Widely tunable eye-safe laser by a passively Q-switched photonic crystal fiber laser and an external-cavity optical parametric oscillator

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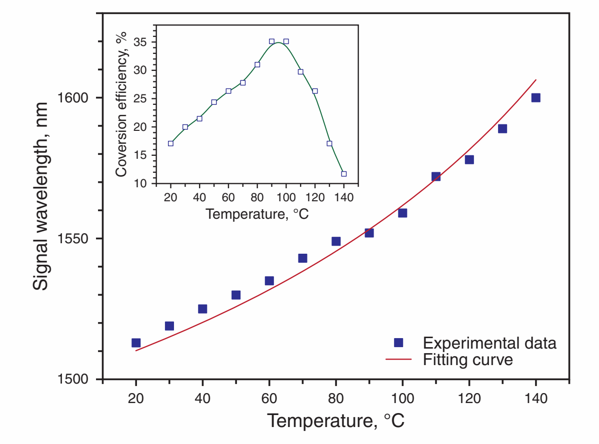
Abstract: We report on a widely tunable passively Q-switched photonic crystal fiber (PCF) laser with wavelength tuning range up to 80 nm. The PCF laser utilizes an AlGaInAs quantum well/barrier structure as a saturable absorber and incorporates an external-cavity optical parametric oscillator (OPO) to achieve wavelength conversion. Under a pump power of 13.1 W at 976 nm, the PCF laser generated 1029-nm radiation with maximum output energy of 750 μJ and was incident into an external-cavity OPO. The output energy and peak power of signal wave was found to be 138 μJ and 19 kW, respectively. By tuning the temperature of nonlinear crystal, periodically poled lithium niobate (PPLN), in the OPO, the signal wavelength in eye-safe regime from 1513 to 1593 nm was obtained.



Tuning curve of signal wavelength *versus* different operating temperature. Inset – the corresponding conversion efficiency with temperature

Widely tunable eye-safe laser by a passively Q-switched photonic crystal fiber laser and an external-cavity optical parametric oscillator

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Key words: photonic crystal fiber laser; tuning range; eye-safe laser

1. Introduction

High-peak-power tunable laser sources have been in demand for the applications in the eye-safe wavelength regime near 1.55-μm such as free-space communication, gas sensing, spectroscopy, and medical treatment [1–4]. In recent years, double-cladding rare-earth doped fiber lasers are of great interest due to their good beam confinement, excellent heat dissipation, spatial beam quality, and high efficiency [5–14]. Because of the broad bandwidth resulted from the amorphous nature of the glass host, directly utilizing erbium doped fiber (EDF) lasers or erbium-ytterbium-codoped double-clad fiber lasers (EYDFL) possess the potential of wavelength tunability [15–19]. However, traditionally a wavelength-selective element such as grating or etalon is desired in the cavity and thus increases the complexity of laser cavity [20–23]. An alternative method for flexibility in tuning wavelength is an optical parametric oscillator (OPO) pumped by a laser source with shorter wavelength [24–28]. Based on the phase matching condition, the signal output wavelength could be controlled by adjusting the temperature of nonlinear crystal, pump incident direction, or pump wavelength.

For pulsed OPO operation, the passively Q-switch gives the advantage of simplification and compactness in

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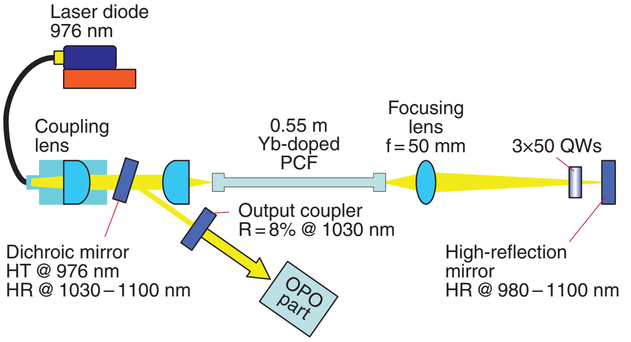

