Silicon Wafer: a Direct Output Coupler in Tm:YLF Laser *

Xi-Kui Ren(任席奎), Chen-Lin Du(杜晨林), Chun-Bo Li(李春波), Li Yu(余利),
Jun-Qing Zhao(赵俊清), Shuang-Chen Ruan(阮双琛)**

Shenzhen Key Laboratory of Laser Engineering, Key Laboratory of Advanced Optical Precision Manufacturing Technology of Guangdong Higher Education Institutes, College of Optoelectronic Engineering, Shenzhen University, Shenzhen 518060

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We present a high power diode-pumped continuous-wave Tm:YLF (Tm^{3+}-doped lithium yttrium fluoride) laser with a piece of silicon wafer as the output coupler (Si-OC laser) directly. Under the pump power of 40 W at 793 nm, a maximum output power of 12.1 W is obtained with a beam quality of $M^2 \leq 1.55$ at 1887 nm, corresponding to an optical-to-optical efficiency of 30.25% and a slope efficiency of 33.21%. To the best of our knowledge, this is the first report on directly utilizing silicon as an output coupler (Si-OC) in the solid Tm:YLF laser system. Due to the intriguing characteristics of silicon, such as negligible absorption in the wavelength region around 2 μm, high damage threshold, low cost and long-pass filter properties, double-side polished monocrystalline silicon wafer is considered as an outstanding candidate output coupler in the high-power laser system 2 μm spectral region, which may dramatically reduce the total manufacturing costs of the 2 μm laser system.

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Operation of solid-state lasers in the spectral region near 2 μm has gained growing interests due to their wide applications in micro-machining and material processing,[1] atmospheric sensing,[2] radar systems,[3,4] molecular spectroscopy,[5] medical applications,[6–8] and so on. Additionally, they can also be adopted as efficient pump sources for pumping optical parametric oscillators (OPOs) and solid-state lasers in the middle-infrared region.[9–11]

In our experiment, for obtaining a laser at 2 μm at room temperature, a Tm:YLF (Tm^{3+}-doped lithium yttrium fluoride) crystal was selected as the gain medium among several laser crystals of Tm:YAG, Tm:YAP, Tm,Ho:YAG.[12–14] Compared with other crystals, the Tm:YLF crystal exhibits many advantages, such as natural birefringence, low tendency to thermal lensing due to the negative thermo-optic coefficient and long upper-state life time (>15 ms).[15,16] Moreover, the Tm:YLF crystal can be efficiently pumped by commercial laser diodes conducted by the AlGaAs-based diode pumping technology at 793 nm, which is beneficial for high-power output in Tm:YLF laser systems.

To date, the output power as much as tens of Watts has been reported in solid Tm:YLF laser systems in both end-pumped and side-pumped configurations. In 2015, Zhu *et al.* reported a 60 W Tm:YLF laser using triple Tm:YLF rod with a slope efficiency of 34.8%.[17] In addition, Ding *et al.* demonstrated a diode-pumped 1.94 μm Tm:YLF laser with the maximum output power of 50.3 W at the incident pump power of 156.9 W, and the optical-to-optical efficiency of 32.1% and the slope efficiency of 41.6% are achieved, respectively.[18] However, in their laser systems, traditional thin film-coated mirrors were chosen as the output coupler, which may have some drawbacks, such as non-robust property of the thin films upon external abrasion and water absorption, complicated manufacturing process of the film coating, and a relatively high cost. In contrast, herein we report that the double-side polished monocrystalline silicon wafer can directly perform as the output coupler. The advantages of using silicon wafer as output coupler are gained from its negligible absorption in the 2 μm spectral region, excellent thermal conductivity and thus a high laser-induced damage threshold.[19–21] Most importantly, the silicon can filter out the entire pump light centered at 793 nm through the solid Tm:YLF laser system, which ensures an output light more pure than that of using the traditional dielectric thin film output coupler.

In this Letter, we demonstrate a five-mirror W-shaped resonator Tm:YLF laser utilizing a piece of uncoated monocrystalline silicon as the output coupler. Under 40 W of incident of pump laser power at 793 nm, a 12.1 W output laser with a beam quality of $M^2 \leq 1.55$ at 1887 nm was obtained, and an optical-to-optical efficiency of 30.25% and a slope efficiency of 33.21%, respectively. Compared with the traditional thin-film-coated coupler mirrors, monocrystalline silicon wafers possess many fascinating properties, i.e., negligible absorption in the wavelength region around 2 μm, excellent thermal conductivity and high laser-induced damage threshold. Further, silicon can filter out the entire pump light at 793 nm, which ensures an output light more pure than that of using dielectric films-coated mirrors as output couplers. Therefore, it should be a very promising strategy to generate high-

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**Corresponding author. Email: scruan@szu.edu.cn
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power output in the wavelength region near 2 μm by directly using double-side polished silicon wafer as the output coupler.

