Effect of temperature on refractive index match of laser glass edge cladding

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An Nd:glass disc requires an edge cladding to absorb the amplified spontaneous emission. The absorption is determined by reflections (R) from disc edges. R is primarily induced by the refractive index (n) mismatch. Thus, the temperature at the cladding interface increases due to absorption, and leads to the variation of n. In order to investigate the effect of temperature on the refractive index match, temperature coefficients ($\mathrm{d}n/\mathrm{d}T$) of the laser glass, adhesive polymer, and cladding glass are measured. The effect of temperature on the refractive index match is discussed. Results show that the indices match below 40 °C.

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Large size Nd^{3+}-doped phosphate glass disc is the core working material in high-peak power solid-state laser systems, such as SG-II, SG-III, LMJ, and NIF, which are able to generate megajoules of energy at petawatt-power levels for laser fusion, as a long-term option to generate electric power[1–4]. In order to decrease the reflectivity of the amplified spontaneous emission (ASE), suppress parasitic oscillations at the edges, and minimize the loss of stored energy of the discs, an edge cladding that absorbs the reflected or scattered 1 μm light is required[5,6]. The discs are cut into rectangle shape. Their edges are ground and polished with a slight tilt. The Cu^{2+}-doped absorbing glass strips are adhesively bonded to the outside edges of the discs using a composite polymer whose refractive index matches to both laser glass and absorbing glass[7–10]. Total reflections (R) from the disc edges are primarily induced by the refractive index mismatch and the imperfections at the laser glass/polymer/cladding glass boundary[9–12]. The threshold of the parasitic oscillation and the reflectivity of ASE are determined by R, which is a function of the refractive index match of the laser glass, the polymer, and the cladding glass[5,12]. Therefore, R must be sufficiently low (e.g., $R < 0.1\%$) when developing the edge cladding[13]. Refractive indices of the laser glass and the cladding glass are close and steady, and the polymer refractive index is possible to be adjusted by adding or subtracting functional groups with different polarizabilities. Refractive indices of the laser glass, the polymer, and the cladding glass are well matched before the temperature rise at the bond interface (room temperature). Since the cladding glass absorbs 1 μm ASE and parasitic oscillations light, then the temperature increases at the bond interface. For example, the temperature can reach 36 °C in the NOVA laser system (a cladding absorption coefficient of 7.5 cm^{-1}, an assuming ASE fluency of 10 $\mathrm{J/cm}^2$ in 0.5 ms)[14], the peak temperature rise is 9.8 °C at the cladding interface with an average of 3.0 °C in the edge cladding glass in NIF-like laser glass amplifier[15]. In addition, the temperature of the Nd:glass slabs will increase when the flash lamps are fired[16]. Obviously, the refractive indices of the laser glass, polymer, and cladding glass will change correspondingly. So, the temperature dependence of the three refractive indices is significantly important to the edge cladding design.

According to Prod'homme's model[17], $\mathrm{d}n/\mathrm{d}T$ is a property of the material and is determined by the density and electronic polarizability, and both of them change with the temperature. When the variation of the electronic polarizability is dominant, the refractive index becomes positive and increases with temperature rise. On the other hand, if the variation of thermal expansion took the domination, then $\mathrm{d}n/\mathrm{d}T$ will be negative and decreases with temperature rise. Temperature increases at interfaces of the disc/polymer/cladding glass when the laser disc is operated. The temperature is proportional to the cladding glass absorption coefficient, decreases exponentially with the distance into the cladding glass, and will lead to the variation of refractive indices[18]. The variation and its effect on refractive index match of laser glass edge cladding are rarely reported in the literature. Here we proposed an easy $\mathrm{d}n/\mathrm{d}T$ measurement method using the prism coupler equipped with temperature control modules. Moreover, the influence of $\mathrm{d}n/\mathrm{d}T$ on the refractive index matching of the laser glass edge cladding was discussed.

