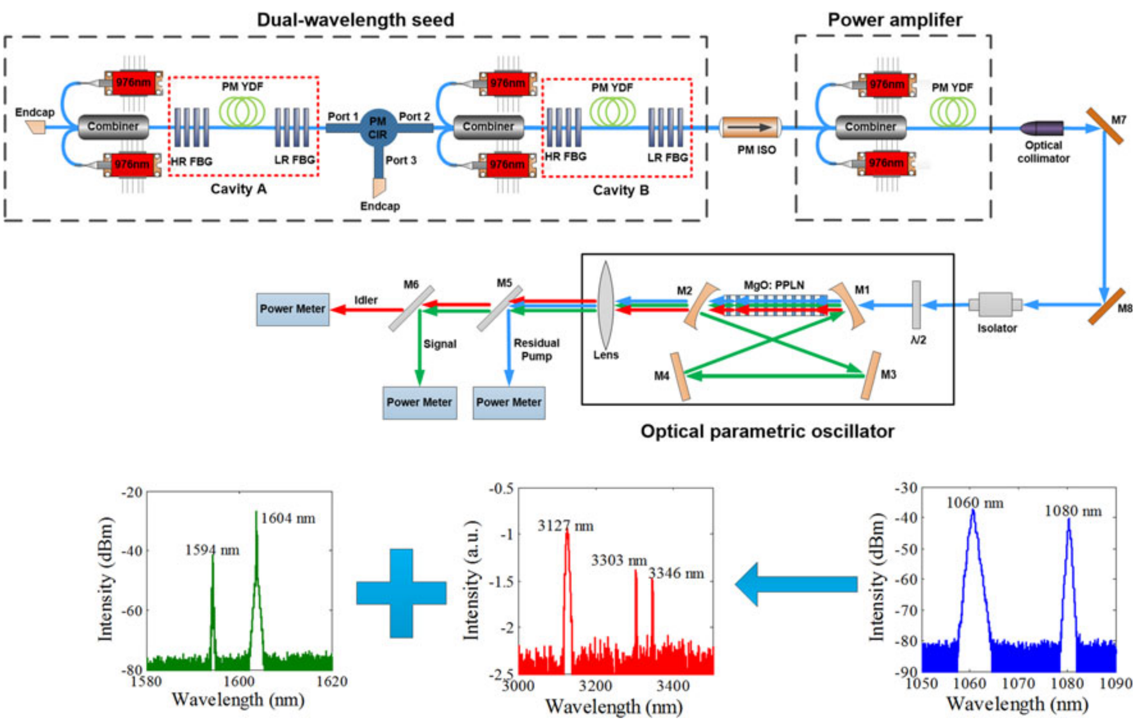

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Multiwavelength Mid-Infrared Laser Generation Based on Optical Parametric Oscillation and Intracavity Difference Frequency Generation

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Abstract: We report a multiwavelength mid-infrared laser based on intracavity difference frequency generation in an MgO-doped periodically poled $LiNbO_3$ optical parametric oscillator, which was pumped by a dual-wavelength fiber MOPA consisting of two parts: dual-wavelength seed and power amplifier. The maximum output power of the linearly polarized pump laser was 65.3 W, and the wavelengths were 1060 and 1080 nm. Three idler emissions with different wavelengths of 3127, 3303 and 3346 nm were obtained under the maximum pump power, and the total idler output reached 7.38 W, indicating a 15% pump-to-idler slope efficiency. The signal laser generated in the experiment had two wavelengths, which were 1594 and 1604 nm under the maximum pump power. Three nonlinear progresses occurred in the experiment, two of them being optical parametric oscillation and the one left being difference frequency generation.

Index Terms: Infrared lasers, fiber lasers, nonlinear crystals, nonlinear.

