# Nd-glass belt lasers with improved beam quality

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Nd-doped phosphate glass belt lasers pumped by laser diodes are demonstrated. The Nd-glass belt with a large cross-section and a small Fresnel number is air-cooled to provide around 18-W continuous wave (CW) output power with a beam quality factor of $M_y^2 \times M_x^2 = 16 \times 3.2$. With 6 pairs of V-grooves scribed on the edges of the glass belt, the beam quality is improved to $M_y^2 \times M_x^2 = 3.5 \times 2.8$ with output power of 13.5 W.

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Thermal aberrations, thermal induced birefringence, and damage of laser medium are well-known limitations for high power diode-pumped solid-state lasers. Several new types of lasers have been designed to solve these problems in the past years. Double-clad fiber laser with large ratio of surface to volume presents excellent cooling properties[1]. Good beam quality is achieved by using single-mode cores in the double-clad fibers. For a multimode core fiber laser, good beam quality can be obtained by use of bend loss or V-grooves. However, small cross sectional area of the single-mode core easily causes serious nonlinear effects and damage in the end surface, which limits higher output power carried by the fundamental mode[2]. Another approach is planar waveguide lasers, where the heat is removed efficiently from thin active layers. Planar waveguide lasers allow width scaling in addition to the normally length scaling, giving an opportunity for laser operation with much higher output power[3,4]. The beam quality in the width direction may be controlled by the design of resonator[5]. Large-core fiber lasers[2], ribbon fiber lasers[6], and multi-core fiber lasers[7] are also proposed to provide higher output power whilst maintaining good beam quality. In this paper, we demonstrate a diode-pumped glass belt laser, which is intervenient between fiber laser and planar waveguide laser. The glass belt has both a long dimension and a large cross-sectional area, resulting in good cooling properties and high damage threshold of the end surface. We obtained 18-W continuous wave (CW) output power with a slope efficiency of 54% and a beam quality factor of $M_y^2 \times M_x^2 = 16 \times 3.2$. Further, the beam quality can be improved by V-groove pairs scribed on the edges of the glass belt. About 13.5-W CW output power is achieved with a beam quality factor of $M_y^2 \times M_x^2 = 3.5 \times 2.8$.

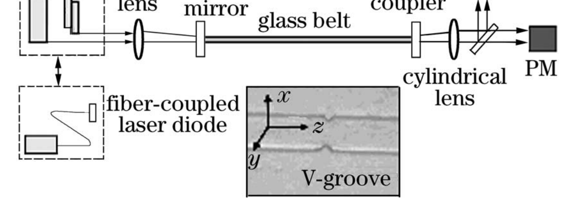

Fig. 1. Experimental setup. PM: power meter.

The experimental apparatus is shown schematically in Fig. 1. The Nd-glass belt is 500-mm-long with a rectangular cross section of 1.5 × 0.3 (mm), made up of phosphate glass with 0.5 wt.-% $\mathrm{Nd}^{3+}$ doping concentration. The glass belt is drawn from a rectangular preform in the similar processing as doing in the fabrication of glass fibers. The end facets of the glass belt are optically polished normal to the propagation axis and no polishing is performed on the $y$-$z$ surface. Here, we refer $z$-axis in the beam propagation direction and $y$-axis in the width direction as shown in Fig. 1. The phosphate glass has a very low melting temperature of 300 °C, which is beneficial to draw the glass belt in complex cross sections[8]. Laser beam propagating in the glass belt can be characterized by the effective Fresnel number, defined by $F_{\mathrm{eff}} = na^2/\lambda L$, where $a$ is the dimension of the belt cross section, $\lambda$ is the laser wavelength, $L$ is the glass belt length, and $n$ is the refractive index. The effective Fresnel numbers of the glass belt are 0.24 and 6.4 in the $x$- and $y$-direction, respectively. Thus, the laser beam can be thought as the free-space propagation in the $y$-direction and be guided in the $x$-direction. The resonator is constructed by two plane mirrors directly attached to the end facets of the glass belt. The input dichroic mirror is coated with $> 99.9\%$ reflectivity at 1.054 $\mu$m and high transmission at 808 nm. The output coupler is 50% reflectivity at 1.054 $\mu$m. The glass belt is mounted on an aluminum stage and air-cooled. A CW laser diode bar with a two-mirror beam shaping system[9] is used to pump the glass belt. The pumping beam after the beam shaping system is collimated to be $8 \times 10$ (mm) dimension with a maximum power of 34 W. Then the pump light is coupled into the glass belt by a double-convex lens with $f = 50$ mm. The refractive index of the phosphate glass is 1.54 with a numerical aperture of 1.2. Therefore, the pump light can be coupled into the glass belt efficiently and the coupling efficiency is greater than 0.95. Additionally, a 20-W fiber-coupled laser diode is also used to pump the glass belt.