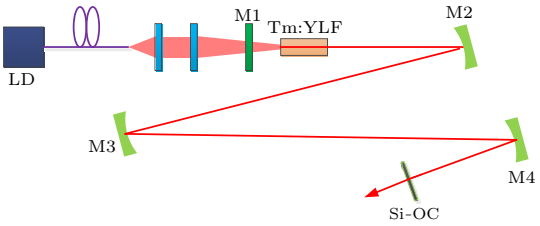

Fig. 1. Schematic diagram of the Si-OC Tm:YLF laser.

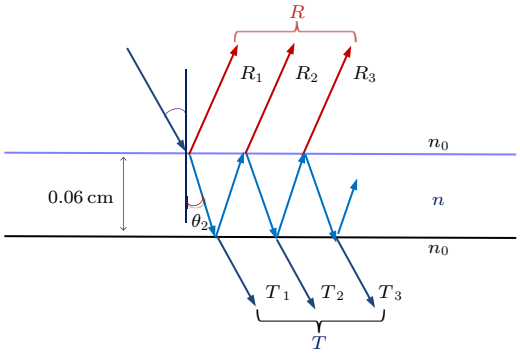

Fig. 2. The diagram of reflection and refraction on the silicon wafer.

Figure 1 shows the schematic diagram of the laser setup. A 20-mm-long a-cut Tm:YLF crystal with cross-sectional area of $3 \times 3\,\mathrm{mm}^2$, and Tm^{3+} atomic concentration of 2 at.% was used as the gain medium. To avoid thermal damage, the crystal was wrapped with indium foil and then held in a copper block, afterwards, the system was kept at 20℃ by a cyclic water-cooling system. To obtain high quality of light beams, the end-pumped diode strategy was selected in our experimental designs. Therefore, for pumping of this medium, a core diameter of 200 μm and a numerical aperture (NA) of 0.22 coupling fiber was adopted in fiber-coupled AlGaAs laser diode (LD) with the maximum output power of 100 W at the central output wavelength of 793 nm. To obtain mode matching between the pump light and laser mode, and enough mode volume, pump light was focused into the crystal by a 1:1.5 coupling lens system. In addition, a five-mirror W-shape resonator with total cavity lengths of 2.9 m was constructed to obtain stable laser operation. M1 is a dielectric-film-coated flat mirror with diameter of 20 mm, exhibiting antireflection at 793 nm, while showing high reflection around broadband of 2 μm. M2, M3 and M4 folded mirrors with the corresponding radii of curvatures of 500 mm, 320 mm and 200 mm were coated by the dielectric films, which were produced the same as that in producing M1 mirror coating. A piece of uncoated double-side polished single-crystal (111)-direction silicon wafer with conductivity of $10000\,\Omega{\cdot}\mathrm{cm}^{-1}$, mean square roughness of <0.5 nm, thickness of 600 μm and area of $5 \times 5\,\mathrm{mm}^2$ was directly selected as the output coupler. According to the ABCD matrix, the beam waist radii at the center of the Tm:YLF crystal and the output coupler were calculated to be 262 μm and 64 μm, respectively.

The optical properties of the Si-OC can be calculated theoretically.[22,23] Figure 2 is the diagram of reflection and refraction on a silicon wafer at an incident angle of θ_1. Because the incident angle is very small, the normal incident radiation is assumed for all reflection and transmission calculations ($\theta_1 \approx 0$). The reflectivity of wafer R_1 at the air–silicon interface can be calculated by

$$R_1 = ((n-1)^2 + \kappa^2)/((n+1)^2 + \kappa^2). \tag{1}$$

The total reflectivity of wafer R can be determined by

$$\begin{aligned} R &= R_1 + R_2 + R_3 + \ldots \\ &\approx R_1 + (1-R_1)R_1 e^{-\alpha 2t} - (1-R_1)R_1^2 e^{-\alpha 2t} \\ &\quad + (1-R_1)R_1^3 e^{-\alpha 4t} - (1-R_1)R_1^4 e^{-\alpha 4t} + \ldots . \end{aligned} \tag{2}$$

Each term in the series is associated with the successive reflections as the light bounces between the surfaces of the silicon wafer. Similarly, the total transmission of wafer T is given by

$$\begin{aligned} T &= T_1 + T_2 + T_3 + \ldots \\ &\approx (1-R_1)e^{-\alpha t} - (1-R_1)R_1 e^{-\alpha t} \\ &\quad + (1-R_1)R_1^2 e^{-\alpha 3t} - (1-R_1)R_1^3 e^{-\alpha 3t} + \ldots . \end{aligned} \tag{3}$$

The real part of the refraction index of silicon is calculated by

$$\begin{aligned} n^2 - 1 &= 10.6684293\lambda^2/(\lambda^2 - 0.301516485^2) \\ &\quad + 0.00304347\lambda^2/(\lambda^2 - 1.13475115^2) \\ &\quad + 1.54133408\lambda^2/(\lambda^2 - 1104^2), \end{aligned} \tag{4}$$

where λ is the wavelength in units of μm, κ is the imaginary part of index of refraction, n is the real part of index of refraction, α is the absorption coefficient in units of cm^{-1}, and t is the thickness of silicon wafer in units of cm.