1. Introduction

In recent years, mid-infrared sources around 3–5 μm have attracted great attention and been extensively investigated [1]–[5]. Gross demonstrated the first fiber-pumped mid-infrared singly resonant optical parametric oscillator (OPO) in 2002 [6]. Kumar and Ebrahim-Zadeh also contributes a lot to the development of the mid-infrared OPOs [7]–[9]. Due to the minimum atmospheric attenuation on the infrared window and a high penetration capability of mid-infrared spectral region, they have been applied to a variety of fields [10]–[12]. In particular, multi-wavelength mid-infrared sources have specific and various applications including chemical sensing and terahertz-wave (THz-wave) generation [13]–[16]. Kawase *et al.* demonstrated a dual-wavelength OPO using a piece of dual-grating cascaded PPLN wafer in 2000 [14]. In the experiment, the PPLN crystal had two grating periods of 29.3 and 29.5 μm, and two independent signal beams were achieved with the

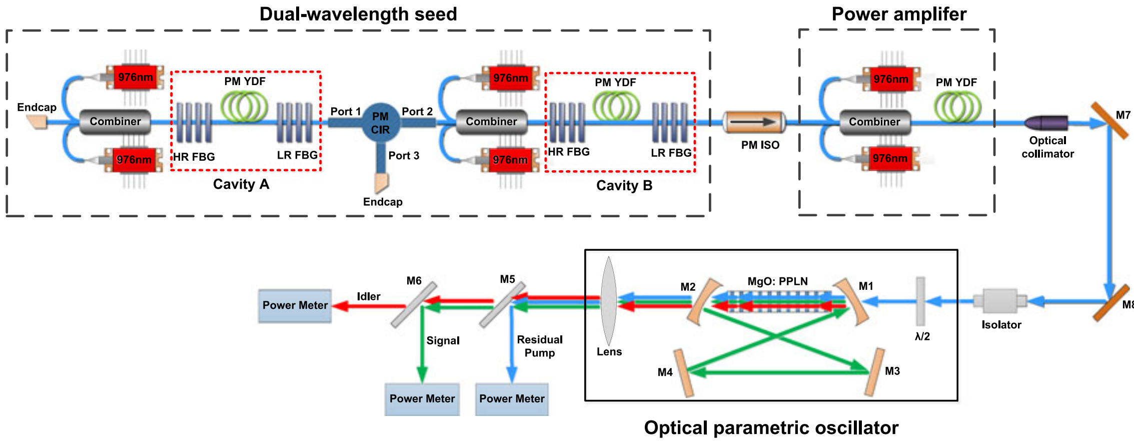

Fig. 1. Schematic diagram of the multi-wavelength mid-infrared laser system.

wavelengths of 1529 and 1546 nm, but obviously, its nonlinear parametric efficiency would be limited because each nonlinear process is just taken place in part of the PPLN crystal as commented in [17]. In 2009, Ji *et al*. reported an OPO with dual idler wave output based on periodically poled MgO: $LiNbO_3$ with a periodically-phase-reversed grating structure, which was pumped by a Q-switched laser. 0.98 W of dual idler-waves at 3.824 and 3.731 μm was achieved at room temperature [18]. Jiang *et al.* demonstrated fiber laser pumped dual-wavelength OPOs based on an aperiodic poled MgO-doped lithium niobate wafer which had a special structure of aperiodic optical superlattice (AOS) [17], [19]. To obtain mid-infrared output with more wavelengths, Asobe *et al*. constructed a novel mid-infrared light source that could generate multiple unequally spaced wavelengths and demonstrated the detection of multiple hydrocarbon gases, namely CH_4, $C2H_4$, and C_2H_6 [20]. Smith *et al*. demonstrated a tandem PPLN and ZGP optical parametric oscillator and obtained multiple wavelength output in the mid-infrared. The signal laser produced by the first PPLN OPO was used to pump the second ZGP OPO and at laser the idler laser with three wavelengths of 3.66, 3.9, and 4.6 μm was generated [21], but the whole system is complicated.