When the glass belt is mounted straightly, the output performance is shown in Fig. 3. The threshold is around 1-W pump power, indicating low scattering loss of our glass belt. The slope efficiency pumped with the beam-shaped diode bar is 54%, which is slightly lower

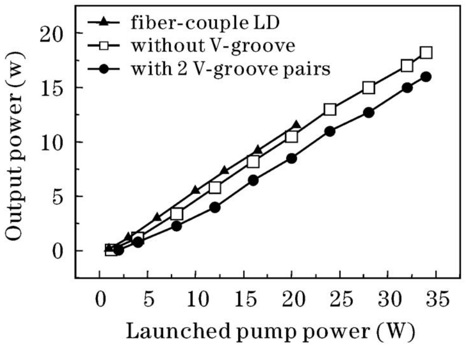

Fig. 2. Output power versus launched pump power.

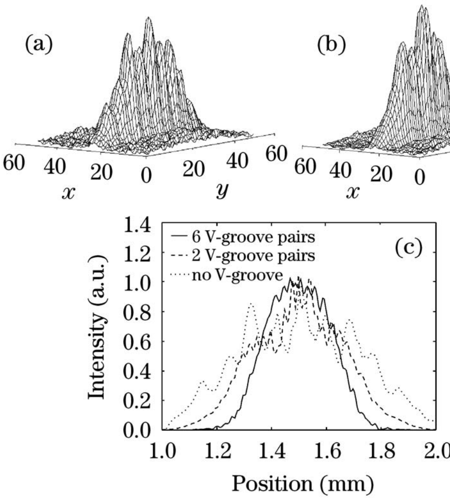

Fig. 3. Output beam pattern (a) with no V-groove, (b) with 2 pairs of V-groove on the glass belt, and (c) intensity profiles.

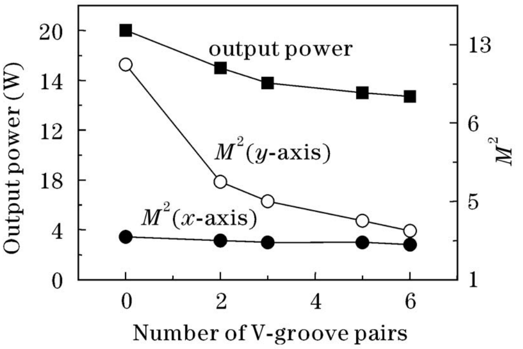

Fig. 4. Output power and beam quality factor $M^2$ versus the number of V-groove pairs on the glass belt.

than 56% for the case pumped with the fiber-coupled laser diode. It maybe results from higher pumping efficiency by using fiber-coupled laser diode. The maximum output power is 18 W with the pump power of 34 W. Although the damage threshold of phosphate glass is one degree less than that of silica glass, due to the large cross-sectional area of the glass belt, the average laser intensity is only 4.5 kW/cm$^2$ and no optical damage is observed on the end facet. The output near-field beam pattern captured by a CCD camera is shown in Fig. 4(a). In the $x$-direction, there are about 3—5 waveguide modes excited in the glass belt. Higher-order waveguide modes are thought to be suppressed by higher reflective loss. Because the belt surfaces are not polished, there is small reflective loss when the laser beam bounces back and forth at the $y$-$z$ belt-air interfaces. The total bouncing number in the glass belt for the $m$th order mode can be estimated by $N = m/F_{\text{eff}}$, where $F_{\text{eff}}$ is the effective Fresnel number in the $x$-direction (thickness). Higher-order modes with larger bouncing numbers will have higher reflective loss than lower-order modes. For example, suppose the reflective loss is 0.1% at each reflection, the second-order mode gives 2% reflective loss during a round-trip in comparison with 1% for the fundamental mode. Unlike in the $x$-direction where the laser beam is represented by the waveguide modes, the guided effect in the $y$-direction is very weak. The laser beam quality in the $y$-direction is determined by resonator structure. Because the laser beam is confined in the glass belt, transversal mode discrimination can not be provided by diffraction loss. The transversal beam pattern as shown in Fig. 3(a) reveals a number of modes oscillating in the $y$-direction. The beam quality factor in the $y$-direction is measured to be $M_y^2 = 12$.