The adhesive polymer was fabricated from commercial resins and curing agents. Polished 10×10×0.5 (mm)^3 Nd^{3+}-doped phosphate laser glass (SIOM N3135 Nd_2O_3 3.5 wt%) and Cu^{2+}-doped phosphate cladding glass (SIOM C3135 CuO 0.35 wt%) samples were prepared. The same size polymer sample was fabricated according to a specified procedure. Based on its optical, mechanical, and other properties, the compositions of this adhesive is uniquely suited for our application. Optically, the polymer should be clear, colorless, and precise refractive index match to the laser glass and the cladding glass. Mechanically, the polymer should possess sufficient mechanical and adhesive strengths to withstand the final ground and polishing processes. Also, it must be resistant to high-fluency flash lamp environment, and bring small residual stress during its curing process. Furthermore, it must have appropriate thermo-optic coefficient, matching with the laser glass and the cladding glass.

The $\mathrm{d}n/\mathrm{d}T$ values of the laser glass, polymer, and cladding glass samples were measured using the prism coupling method[19]. Figure 1 shows a schematic diagram of the measurement facility. The prism coupler was equipped with temperature control modules. The measuring system employed two heating elements in the prism clamp and one in the coupling head. Two independent feedback modules control these heating elements to maintain the prism clamp and the coupling head at desired temperature measurement, respectively. Another two independent thermocouple controlling modules were used to control and maintain the temperature of the prism and the coupling head at the same temperature. This technique could eliminate the temperature gradients across the prism/sample/coupling head interfaces. This temperature gradient would lead to uncertainty of the temperature variation in the sample and affect the accuracy of the refractive index measurement. Lasers of the 632.8 and 1064 nm wavelength transverse electric modes were used as the light source in the experiment. In order to validate the reliability of the thermo-optic coefficient measurement method, $\mathrm{d}n/\mathrm{d}T$ of fused silica was measured. For all the wavelengths, variations of temperature ranged from 25 to 150 °C. The measured $\mathrm{d}n/\mathrm{d}T$ values are $+8.9\times10^{-6}$/°C at 1064 nm and $+8.1\times10^{-6}$/°C at 632.8 nm, which are close to the values reported in Ref. [20] ($+10.0\times10^{-6}$/°C at 1064 nm and $+9.0\times10^{-6}$/°C at 632.8 nm). Results indicate that the method using the prism coupler equipped with temperature controlling modules can provide reliable measurement of $\mathrm{d}n/\mathrm{d}T$.

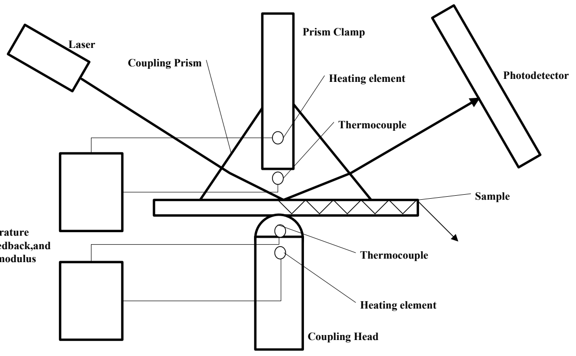

Fig. 1. Apparatus for measuring the temperature coefficients of refractive index.

For all glass samples and measured wavelengths, the temperature range was 25–150 °C in 20 °C steps. $\mathrm{d}n/\mathrm{d}T$ of the glass samples for two wavelengths is shown in Fig. 2. It is linear and negative (on the order of 10^{-6}). The values calculated by the slope are about -4.52×10^{-6}/°C at 632.8 nm and -4.93×10^{-6}/°C at 1064 nm for the laser glass. Likewise, for the cladding glass, the values are about -4.68×10^{-6}/°C at 632.8 nm and -4.07×10^{-6}/°C at 1064 nm. This means that there are slight differences between $\mathrm{d}n/\mathrm{d}T$ of the laser glass and that of the cladding glass for different wavelengths, which indicate that the variations of n changes almost equally, which is helpful for the refractive index match when the temperature changes, and it is due to the similar compositions of the laser glass and the cladding glass.