Figure 1 (online color at www.lphys.org) Schematic sketch of the external-cavity optical parametric oscillator pumped by the passively Q-switched photonic crystal fiber laser

experimental setup. In addition to the mostly used transition metal-doped crystals, semiconductor material with a periodic quantum-well (QW) structure has been demonstrated as a saturable absorber in the EYDFL to achieve a 105-μJ passively Q-switched 1.54-μm laser [29] and in the ytterbium doped photonic crystal fiber (PCF) laser to achieve an 1.1-mJ passively Q-switched 1.03-μm laser [30]. In 2010, the performance of eye-safe laser with a passively Q-switched PCF laser in an intracavity OPO was firstly reported [31]. In the published work, the fundamental wavelength is fixed at the maximum gain peak and a temperature-insensitive x-cut KTiOPO (KTP) was used in the OPO, this makes it inflexible to realize a broadly tunable laser. Periodically poled lithium niobate (PPLN) is a powerful quasi-phase-matching (QPM) nonlinear crystal in OPOs for generating near-infrared (NIR) to mid-infrared (MIR) radiation because of its advantages of high nonlinear coefficient (~ 15 pm/V) and broad transmission spectrum (up to 4.5 μm) [28,32–34]. In addition, the high refractive-index-temperature coefficient makes a signal wavelength shift up to 0.5 nm/°C at a pump source of 1030 nm for a grating period of 28 – 30 μm. Therefore, it is well worthy of investigation to utilize the QPM nonlinear crystal in an OPO pumped by a passively Q-switched ytterbium-doped PCF laser to generate broadly tunable eye-safe wavelength radiation.

Here we report, for the first time to our knowledge, on a widely tunable eye-safe laser based on a PCF. An optical parametric oscillator was pumped by a passively Q-switched PCF laser with AlGaInAs QWs as a saturable absorber. First, the 1029-nm PCF laser with pulse energy of 750 μJ at a pulse repetition rate of 6.5 kHz was established under a pump power of 13.1 W at 976 nm. The PCF laser was used to pump an OPO to generate eye-safe signal wave. By tuning the temperature of PPLN in the OPO cavity from 20 to 140°C, the tuning range of signal wavelength was over 80 nm from 1513 to 1593 nm. A maximum peak power of 19 kW and pulse energy of 138 μJ was obtained under the pump energy of 390 μJ.

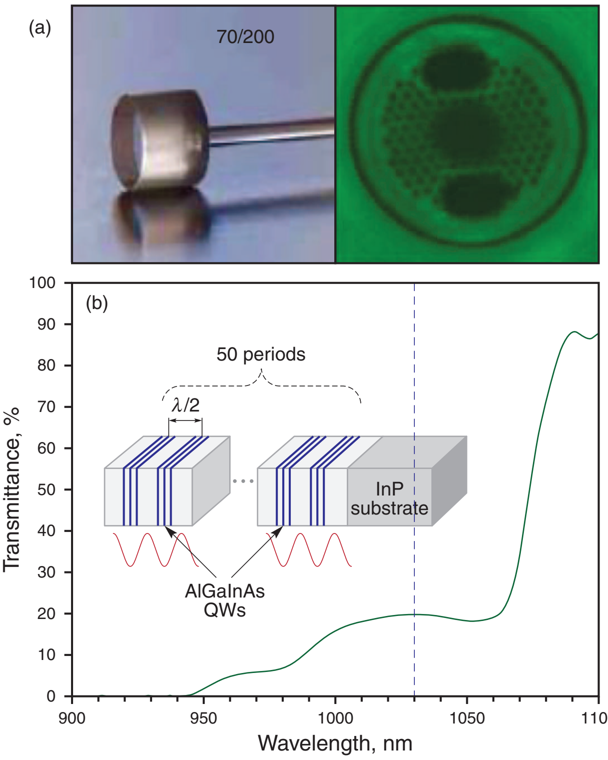

Figure 2 (online color at www.lphys.org) (a) – image of cross section of rod-type PCF and (b) – transmission spectrum and structure of AlGaInAs saturable absorber

