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Letter

A High-Power and Highly Efficient Semi-Conductor MOPA System for Lithium Atomic Physics

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Abstract: A compact and highly efficient 670.8-nm semi-conductor master oscillator power amplifier (MOPA) system, with a unique optical design, is demonstrated. The MOPA system achieves a continuous-wave (CW) output power of 2.2 W, which is much higher than commercial products using semi-conductor devices. By comparing solid state lasers and dye lasers, higher wall-plug efficiency (WPE) of 20 % is achieved. Our developed laser system also achieves spectral line-width of 0.3 pm (200 MHz) and mode-hop free tuning range of 49 pm (32.6 GHz), which is very suitable for experiments of lithium atomic physics at several-watt power levels, such as Bose-Einstein condensation (BEC) and isotope absorption spectroscopy.

Keywords: laser optical system; MOPA; semiconductor optical amplifier; beam combination

1. Introduction

Nowadays, 670.8-nm tunable lasers with high power, compact volume and high efficiency are demanded for experiments of lithium atomic physics, such as atomic cooling and trapping [1–3], and isotope absorption spectroscopy [4].

Several approaches have been demonstrated previously. Solid state lasers usually yield 1342-nm lasing by Nd:YVO4 or Nd:YAP crystal at first, then shift to 671-nm lasing by second harmonic generation (SHG), which can achieve output optical power of 1.2 W [5,6]. However, wall-plug efficiency (WPE) of solid-state lasers is very low and wavelength tuning is difficult to achieve. Dye lasers can directly yield 671-nm pulsed lasing by pumping light, without using SHG, which can achieve average optical power of 2 W and is commercially available [7]. However, they are usually large in volume and toxic. Laser diodes based on InGaP/AlGaInP quantum well can achieve continuous-wave (CW) output power of 5.6 W with very high WPE of 41% [8], although the optical spectrum is a multiple longitudinal mode. Commercial tunable lasers based on semi-conductor devices can only achieve a CW output power of 500 mW [9–11]. They usually use a very simple master oscillator power amplifier (MOPA) scheme, which includes only one tapered semi-conductor optical amplifier (SOA).

In this letter, a specially designed semi-conductor MOPA system using tapered SOA array will be demonstrated. Our expanded scheme of laser optical system can achieve much higher CW output power than commercial products, meanwhile good performance of narrow linewidth and wavelength tuning remains.

2. Experiment and Results

Experimental configuration of the MOPA system includes an external-cavity master oscillator and a double-stage power amplifier, as shown in Figure 1.

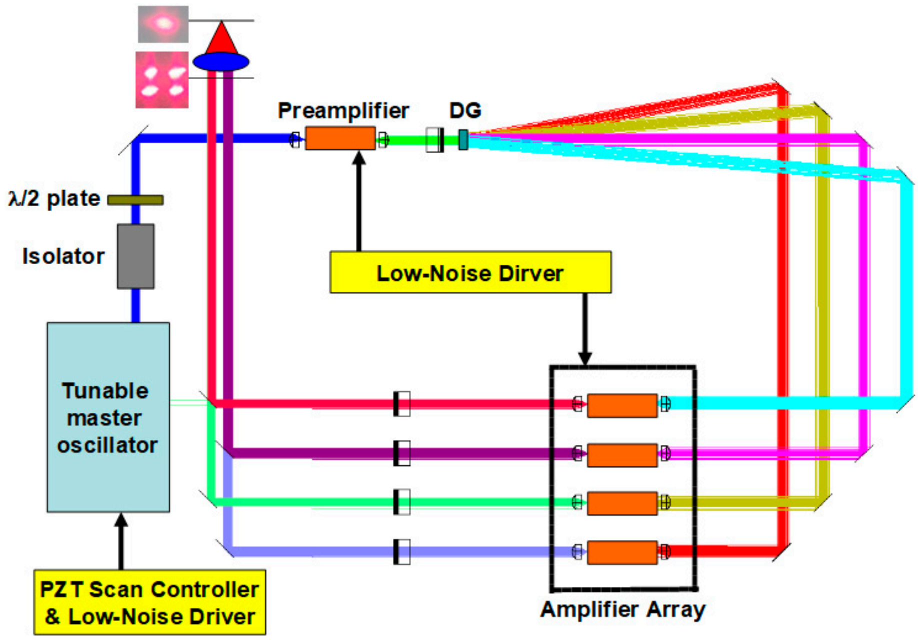


Figure 1. Configuration of the master oscillator power amplifier (MOPA) system. The inset shows the output and focused beam spots. DG: Dammann grating.