To improve the beam quality in the $y$-direction, pairs of V-groove are scribed in the edges of the glass belt with a CO$_2$ laser. The V-grooves are 0.40-mm-wide and $0.20 \pm 0.03$-mm-deep along the $y$-direction. A micrograph of a pair of V-grooves is also shown in Fig. 1. The characteristic pumping absorption length in the glass belt is around 20 mm. Thus, the V-groove pairs should be placed more than 50 mm away from the belt ends to avoid large leakages of pump light from the V-grooves. At first, two pairs of V-grooves are scribed 100 mm away from each ends in the glass belt. The output beam pattern is shown in Fig. 3. The beam width in the $y$-direction is reduced and the beam profile becomes smoothly. The V-grooves serve as in-line apertures filtering out the higher-order modes in the $y$-direction. These in-line apertures suppress off-axis amplified spontaneous emissions (ASE) as well as minimize the edge-diffraction effects. The beam quality factor is improved to $M_y^2 = 6$. As a consequence of scattering loss introduced by the V-grooves, the maximum output reduces to 15 W when the glass belt is pumped by the beam-shaped diode bar.

We add more V-groove pairs in the middle of the glass belt to improve the beam quality further. The V-groove pairs are equally separated along the glass belt between the first two V-groove pairs. In fact, the laser properties are not sensitive to the positions, at which the V-groove pairs are scribed. The beam quality factors $M_y^2$ and the maximum output powers are shown in Fig. 4 as a function of the number of V-groove pairs. The beam quality factor in the $y$-direction decreases to $M_y^2 = 3.5$, and the maximum output power becomes 13.5 W when 6 pairs of V-grooves are scribed in the glass belt. The beam quality will be improved slightly when more V-groove pairs are applied. Although the V-grooves are scribed along the $y$-direction, it is surprised that the beam quality in the $x$-direction is also improved from $M_x^2 = 3.2$ to $M_x^2 = 2.8$. This phenomenon may be explained by absence of ASE and reduction of the mode volume in the whole glass belt.

As the glass belt is pumped longitudinally, the uniform pumping is achieved by multiple reflections on the wall of the glass belt. It is expected that the laser performance is independent of the pumping source. This is confirmed by similar performance with pumping of the fiber-coupled laser diode. The beam quality factor is improved to $M_y^2 \times M_x^2 = 3.5 \times 2.8$ at the expense of decreasing in the slope efficiency to 40% with 6 pairs of V-grooves. The laser output from the glass belt is astigmatic in the $x$- and $y$-direction. However, the astigmatism can be corrected simply by a cylindrical lens. Moreover, because the thermal lens effects are negligible in the glass belt lasers, the beam collimation is unchanged over all pump power range in the experiments.

In conclusion, we have demonstrated Nd-doped phosphate glass belt lasers longitudinally pumped by laser diodes. The glass belt lasers with large ratios of surface to volume and small effective Fresnel numbers were air-cooled, providing a maximum CW output power of 18 W with an optical slope efficiency of 54%. With V-groove pairs scribed on the edges of the glass belt, the output beam quality was improved to $M_y^2 \times M_x^2 = 3.5 \times 2.8$ with the output power decreasing to 13.5 W and a slope efficiency of 40%. No optical damage on the end surface was observed. Because area of the end surface of glass belt laser is two orders larger than those of conventional fiber lasers, the maximum power carried by the glass belt will be over several kW. And more output power can be expected by using higher power pumping sources.

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