2. Diode pumped PCF laser with AlGaInAs semiconductor absorber

The schematic of external-cavity OPO pumped by a passively Q-switched PCF laser is depicted as Fig. 1. The experimental setup could be separated into two major parts, one is a diode pumped passively Q-switched PCF laser and the other one is a singly resonating OPO. The PCF laser cavity consists of a 55-cm polarization maintaining (PM) Yb-doped PCF and an external feedback cavity with a saturable absorber. The external cavity incorporates with a focusing lens of 50-mm focal length to focus the fiber output into the saturable absorber and a high reflective mirror behind the saturable absorber for feedback. The rod-type PCF has a large mode field diameter of 55 μm to push the nonlinear threshold up to higher level than conventional single mode fiber. And a low numerical aperture value of 0.02 permits to sustain the operation in single transverse mode and excellent beam quality. The pump cladding of the PCF has a diameter of 200 μm and an air-cladding to maintain a high numerical aperture of 0.6. The image of the cross section of the PCF is depicted as Fig. 2a. The small ratio between the inner pump cladding and 70-μm core diameters brings about the pump absorption coefficient to be 30 dB/m at 976 nm. The PCF was surrounded with a 1.7-mm thick outer cladding and was sealed with

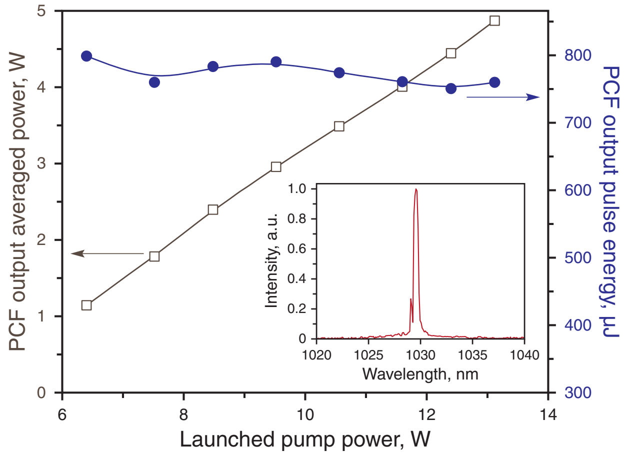

Figure 3 (online color at www.lphys.org) Output power of the passively Q-switched PCF laser versus the 976-nm launched pump power. Inset – the lasing spectrum obtained with 12.5 W of pump power

end-caps for protection. The boron doped stress-applying parts were adopted to induce birefringence that produces diverse spectral losses to form a linearly polarization state for the fundamental mode. The saturable absorber is a structure of AlGaInAs QW/barrier grown on a Fe-doped InP substrate by metalorganic chemical-vapor deposition, as depicted in Fig. 2b. The structure consists of 50 groups of AlGaInAs QW/barrier. Each group contains three 8-nm-thick QWs and 10-nm-thick barriers. In order to increase the damage threshold, each group of quantum wells is designed to be located at the nodes of the pumping mode, or to have intervals of half-wavelength separated by barriers. A window layer of InP was deposited on the gain structure to prevent surface recombination and oxidation. Both surfaces of the saturable absorber were coated to have anti-reflection coating at 1030 nm ($R < 0.2\%$). The initial transmission of the saturable absorber was measured to be 19%. The mode diameter on the saturable absorber was estimated to be approximately 400 μm. The pump source was a 20-W 976-nm fiber-coupled laser diode with a core diameter of 200 μm and a numerical aperture of 0.2. Focusing lens with 25-mm focal length and 90% coupling efficiency was used to re-image the pump beam into the fiber through the dichroic mirror with high transmission (HT, $T > 90\%$) at 976 nm and high reflectivity (HR, $R > 99.8\%$) within 1030 – 1100 nm. The pump spot radius was approximately 100 μm, and the pump coupling efficiency was estimated to be around 80%. The pulse temporal behavior was recorded by Leroy digital oscilloscope (Wavepro 7100, 10 G samples/sec, 4 GHz bandwidth) with a fast InGaAs photodiode.

