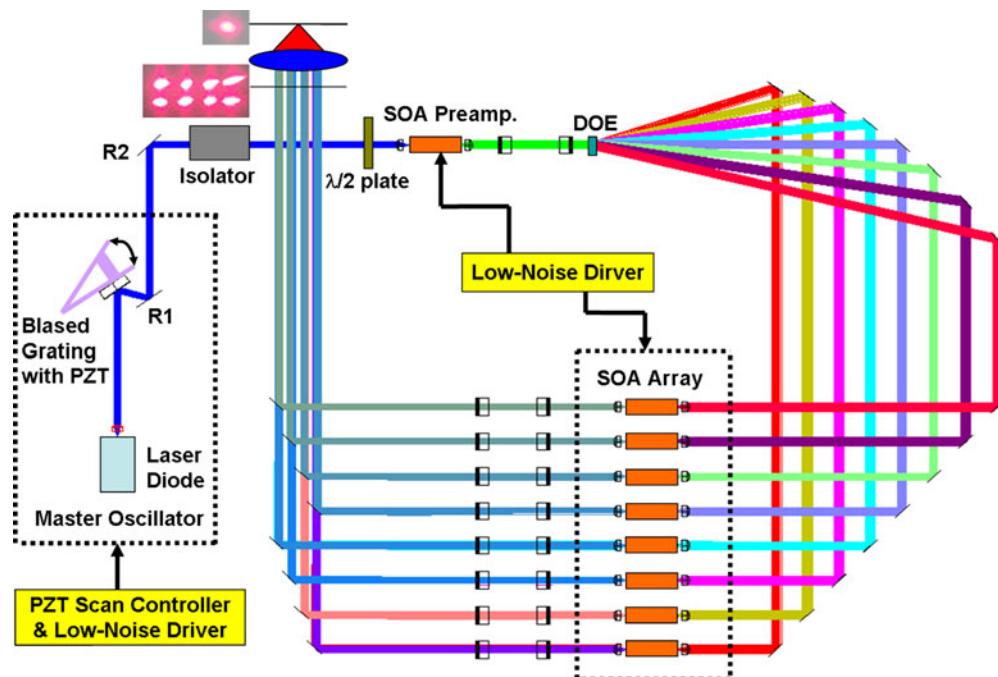


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Abstract: A highly efficient 670.8-nm high-power narrow-linewidth wavelength-tunable laser source with master oscillator power amplifier structure is demonstrated, which yielded CW output power of 4.5 W with spectral linewidth of 0.3 pm and mode-hop free tuning range of 52 pm (35 GHz). The total conversion efficiency of 20% was achieved. The developed narrow-linewidth tunable laser source can provide better performance than others ever reported at 670.8 nm for many applications, such as laser isotope separation, Bose–Einstein condensation experiments, and mid-infrared laser generation.

Index Terms: Tunable lasers, diode lasers, laser amplifiers, laser beam combining, diffractive optics.

1. Introduction

High-power and highly efficient 670.8-nm narrow-linewidth wavelength-tunable laser sources are requested for lithium atom laser isotope separation [1], lithium atom cooling and trapping into Bose–Einstein condensation (BEC) [2]–[4], mid-infrared laser generation by optical heterodyne for gas sensing [5] and second-harmonic generation towards 335 nm.

Several approaches have been reported for lasing at 670 nm. Dye lasers can obtain 1 W at 670 nm [6], which have a disadvantage of continuous toxic waste liquor production. Solid state lasers employing Nd:YAP or Nd:YVO₄ for lasing at 1342 nm and then using LBO to obtain second-harmonic generation towards 671 nm [7], [8], are lack of fine wavelength tuning and with very low total conversion efficiency. Broad-area diode lasers based on InGaP/AlGaInP quantum wells can achieve 5.6 W with total conversion efficiency of as high as 41% at 670 nm [9], which also have advantages of simple, compact, stable, reliable and robust. Since semiconductor devices demonstrate excellent potentiality, available commercial narrow-linewidth tunable laser sources at 670 nm are based on all-semiconductor MOPA structure with maximal output power of 500 mW [10]. The output power of commercial scheme is limited by using only one tapered SOA. Combining