The master oscillator is a Littrow-type external-cavity oscillator, as shown in Figure 2. It is comprised of a Fabry-Perot laser diode with GaInP/AlGaInP quantum wells and AR/HR facet coating, an aspherical collimated lens with 2.75-mm focal length, a blazed grating of 1800 lines/mm, and a reflector. The first order of the grating feeds back to the laser diode for locking the wavelength and the zero order is the output of the master oscillator. The external-cavity length is about 6 cm, which is defined from rear facet of the laser diode to the blazed grating. The optical spectrum is shown in Figure 3. A single-frequency operation at 670.8 nm, with side mode suppression ratio (SMSR) of more than 16 dB, is observed. A piezoelectric ceramic component is attached to the back of the grating. By properly designing the rotation arm length and PZT moving step, the oscillating wavelength can be finely tuned at 0.2-pm resolution. The mode-hop free tuning range of 49 pm (32.6 GHz), from 670.820 to 670.771 nm, was achieved by tuning the PZT voltage from 1 to 69.9 V, as shown in Figure 4. Wider tuning range of more than 10 nm with mode hopping was also achieved, combined with a driving current tuning of the laser diode. The maximal output power is about 30 mW under CW driving current of 83 mA. The master oscillator is temperature controlled at 25 °C by two, single-stage, Peltier coolers for suppressing the working wavelength perturbation. Besides that, an optical isolator (Thorlabs IO-5-670-VLP) is inserted to protect the laser diode from the cascaded optical pre-amplifier.

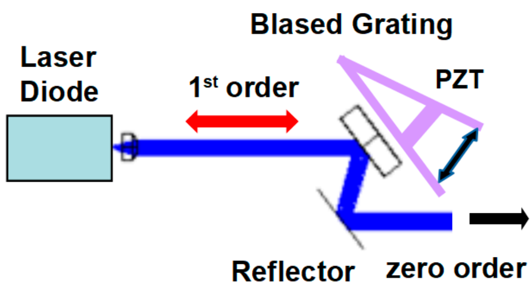


Figure 2. Configuration of the tunable master oscillator.

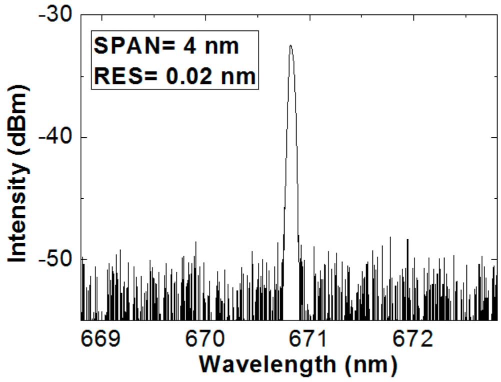


Figure 3. The optical spectrum of the external-cavity master oscillator.

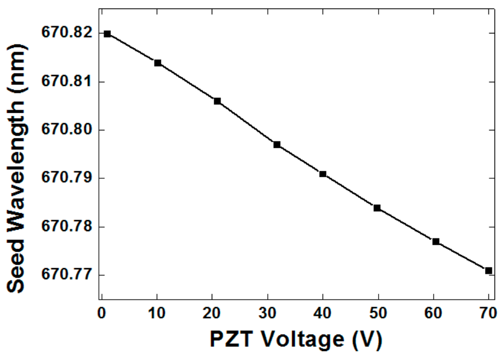
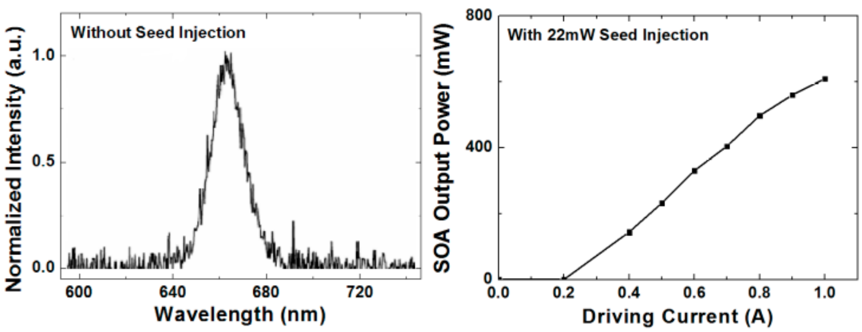


Figure 4. The wavelength tuning versus PZT piezoelectric ceramic control voltage.