Table 1. Various values of the parameters used in the calculations.

λ (μm)	κ	α (cm^{-1})	t (cm)
1.887	0	0	0.06

By using Eqs. (1)–(4) and the data in Table 1, the transmittance of silicon and the reflectivity of wafer are calculated to be 53.3862% and 46.6138%, respectively, at 1.887 μm.

The transmittance spectra of the silicon used in our experiments were measured by the high-performance lambda spectrometers (lambda 950, UK) at room temperature 25℃. Figure 3 shows that the transmittance of the silicon is fluctuated around 48% in the region ranging from 1400 nm to 2200 nm. The transmittance measured is lower than the transmittance calculated for the absorptive phenomena associated with surface roughness, damage, or anomalies. It

is also clearly revealed that the light with wavelength below 900 nm cannot pass through the silicon wafer. In this scenario, monocrystalline silicon can perform as a long-pass filter, which can prevent the transmission of pump light at 793 nm, therefore the output light would be more pure.

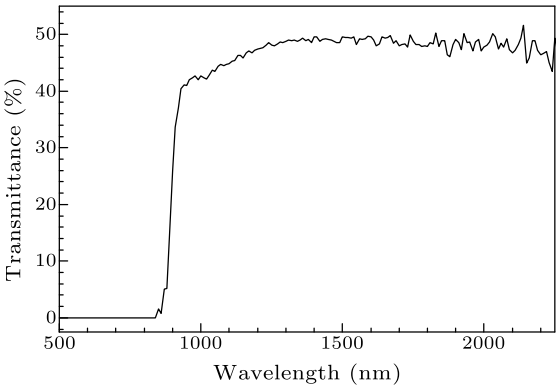

Fig. 3. Transmittance spectra of the double-side polished silicon output coupler.

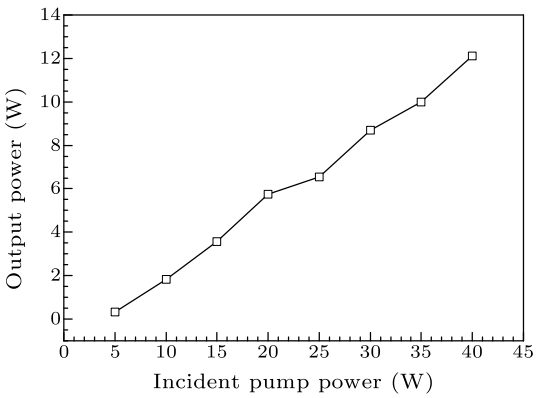

Fig. 4. The output power versus the incident pump power using the double-side polished silicon wafer.

The output power as a function of the incident pump power is shown in Fig. 4. The output power in the experiments was measured by a Newport 842.PE energy meter. By using monocrystalline silicon as the output coupler, the laser system demonstrated the threshold of 5 W. Importantly, a linear relationship between the output power and the incident pump power was observed in our laser system. A maximum of output power of 12.1 W centered at 1887 nm was achieved under the pump power of 40 W, given an optical-to-optical efficiency of 30.25% and a slope efficiency of 33.21%, respectively. To avoid the damage of Tm:YLF crystals, we did not further increase the incident pump power.

The spectrum of Si-OC recorded by an FT-IR spectrometer TENSOR 27 under the incident pump power of 20 W is demonstrated in Fig. 5. It shows that the Si-OC laser exhibits the central wavelength at 1887 nm. In addition, the negligible shift of the output wavelength was observed with the increasing pump power in our experiment. Moreover, the laser spectrum generated from the Si-OC was ultrapure due to the fact that the monocrystalline silicon wafer can perform as a long-pass filter, which can prevent the transmission of pump light in the short wavelength region (e.g., <840 nm).

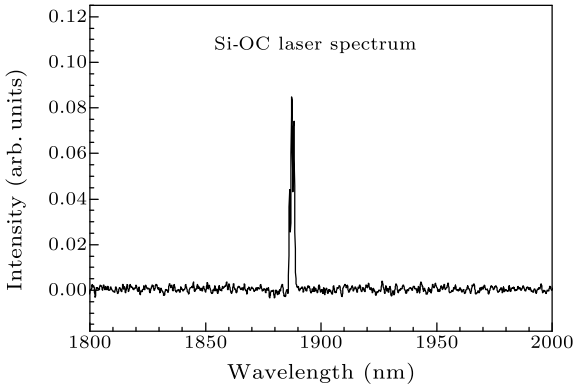

Fig. 5. Spectrum of the Si-OC laser.