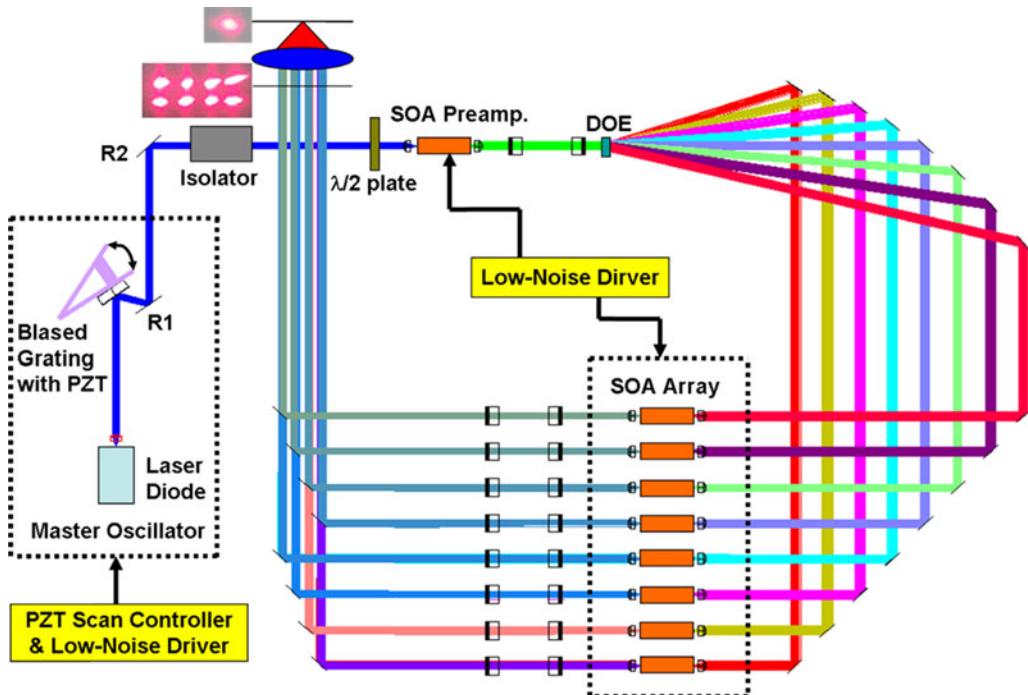


Fig. 1. Schematic setup of the narrow-linewidth wavelength-tunable MOPA system. The insets at the exit pupil show the original and focused beam spots.

with a tapered SOA array and appropriate beam transform, an extended MOPA scheme will achieve much higher output power. Meanwhile, narrow linewidth and frequency tuning can be maintained.

In this contribution, a high-power narrow-linewidth wavelength-tunable 670.8-nm MOPA system using an external-cavity oscillator as the seed source and a tapered SOA array as the power amplifier will be presented. Excellent performance with output power of 4.5 W and total conversion efficiency of 20% will be demonstrated.

2. Experimental Setup and Results

The narrow-linewidth wavelength-tunable MOPA system consists of a Littrow-configuration external-cavity master oscillator and a two-stage power amplifier. The schematic setup of the MOPA system is shown in Fig. 1.

The seed source is a Littrow-configuration external-cavity oscillator. A Fabry-Perot laser diode based on InGaP/AlGaInP quantum wells, an aspherical collimation lens and a 1800 lines/mm blazed grating with first order diffractive efficiency of 70% were utilized to build the structure. The first diffractive order of the grating element was fed back to the laser diode for locking and stabilizing the oscillating frequency and the zero diffractive order was used as the output seed light. The external-cavity length of the master oscillator was 6 cm, which is defined by the rear facet of the laser diode and the blazed grating. Thus, the single-frequency linewidth can be compressed to ~ 1 MHz. The incident beam angle can be finely tuned by a linear PZT component with resolution of ~ 10 nm at the back side of the grating. The grating rotation arm length was ~ 20 mm. With these proper design, the oscillating wavelength can be finely tuned with minimum resolution of 1 pm. The master oscillator was temperature controlled at 25 °C by Peltier cooler in order to maintain stable oscillation. The maximal output power of the master oscillator was 30 mW, which was measured by a thermal power meter (OPHIR 30(150)A-LP1-18). The optical spectrum was measured by an optical spectrum analyzer (ANDO AQ6317B), shown in Fig. 2(a). Single-mode operation around 670.8 nm was observed. The spectral linewidth was measured by a scanning Fabry-Perot interferometer