The output power, pulse energy and output spectrum are shown in Fig. 3. The maximum output power was obtained to be 4.9 W under the 13.1 W of pump power and it turns out conversion efficiency over 37%. The central peak of wavelength is dependent on the pump power and distributes from 1031 to 1029 nm with increasing the pump power. The inset of Fig. 3 shows the output spectrum of PCF laser with the 13.1 W of pump power. The full width at half maximum FWHM of bandwidth is around 0.5 nm and the M^2 factor was measured to be less than 1.3 over the complete output power range, owing to the low-NA feature of the fiber. The laser output was measured to be linearly polarized with an extinction ratio of approximately 100:1. Fig. 4a and Fig. 4b show the traces of output pulses under a lower and higher pump power level, 6.3 and 13.1 W, respectively. A self-modulation phenomenon inside the Q-switched envelope was obviously observed in pulsed fiber lasers for high pump power. This phenomenon is generally considered to arise from the stimulated Brillouin scatter-

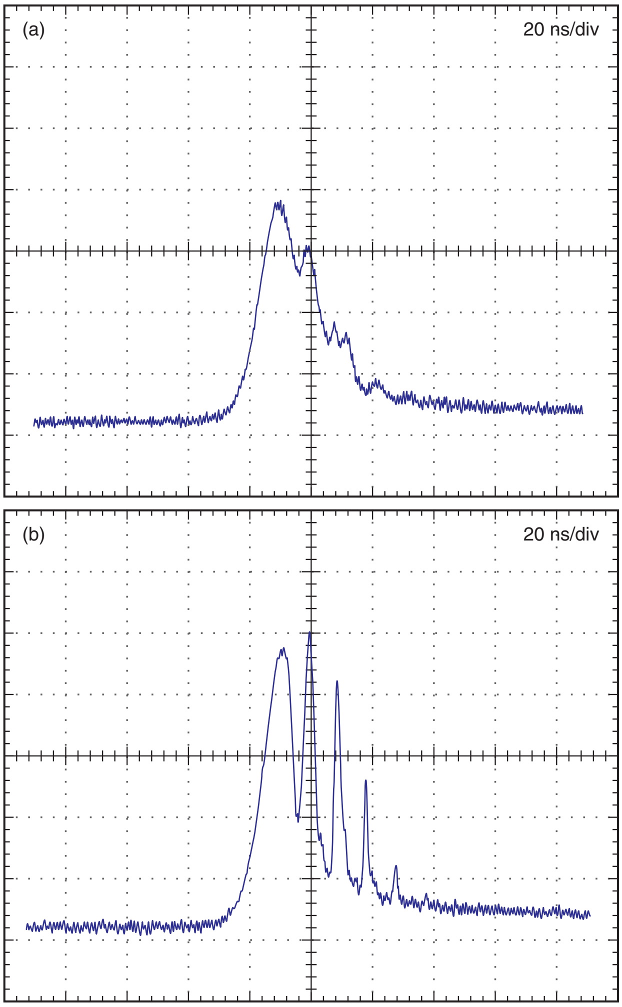

Figure 4 (online color at www.lphys.org) Typical oscilloscope traces of output pulses of the passively Q-switched PCF laser. (a) – pulse shape with 6.3 W of pump power and (b) – pulse shape with 13.1 W of pump power

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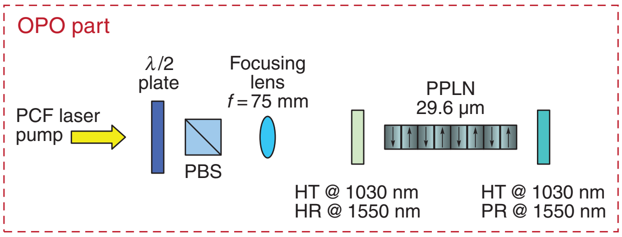