Compared with other kinds of pump lasers, fiber laser has many advantages such as high efficiency, excellent beam quality, compact structure and good portability [22], [23]. Dual-wavelength fiber laser has been deeply discussed [24]–[26] and can be applied as the pump source for the time being. In this letter a high power multi-wavelength mid-infrared OPO system pump by a fiber laser is proposed for the first time. The pumping source was a dual-wavelength linearly polarized fiber laser whose power reached 65.3 W. The output laser was incident into a singly resonant ring cavity. A total idler output power of 7.38 W was obtained under the maximum pump power and had three wavelengths: 3127, 3303, and 3346 nm. This is the first time to our knowledge that a multi-wavelength mid-infrared laser was obtained by using a dual-wavelength fiber laser as the pump source.

2. Experiment Setup and Results

The schematic diagram of the multi-wavelength mid-infrared laser system is shown in Fig. 1. The structure of the pump source consisted of fiber master oscillator power amplifier is similar to that described in [27] which contained two parts: the dual-wavelength seed and the power amplifier. The seed consisted of two cascaded Yb-doped fiber lasers, whose central wavelengths were 1080 and 1060 nm (named as cavity A and cavity B), respectively. Cavity A was designed as a linear cavity and made up with a pair of fiber Bragg gratings (FBGs), of which both the central wavelengths were 1080 nm and 16 m of 10/125 μm double cladding polarization-maintaining Yb-doped fiber. It was pumped by two 976 nm laser diodes with the total maximum power of 106 W. The structure of cavity

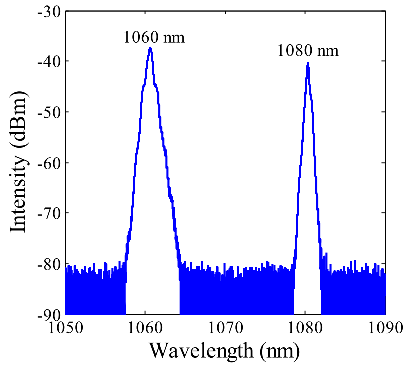

Fig. 2. Measured spectra of the dual-wavelength laser with the maximum output power.

B was similar to cavity A, except for the central wavelengths of the FBGs, which were 1060 nm. It was also pumped by two 976 nm laser diodes, each with the highest power of 58 W. The 1080 nm laser formed in cavity A passed through a polarization-maintaining circulator which was used to avoid any residual back reflection and injected into the whole 1060 nm Yb-doped fiber laser in the core. After the dual-wavelength seed was a polarization-maintaining fiber isolator. In the amplifier stage two 976 nm laser diodes with the total power of 80 W were used as the pump source. The gain fiber was a length of 10/125 μm double cladding polarization-maintaining Yb-doped fiber. Finally, the dual-wavelength pump laser was outputted through an optical collimator.

In the experiment the output power and spectrum of the pump laser was measured firstly. The linearly polarized laser of the dual-wavelength seed had the maximum power of 2.5 W under the circumstances where four laser diodes used as the pump source for cavity A and B didn't work to full capacity. After the amplifier stage the maximum pump power was increased to 65.3 W, which revealed that the conversion efficiency reached 78.5%. The output spectrum of the dual-wavelength laser with the maximum output power was measured using an optical spectrum analyzer, and is presented in Fig. 2. It reveals that the output fiber laser had two central wavelengths located in 1060 and 1080 nm. The 3 dB bandwidth of the 1060 nm laser was 0.8 nm while that of the 1080 nm laser was 0.3 nm. Limited by the measurement conditions, we couldn't separate the two pump emissions in the experiment. As an alternative, we estimated the power ratio between 1060 and 1080 nm to be about 4:1 using the integral intensity method via Fig. 2, which means that in the total maximum pump power of 65.3 W, the power of 1060 nm laser was about 52 W while the power of 1080 nm laser was just about 13 W.