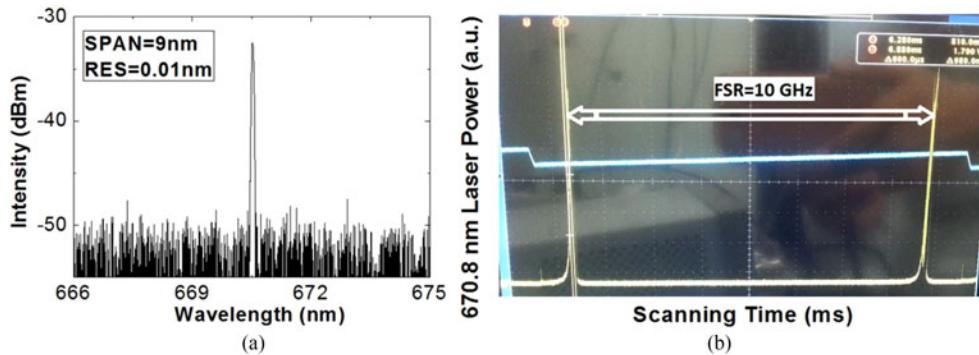


Fig. 2. The optical spectrum (a) and the spectral linewidth (b) of the external-cavity master oscillator.

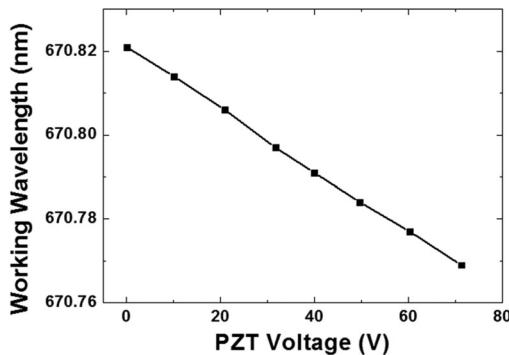


Fig. 3. The working wavelength of master oscillator versus PZT control voltage.

(THORLABS SA210-5B and SA201 controller) with 10 GHz free spectral range (FSR), shown in Fig. 2(b), which was narrower than 60 MHz resolution limit of the interferometer. The mode-hop free wavelength tuning range was 52 pm (35 GHz) from 670.821 nm to 670.769 nm by tuning the PZT control voltage from 0 V to 71 V, observed by a wavelength meter (High Finesse WS-7R 0241), shown in Fig. 3. Broader tuning range of several nanometers with mode hopping was also achieved, by tuning the driving current and working temperature of the Fabry-Perot laser diode.

The narrow-linewidth seed light from the master oscillator was firstly coupled into a SOA preamplifier based on InGaP/AlGaInP quantum wells by reflectors R1 and R2. The SOA chip was fabricated with structure of a 2-mm-long tapered gain waveguide and then C-mount packaged. The input near-field width was $3 \mu\text{m}$ and the output near-field width was $190 \mu\text{m}$. Fig. 4(a) shows the SOA gain spectrum at 25°C without seed injection. As broad as 17 nm (FWHM) gain spectral range from 656 nm to 673 nm was observed. An optical isolator was inserted after the master oscillator to prevent disturbance from backward light. A half-wave plate was positioned before the SOA amplifier to rotate the linear-polarization state for maximizing amplified efficiency of the SOA preamplifier. Two aspherical lenses were used to couple the seed light into the SOA preamplifier and collimate the amplified light, respectively. The coupling loss was estimated $\sim 50\%$. The SOA preamplifier yielded CW output power of 625 mW with 25 mW seed injection at driving current of 1.0 A, shown in Fig. 4(b). Thus, the amplification of the SOA chip was above 10 dB. Besides, two cylindrical lenses were utilized to correct the astigmatism of the amplified light for compressing far-field angle of the slow axis.