Figure 5 (online color at www.lphys.org) Schematic sketch of the OPO setup. A half-wave plate and polarization beam splitter cube were settled in front of OPO to control the input pump power

ing (SBS) which can provide strong feedback to the cavity together with pulse compression [35–38]. The SBS-related pulses have been demonstrated in different fiber laser designs, such as self-Q switched [35–37], actively Q-switched [38,39], and passively Q-switched [40,41] fiber lasers. Although the strong SBS effect might deteriorate the pulse stability to some extent, the pulse-to-pulse amplitude fluctuation could still be maintained to be less than 8.0% in rms at the maximum pump power of 13.1 W. The output repetition rate ranges from 1.5 to 6.5 kHz and is related to pump power. The pulses with maximum peak power of 170 kW and pulse energy up to 750 μJ were obtained.

3. Tunable eye-safe laser with an external-cavity OPO

The 750-μJ passively Q-switched PCF laser at a repetition rate of 6.5 kHz was used as a pump source in the external-cavity OPO, as depicted in Fig. 5. The nonlinear crystal in is a 0.76-mm thick and 2-cm long congruent PPLN with a poling period of 29.6-μm. The singly-resonant OPO cavity consists of two BK7 plane mirrors, the front mirror and output coupler. The front mirror is coated with high transmission at pump wavelength ($T > 90\%$) and high reflectivity from 1500 to 1600 nm ($R > 99\%$). The output coupler is coated with high transmission at pump wavelength ($T > 90\%$) and partial reflectivity from 20 to 90% corresponding to the wavelength from 1510 to 1590 nm. A focusing lens with 75-mm focal length was used to focus the pump source into the PPLN crystal. The pump spot size inside PPLN was measured to be around 300 μm. Between the PCF laser and external-cavity OPO, a half-wave plate and a polarization cube were bundled together to control the pump incident power. The maximum average pump incident power was limited to 2.6 W, or the pulse energy limited to 390 μJ for the consideration of photorefractive effect and damage threshold of PPLN. The PPLN was temperature controlled from 20 to 140°C by an oven to adjust the phase matching wavelength.

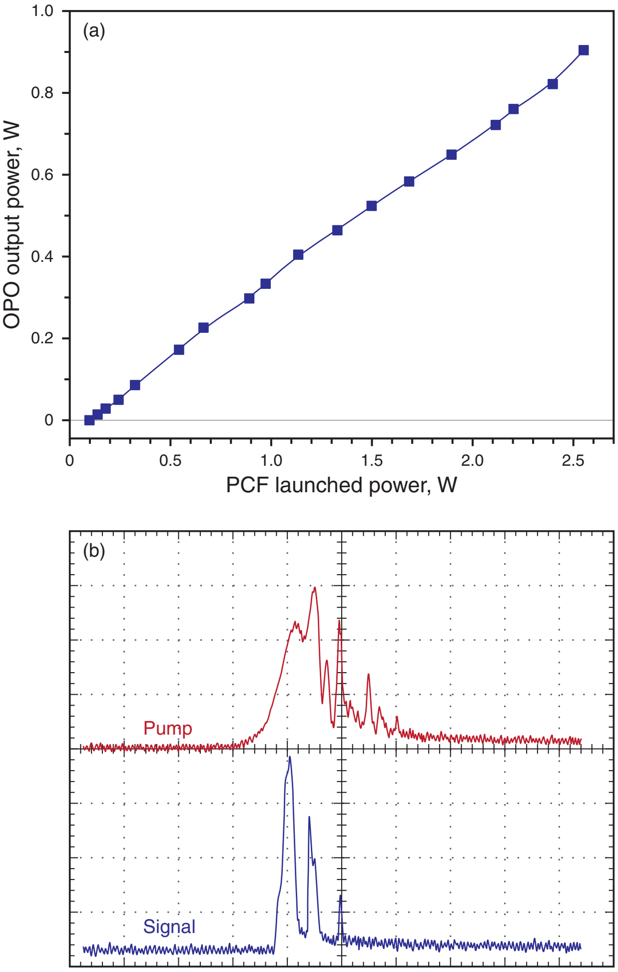

Figure 6 (online color at www.lphys.org) Output performance of external-cavity OPO. (a) – averaged output power of signal wave versus averaged power of PCF laser and (b) – temporal traces of pump and signal wave