For the polymer measurement, the temperature range was set to 25–55 °C in 5 °C steps because the transition temperature (T_g) of adhesive polymer was about 40 °C. The experimental results are depicted in Fig. 2. It is seen that the $\mathrm{d}n/\mathrm{d}T$ is linear and negative below and above T_g. The values calculated by the slope are about -1.68×10^{-4}/°C at 632.8 nm and -1.20×10^{-4}/°C at 1064 nm below T_g. Similarly, above T_g, the values are about -2.97×10^{-4}/°C at 632.8 nm and -3.11×10^{-4}/°C at 1064 nm. This means that $\mathrm{d}n/\mathrm{d}T$ decreases faster over the polymer transition temperature.

Refractive indices with the temperature variation at a given wavelength are shown in Fig. 2. It can be seen that the refractive indices of the laser glass, polymer, and cladding glass at 25 °C are 1.5385, 1.5412, and 1.5416 at 632.8 nm and 1.5306, 1.5312, and 1.5336 at

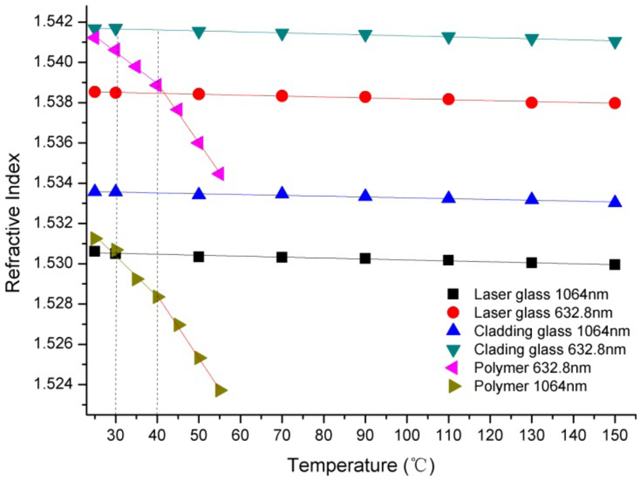

Fig. 2. $\mathrm{d}n/\mathrm{d}T$ of the three materials at 632.8 and 1064 nm wavelength.

1064 nm, respectively. Refractive indices of the three materials are in good agreement with the refractive index match: laser glass < polymer < cladding glass[7,21]. For 632.8 nm, the refractive indices match well even though the temperature increases close to the polymer transition temperature (about 40 °C). For 1064 nm, the indices also match well below 30 °C, which is close to the temperature at the interface after laser shot because the appropriate absorption coefficient ($3-5\ \mathrm{cm}^{-1}$) of the Cu^{2+}-doped cladding glass is adopted[22–24]. The polymer refractive index is lower than that of the laser glass when it is close to the polymer transition temperature. The refractive indices at T_g are 1.5305 and 1.5284 at 1064 nm for the laser glass and the polymer, respectively. The refractive index variation is not beyond ±0.003. This refractive index matching remains for the tilting laser disc edges, which makes the tolerance on index matching be relaxed[9,10].

In conclusion, we investigate and measure the refractive indices versus temperature of the Nd^{3+}-doped phosphate laser glass, the adhesive polymer, and the Cu^{2+}-doped phosphate cladding glass using the prism coupling method. Effect of temperature on the refractive index match of the edge cladding is discussed. The $\mathrm{d}n/\mathrm{d}T$ values of the laser glass and the cladding glass are linear and negative (in the order of 10^{-6}), and that of the polymer is similarly linear and negative (in the order of 10^{-4}). Below about 30 °C, the indices match well at 632.8 and 1064 nm. When it is close to the polymer transition temperature, the refractive index variation is not beyond the tolerance on index (±0.003). The refractive index remains the same for the tilting laser disc edges. Therefore, the refractive index variations with temperature have similar tendency and scarcely affect the refractive index matching. All investigative results can be employed for designing and developing the laser glass edge cladding.

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