In order to couple the pre-amplified light into the SOA array, a diffractive optical element (DOE) was utilized for 1-dimensional equal-power multiple-beam splitting. A Dammann grating was designed for this function and fabricated on fused silica substrate. It was with period of $8.15 \mu\text{m}$ and the

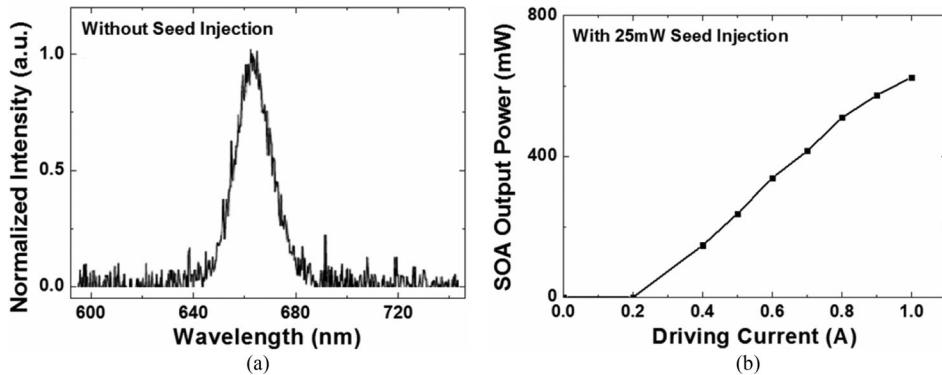


Fig. 4. The 670 nm SOA gain spectrum without seed injection (a) and P-I curve with 25 mw seed injection (b).

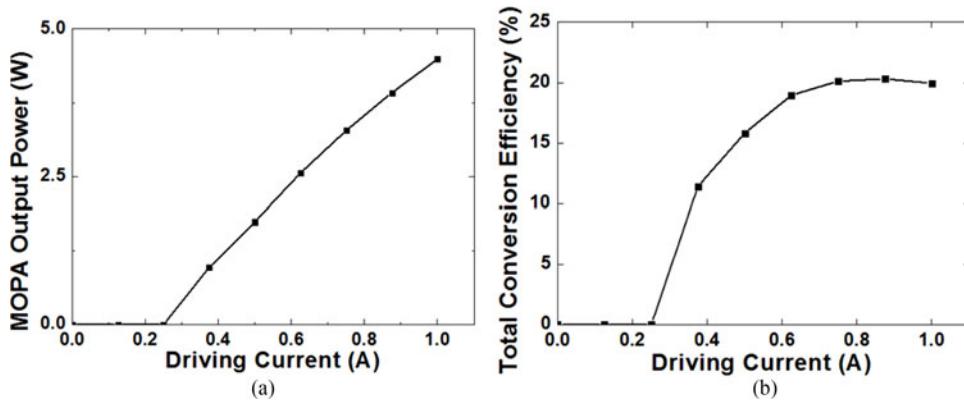


Fig. 5. The output power of MOPA system: (a) output power versus driving current, (b) total conversion efficiency versus driving current.

beam-splitting angle interval was about 4.7° . The total diffractive efficiency of the Dammann grating after AR coating was 80%. Power distribution of the multiple diffractive orders was measured by a slit. With 350-mW collimated light incidence, all the effective diffractive orders exceeded optical power of 30 mW, which were sufficient for seeding the SOA array.

The SOA array was built by 8 tapered SOAs with the same performance as the SOA preamplifier. The SOAs were mounted on a specifically designed compact copper heat sink with Peltier coolers below. For improving and maintaining the amplified efficiency, the SOA array was cooled to 15°C . Each seed beam after the DOE was directionally controlled by a pair of reflectors for coupling into the respective SOA unit, as shown in Fig. 1. Beam shaping of each SOA unit was the same as the SOA preamplifier. Besides, the DOE was tilted slightly to prevent the backward light from damaging the SOA preamplifier. Each SOA unit yielded CW output power of 587 mW at driving current of 1.0 A and thus total output power of 4.7 W was achieved by the SOA array.