The performance of output power of external-cavity OPO pumped by passively Q-switched PCF laser is shown in Fig. 6a. The temperature of PPLN was controlled at 100°C. Under the pump power of 2.6 W, the output average power of 0.9 W at signal wave was obtained and corresponds to pulse energy of 138 μJ. The conversion is about 35% and the slope efficiency is up to 37.5%. From the temporal pulse traces of pump and signal wave shown in Fig. 6b, the signal pulse shape possesses several spikes which were resulted from SBS effect in pump source as mentioned above. Such an effect can be reduced for lower operating power of PCF laser as depicted in Fig. 4a. The maximum output peak power of signal wave was estimated to be 19 kW with an effective pulse width of 7.3 ns.

The temperature of PPLN was tuned from 20 to 140°C in an interval of 20°C. The output wavelength of signal wave shifts from 1513 to 1593 nm and total 80-nm tun-

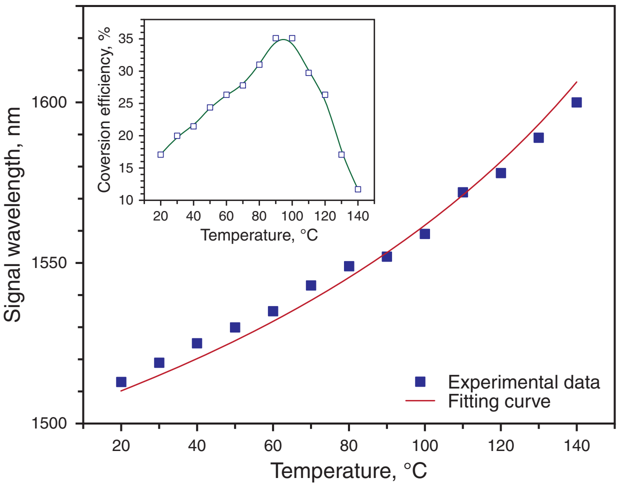

Figure 7 (online color at www.lphys.org) Tuning curve of signal wavelength *versus* different operating temperature. Inset – the corresponding conversion efficiency with temperature

ing range was obtained. Fig. 7 shows the wavelength of output signal in different operating temperature. The experimental data with empty circles is in good agreement with theoretical data calculated from Selmier's equations [42,43]. Higher temperature and larger wavelength is possible. However, the reflectivity of output coupler used is not uniform within the tuning range of wavelength. Besides, with increasing the temperature higher than 140°C, the idler phase-matching wavelength gradually approaches 2.8 μm, which locates at the peak absorption of lithium niobate [44]. As a result, higher loss will be induced in the cavity for operating temperature higher than 140°C. On the other hand, for lower operating temperature, the photorefractive effect of congruent PPLN will get stronger and limit the output performance. Therefore, there is an optimum efficiency for a specific temperature, as depicted in the inset of Fig. 7. In this experiment, the conversion efficiency varies from 11 to 35% and the optimum temperature is found to be around 100°C. At the optimum point, the phase-matching signal wavelength is 1559 nm with a corresponding output reflectivity of 65%.

4. Summary

We achieved a widely tunable passively Q-switched photonic crystal fiber laser by means of an external-cavity optical parametric oscillator. With an AlGaInAs Qs/barrier structure as a saturable absorber in the 1029-nm PCF laser, the fundamental pulse with energy up to 750 μJ was obtained and was incident into the OPO cavity. Under the pump energy of 390 μJ, the maximum output energy and peak power of signal wave was found to be 138 μJ and 19 kW, respectively. By tuning the temperature of nonlinear crystal, PPLN, over 80-nm tuning range of the signal output wavelength from 1513 to 1593 nm was obtained.

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