As Fig. 1 shows that the dual-wavelength pump laser was reflected by two HR at 1.0–1.1 μm mirrors (M7 and M8) and injected into the OPO cavity. An isolator was inserted between the dual-wavelength fiber laser and the OPO to avoid any residual back reflection. A half-wave plate was placed behind the isolator to align the polarization direction of the fiber laser accordingly. The OPO cavity was designed as a singly resonant ring cavity which was composed of two concave mirrors M1 and M2 with the radius of curvature of 150 mm, two plane mirrors M3 and M4 and a periodically poled MgO: PPLN crystal. All the mirrors had high transmission for the idler over 3–4 μm and the pump over 1–1.1 μm, thus ensuring SRO operation. The mirrors M1, M3 and M4 had HR coating for the signal over 1.4–1.7 μm and the mirror M2 is the output coupling mirror. An MgO:PPLN crystal was used as the nonlinear medium. It had a size of 50 mm $\times$ 10 mm $\times$ 1 mm, contained a single grating period of $\Lambda = 31$ μm. The crystal faces had AR coating for all three wavelength bands. After the cavity, there was a collimating lens to make the output laser parallel for accurate measurement. Two filters were placed after the collimating lens for separating the three kinds of lasers. The first one M5 had HR coating for 1.0–1.1 μm and high transmission for the signal and the idler. The second one M6 had HR coating for the signal and high transmission for the idler. Three power meters were used to measure the power of the residual pump laser, the signal laser, and the idler laser.

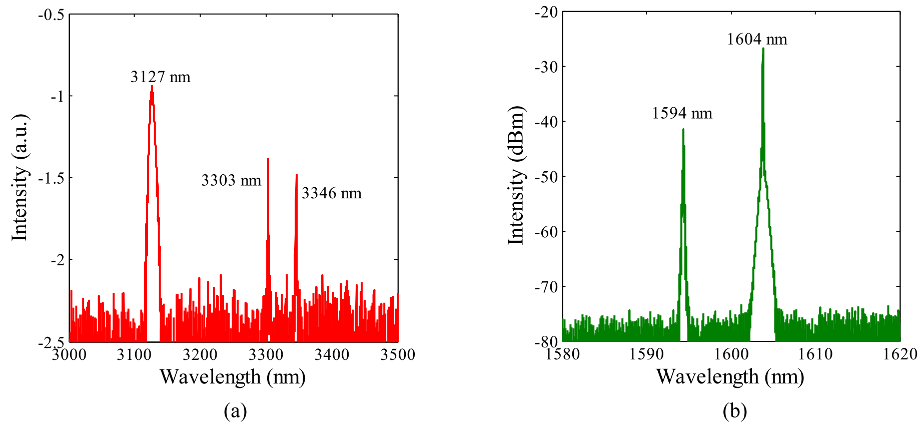

Fig. 3. Measured spectra of the OPO under the maximum pump power. (a) Idler. (b) Signal.

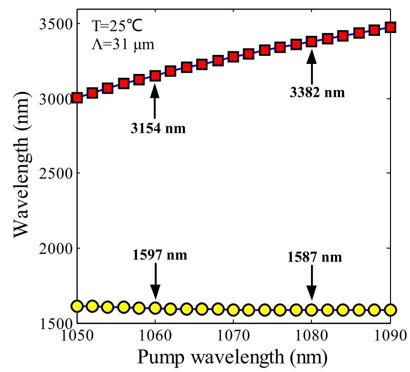

Fig. 4. Wavelength tuning simulation with the variation of pump wavelength.

The output spectra of the OPO output under the maximum pump power were measured using an optical spectrum analyzer (ANDO, AQ6370D) and a Bristol infrared spectrum (Bristol, 721B) and are presented in Fig. 3(a) and (b) on a logarithmic scale, respectively. It can be seen from Fig. 3(a) that the mid-infrared output obtained in the experiment had three central wavelengths which were 3127, 3303 and 3346 nm under the maximum pump power. It reveals that three nonlinear processes occurred in the experiment. Fig. 3(b) shows that two signal emissions were generated in the experiment whose central wavelengths were 1594 and 1604 nm under the maximum pump power. Both the 10 dB bandwidth of the 1594 and 1604 nm signal waves was about 0.2 nm, which was not very accurate due to the measurement accuracy of the optical spectrum analyzer. Also affected by the measurement accuracy, the 3 dB bandwidth of two signal waves cannot be obtained. But Fig. 3(b) indicates that the 1604 nm signal spectrum was, on the whole, much wider than the 1594 nm signal wave. It was analyzed that the bandwidth difference between two signal waves is caused by the power difference of the two pump waves. Higher the pump power is, wider the signal spectrum is. The power of the 1060 nm radiation was much larger than that of the 1080 nm radiation, which led to the wider spectrum of the 1604 nm signal wave. To figure out types of nonlinear processes in the experiment, wavelength tuning of the OPO under the circumstances where the grating period of the nonlinear crystal is 31 μm, the room temperature is 25 °C and the pump wavelength ranges from 1050 to 1090 nm is simulated as shown in Fig. 4. It can be obviously seen from the picture that the idler and signal wavelengths are 3154 and 1597 nm when the pump wavelength is 1060 nm while it changes to 3382 and 1587 nm when the pump wavelength is 1080 nm. Compared with the experiment results, it comes to a conclusion that the idler emissions with the wavelengths of 3127 and 3346 nm were generated resulting from the optical