The multiple beams emitting from the SOA array were realigned coaxially and very closely by two groups of reflectors, which is also called spatial beam combination. Finally, a beam pattern including 2×4 spots with $11.8 \text{ mm} \times 4.5 \text{ mm}$ ($1/e^2$) in size was obtained at the exit pupil, and a focused beam spot with diameter of 4.2 mm ($1/e^2$) after a 1-m-focal-length plane-convex lens was also observed, shown in the insets of Fig. 1. Thus, total beam quality can be calculated, which was $12.4 \text{ mm.mrad} \times 4.7 \text{ mm.mrad}$ (half beam width and half angle) in lateral and vertical directions. Besides, due to the uncontrolled optical phase of each SOA element, stable interference pattern was not observed at the focal plane. The maximal CW output optical power of the MOPA system was 4.5 W, as shown in Fig. 5(a). The Fig. 5(b) shows the total conversion efficiency of the MOPA

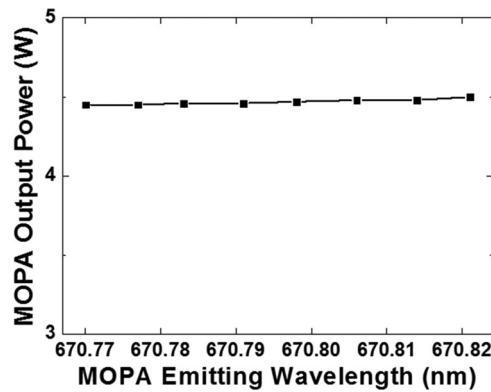


Fig. 6. The power fluctuation of the MOPA system during fast manual wavelength scanning.

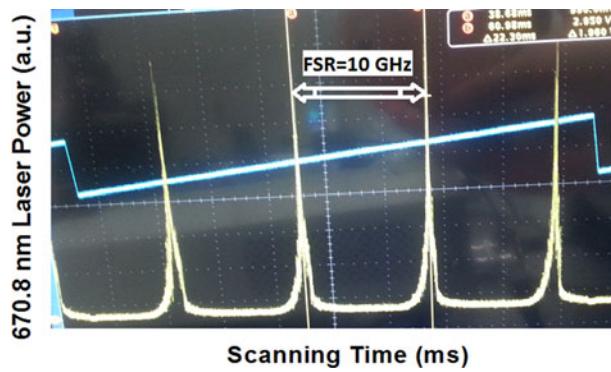


Fig. 7. The spectral linewidth of the MOPA system measured by a scanning Fabry-Perot interferometer with 10 GHz FSR.

system, which is defined as the ratio of output optical power and total input electric power. The highest total conversion efficiency was achieved as high as 20%. Single-frequency tuning of the MOPA system was realized by tuning the master oscillator and measured at the highest output power. The mode-hop free tuning covered the full range of the master oscillator, while the output optical power fluctuated within 0.05 W during fast manual frequency scanning, shown in Fig. 6. The spectral linewidth of the MOPA system was measured to be 0.3 pm (200 MHz) at the highest output power by adding several attenuators, shown in Fig. 7.

Besides, the stability of the MOPA system was also tested. The wavelength was monitored by a wavelength meter and the output optical power was monitored by a thermal power meter. During 2 hours, the wavelength fluctuated within 2 pm and the output optical power fluctuated within 0.2 W.

In the future, DFB laser diodes emitting at 670.8 nm will be fabricated to replace the external-cavity tunable master oscillator. Besides, reconstruction-equivalent-chirp technology which can obtain precise wavelength spacing is also a good choice for non-mechanical seed source [11], [12]. The SOA array will be fabricated on a monolithic integrated chip and coherent beam combination with active closed-loop optical phase control will also be built. Thus, volume and weight of the MOPA system will be reduced and the beam quality will be improved significantly.

3. Conclusion

In conclusion, this paper has demonstrated a highly efficient narrow-linewidth tunable MOPA system with CW output power of 4.5 W, which is, to the best of our knowledge, the highest CW output

power ever reported at 670.8 nm. Besides, the demonstrated MOPA system has also achieved total conversion efficiency of as high as 20%, due to directly electrically pumped operation mode of the SOAs based on InGaP/ AlGaN/P quantum wells. The spectral linewidth was 0.3 pm at the highest output power. The wavelength tuning range covered 52 pm (35 GHz) from 670.769 nm to 670.821 nm. The demonstrated laser source can provide excellent performance for many applications, such as lithium atom cooling, lithium atom vapor laser isotope separation and mid-infrared laser generation.

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