In order to supply sufficient seed power for the amplifier array, a SOA pre-amplifier is utilized. All the SOA chips in the MOPA system are uniform, which are based on GaInP/AlGaInP multiple quantum wells embedded in 150-nm AlGaInP p-waveguide and n-waveguide layers. The chips are designed and fabricated into 2-mm long, single-pass (with double-facet antireflection coating), tapered waveguide, with a tapered angle of 6°. Figure 5a shows the SOA spontaneous emitting spectrum without seed injection. A total gain spectral range of 17 nm (FWHM), centering at 665 nm, was obtained. A $\lambda/2$ plate was inserted before the SOA to adjust the polarization of the seed beam, in order to maximize the amplified efficiency, as shown in Figure 1. When 22 mW seed from the master oscillator was injected, the amplified output power reached 610 mW at driving current of 1.0 A, as shown in Figure 5b. The small-signal gain is above 14 dB. A pair of D-ZLaF52La aspherical lenses with 2.75-mm focal length were used for coupling the input light and collimating the output light. Besides that, a fused-silica cylindrical lens with 25-mm focal length was inserted to compensate the astigmatism of the tapered SOA.



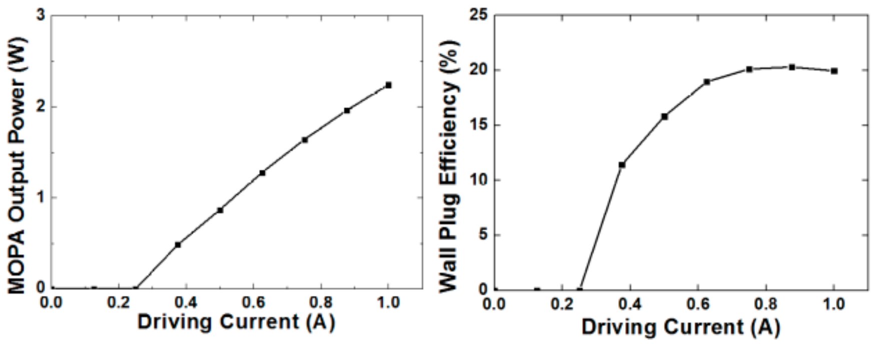
(**a**) (**b**)

Figure 5. Gain spectrum without seed injection: (**a**) and P-I with seed injection; (**b**) of the 670 nm semi-conductor optical amplifier (SOA).

For coupling the beam from the pre-amplifier to the amplifier array, multiple beam splitting was needed. We designed and fabricated a Dammann grating, with a profile of (0, π) phase step on fused silica substrate to function. The repetition period was 8.15 μm and the split angle was 4.7°. The total diffractive efficiency was 76% with AR coating. The optical power of each effective order was measured and achieved more than 50 mW, which means the uniformity of the split beams was good enough for our application.

The amplifier array was comprised of 4 tapered SOAs. A compact heat sink, with temperature control was designed to load the SOAs. Each diffractive order of the Dammann grating was finely adjusted by a pair of mirrors for coupling to the corresponding SOA in the amplifier array, as shown in Figure 1. Finally, a total CW output power of 2.4 W was achieved.