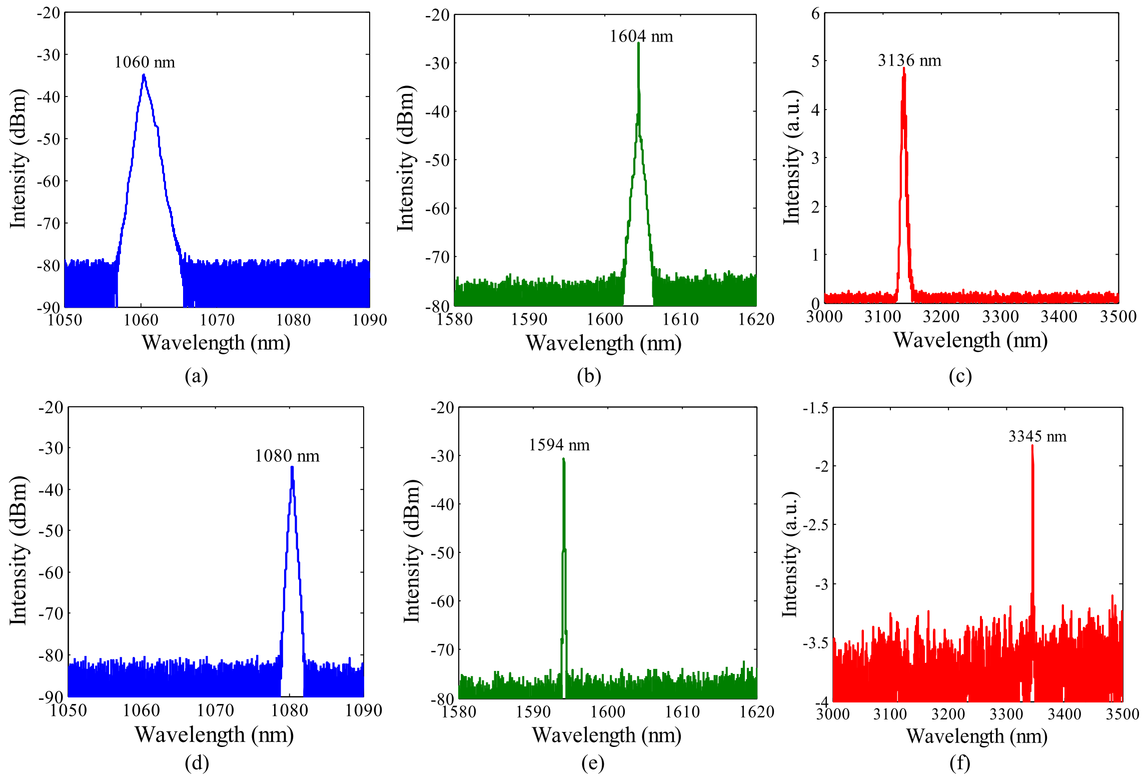

Fig. 5. Measured spectra of the OPO output when the pump wavelength is 1060 and 1080 nm separately.

parametric oscillation of the 1060 and 1080 nm pump laser, while the idler laser with the wavelength of 3303 nm was generated due to the intracavity difference frequency generation between the 1080 nm pump laser and the 1604 nm signal laser. The difference frequency generation result also fitted in with the energy conservation law $hc/\lambda_p = hc/\lambda_s + hc/\lambda_i$ (‘*p*’, ‘*s*’, ‘*i*’ means the pump laser, the signal laser and the idler laser respectively). Three nonlinear processes happened in the experiment. The measured signal and idler wavelengths are not exactly in agreement with the theoretical calculated values. It is due to the inaccuracy of the Sellmeier equation for the MgO-doped LN crystal, thermal effect and also the fabrication restrictions.