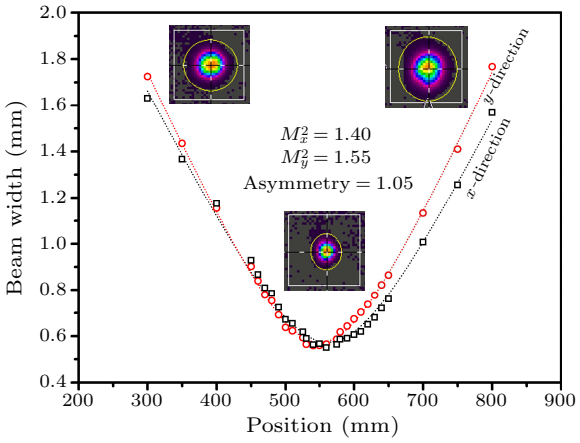

Fig. 6. Beam widths versus the distance between the lens and the CCD detector of the Tm:YLF laser using the double-side polished silicon wafer as the output coupler. Insets show the two-dimensional beam profiles obtained at distances of 300 mm (left), 550 mm (middle) and 800 mm (right) between the lens and the CCD detector.

To determine the beam quality factor of the Si-OC laser, we guided the laser beam through a 350-mm focal length lens and measured the beam diameter with assistance of an Pyrocdm Ⅲ CCD detector. Figure 6 shows the measured beam widths under the output power of 12.1 W through the Si-OC Tm:YLF system with varying distance between the lens and the CCD detector ranging from 300 mm to 800 mm. The output-beam-quality factors of M_x^2 and M_y^2 were 1.40 and 1.55 in horizontal and vertical directions, respectively, and the corresponding beam asymmetry was measured to be 1.05 under the maximum output power of 12.1 W. Circularly symmetric beam profiles with the Gaussian distributions at distances of 300 mm, 550 mm and 800 mm from the focal lens are shown in the insets of Fig. 6, which indicate an excellent beam quality of the Si-OC laser at the maximum output power (12.1 W).

To characterize the operation stability of the Si-OC laser, the long-term stability of the Si-OC laser output power was also investigated over a period of 60 min (Fig. 7). After a long time (e.g., 60 min) operating of the Si-OC laser under the maximum output power mode, the laser output power fluctuated between 11.9 W and 12.2 W. Based on the measured power data, the mean square error (MSE) can be calculated to be 0.1091 W. To divide the RSE value by the mean value of the output power of 12.09 W, the obtained relative variation is only 0.9%. The small relative variation indicates that the Si-OC laser exhibits high temporal stability, indicating the potential practicality of monocrystalline silicon wafer for the stable high-power laser system in the band at 2 μm.

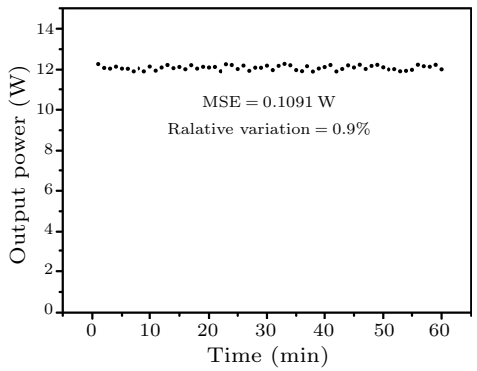

Fig. 7. Stability of the Si-OC laser output at the maximum output power over a period of 60 min.

In conclusion, an uncoated double-side polished monocrystalline silicon wafer has been directly used as an output coupler in a 5-mirror W-shape Tm:YLF laser system. The maximum output power of 12.1 W under an incident pump power of 40 W is achieved at 1887 nm, corresponding to the optical-to-optical efficiency of 30.25%, and the slope efficiency of 33.21% at room temperature. The output-beam-quality factors of M_x^2 and M_y^2 are 1.40 and 1.55 in horizontal and vertical directions, respectively. The corresponding beam asymmetry is measured to be 1.05 under the maximum output power in the Si-OC laser, exhibiting an excellent laser beam quality. Due to the intriguing characteristics of silicon, such as negligible absorption around 2 μm wavelength region, high damage threshold, low cost and long-pass-filter properties, double-side polished monocrystalline silicon wafer is considered as an outstanding candidate output coupler in the high power laser system 2 μm spectral region, which may dramatically reduce the total manufacturing costs of the 2 μm laser system.

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