A spatial beam combination was built to compress the total size of the 4 sub-beams from the amplifier array. Four mirrors were used to rearrange the sub-beams into a 2 × 2 pattern, as shown in Figure 1. The propagation direction of all the sub-beams is highly uniform by finely adjusting the mirrors. The total combined beam size is 4.5 mm in diameter (defined by 90% of the total energy) and a 4.2-mm-in-diameter (defined by 90% of the total energy) focused beam spot is obtained by a 1-m-focal-length lens. The total beam quality can be calculated to be 4.5 mm × 4.2 mm/4 = 4.7 mm.mrad (half beam width and half angle). Figure 6a shows the P–I curve of the MOPA system. Maximal optical power of 2.2 W was obtained. Figure 6b shows the WPE of the MOPA system. The highest WPE achieved was 20%. Mode-hop free tuning range of 49 pm at 2.2 W output power level was achieved by tuning the master oscillator, meanwhile only 0.03 W power change was observed, as shown in Figure 7. Figure 8 shows the screenshot of the oscilloscope in spectral linewidth measurement by a Fabry-Perot interferometer (THORLABS SA210-5B and SA201 controller) with resolution of 67 MHz and free spectral range (FSR) of 10 GHz. The linewidth can be calculated as 0.446 ms / 22.30 ms × 10 GHz = 200 MHz (0.3 pm). In addition, the stability of the MOPA system was investigated during 2.5 hours of operation. We observed only 2 pm of wavelength change and 0.1 W of power change within this time.



(**a**) (**b**)

Figure 6. Optical power (**a**) and wall plug efficiency (**b**) of the MOPA system versus driving current.

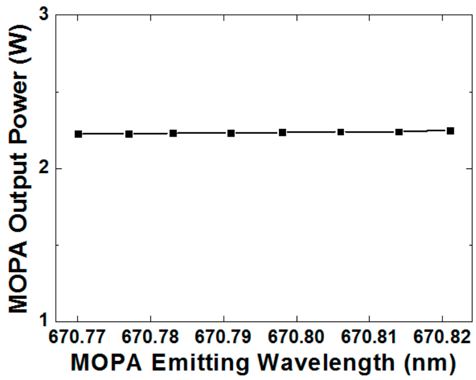


Figure 7. Power fluctuation of the MOPA system during wavelength scanning.

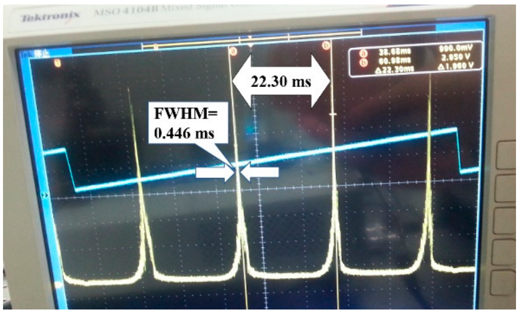


Figure 8. Spectral linewidth measured by a scanning Fabry-Perot interferometer with 10 GHz FSR.

3. Conclusions

In this letter, a 670.8-nm MOPA system is demonstrated. A unique laser optical system, including an external-cavity master oscillator and a double-stage power amplifier was designed and investigated in the experiment. A mode-hop free wavelength tuning range of 49 pm (32.6 GHz) and spectral linewidth of 0.3 pm (200 MHz) were achieved at 2.2 W output power level. From Figure 4 in [4], we can see that the FWHMs of all the three Doppler-broadened absorptive valleys ($^7LiD_2$, $^7LiD_1$ + $^6LiD_2$ and $^6LiD_1$) achieved a level of several GHz. Therefore, in applications of lithium atomic absorption, lasers with linewidth of 100 MHz ~ 1 GHz are more efficient than ones with linewidth of 100 kHz, as used in the experiments of [4]. The output beam is compressed to the size of 4.5 mm in diameter with divergence angle of 4.2 mrad by a spatial beam combination, resulting in a beam quality of 4.7 mm.mrad (half beam width and half angle). The combined beam is observed without separation within $\pm$100 mm before and after the focal plane by a 1-m-focal-length lens. Therefore, our laser source is suitable for coupling into a long and slim tube full of lithium vapor in real application. Compared with solid state lasers and dye lasers, the direct semi-conductor MOPA scheme can achieve much higher WPE (20%) and lower SWAP (size, weight, and power consumption). Besides that, the output power level is much higher than commercial products using semi-conductor devices. Thus, our developed MOPA system is very suitable for experiments of lithium atomic physics at several-watt power levels.

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Conflicts of Interest: The authors declare no conflict of interest.

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