To further verify the conclusion obtained by Fig. 4, the OPO system was pumped just by the 1060 nm laser and 1080 nm laser separately with the maximum pump power under the circumstances where just one of cavity A and cavity B worked. Measured spectra of the pump, signal and idler laser under the maximum pump power were shown in Fig. 5(a)–(f), respectively. As can be seen, the wavelengths of the signal and idler laser were almost the same as what shown in Fig. 3. The tiny discrepancy between them was the measurement error of the wavelength meter. Figs. 4 and 5 all verified that in the experiment, the optical parametric oscillation happened to the 1060 and 1080 nm pump laser and another nonlinear process was difference frequency generation between the 1080 nm laser and the signal laser generated by the 1060 nm laser.

The total idler power dependence on the pump power was measured and shown in Fig. 6, which reveals that under the maximum pump power of 65.3 W, the total idler power reached 7.38 W. The corresponding pump-to-idler conversion efficiency was about 15%. The pump laser was no more amplified for preventing high power laser from damaging the crystal or other devices of the system, but Fig. 6 reveals that no saturation phenomenon was observed, indicating the possibility of obtaining higher OPO multi-wavelength output power by increasing the pump power. In the experiment, three idler emissions with different wavelengths only appeared until the pump power reached 43 W. When the pump power was between 47 W and the threshold, just two idler

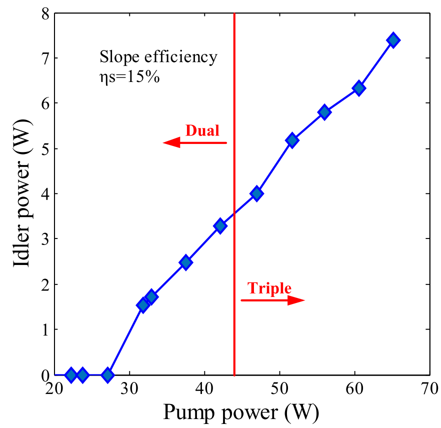

Fig. 6. Total idler power dependence of the OPO on the pump power.

emissions were obtained which were analyzed to be the optical parametric oscillation of the 1060 and 1080 nm pump laser. Limited by the measurement conditions, we could not separate the three idler emissions in the experiment. As an alternative, we estimated the power ratio between 3127, 3303 and 3346 nm to be about 17.5:1:1.2 through the linear coordinates of the infrared spectrum.

3. Conclusion

In summary, we have experimentally demonstrated a multi-wavelength optical parametric oscillator pumped by a dual-wavelength fiber laser with the wavelength of 1060 and 1080 nm. Under the maximum pump power of 65.3 W, three idler emissions with the wavelengths of 3127, 3303, and 3346 nm were obtained and the total idler output reached 7.38 W, revealing a high pump-to-idler slope efficiency which reached 15%. It was analyzed that in the whole experiment, three nonlinear processes happened, two of which were optical parametric oscillation of the two pump laser, and the one left was difference frequency generation between the 1080 nm pump laser and the signal laser generated by the 1060 nm pump laser. To the best of our knowledge, this is the first report of a multi-wavelength mid-infrared OPO pumped by a dual-wavelength fiber laser. Compared to other methods obtaining multi-wavelength output in a mid-infrared OPO system, this method does not need crystals with special structures or change cavity structure and is simple and convenient. Future work will be focused on increasing the output power and extending the wavelength generated. It can be expected that these techniques will lead to a feasible scenario in many applications.

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