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Final Report for AOARD Grant 134105 “Advanced Waveguide Lasers Based on Optically Transparent Polycrystalline Materials for Power Scaling Studies”

20 Feb 2015

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Abstract:

Advanced waveguide lasers based on optically transparent polycrystalline materials for power scaling studies was performed in this research. Aim of this research is development of highly efficient solid state lasers with high beam quality and stable laser operation from optically transparent polycrystalline materials whose properties can be optimized by engineering the critical features of the polycrystalline laser material / structure combination. Simplification of the waveguide structure and improvement of the ability for cooling of the heat sink were investigated in this work. Then, control of the beam profile and improving the oscillation efficiency was also investigated by using the advanced ceramic design. All ceramic waveguide composite core sample having end-cap and Nd doping gradient structure were successfully fabricated for this purpose. Optical qualities of each ceramic composite sample were inspected in details by polarizer and optical microscope.

Keywords: Transparent ceramics, transparent polycrystalline material, waveguide ceramic, direct-formed ceramic composite

1. Introduction

Waveguide laser is one of the ideal lasers for power scaling studies. Advantage of waveguide type laser is as follows. (1)Cooling from the large surface can suppress a heterogeneous distribution of temperature inside a laser gain medium. Reduced thermal lens effect improves saturation of laser output with a high beam quality. (2)The long propagation length of pumping beam can generate laser output power effectively (i.e., high-gain and high-efficiency). (3) Because a higher concentration of laser active ions can be homogeneously doped in ceramic gain media as compared with glass fiber, high output power laser oscillation with high efficiency can be expected from a small sample volume.

From 2010, ceramic waveguide laser was developed, and investigated their fundamental laser oscillation properties. Thermal conductivity of YAG ceramics is close to that of single crystal YAG. Waveguide type laser can suppress the heat gradient in the core by cooling off from a wide surface of YAG. Figure 1 shows designed ceramic waveguide sample. The thickness of core (0.6at% Nd:YAG) is 400 μ m. The structure in which Nd:YAG layer is sandwiched in YAG (thickness of 400 μ m) was made to cool the Nd:YAG core layer

effectively as compared with that of simple single crystal structure. A sintering bonding technique was used for interface bonding between YAG and Nd:YAG. Interfaces of YAG and Nd:YAG are strongly bonded at the atomic level. As a result, the total thickness of the core part becomes 1.2 mm. Sapphire superior in thermal conductivity was used as cladding for pumping laser. Accordingly, the core (YAG-Nd:YAG-YAG) was sandwiched by a sapphire (thickness of 400 μ m). TIR (total internal reflection) at clad interface for pumping laser can effectively generate laser output power along the long propagation length (high-gain and high-efficiency).

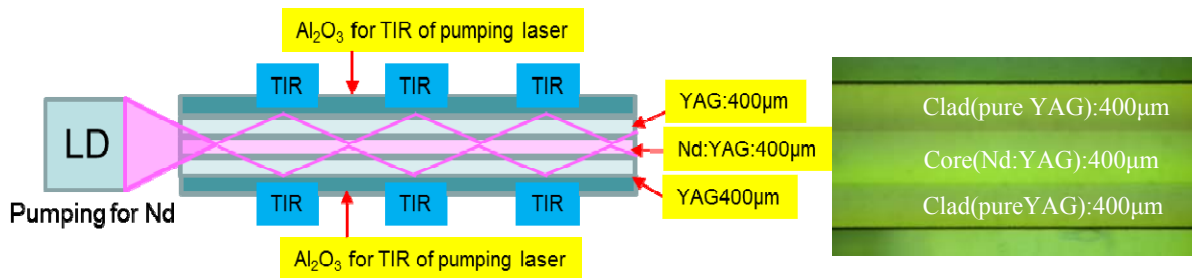


Fig 1. Design of a waveguide sample.

A slab sample with the dimension (62 x 16 x 1.2mm) as the waveguide sample was prepared by bonding in the middle of the slab and tested for high power laser experiment. When the absorbed power reached 1120W, slope efficiency was about 47% and maximum output power of 513 W was successfully achieved. In contrast, a technical problem for power scaling became clear in ceramic waveguide laser. A large-sized sample which is not obtainable in a single-crystal laser material can be produced by the ceramic technology, but technical difficulty of the interfacial bonding of YAG and Nd:YAG in the core goes up as sample size becomes larger and larger. In addition, regarding the intensity of an oscillated laser beam, it is very strong at both ends of the waveguide sample because pumping laser is not absorbed to waveguide sample uniformly (see Fig. 2). Therefore, the structure control of the active ion in the waveguide core is indispensable for the control of laser beam intensity and beam quality.

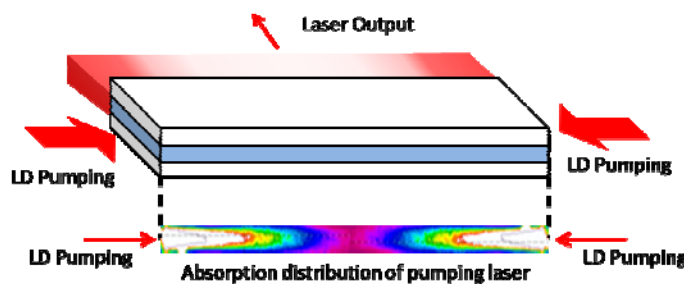


Fig. 2. Power intensity of an oscillated laser beam.

In this work, we fabricated advanced ceramic waveguide for power scaling studies. The most important is the investigation on design flexibility and the possibility of the ceramic technology on waveguide laser. A large-sized waveguide sample which was not obtainable from conventional melt growth technology is required for power scaling studies. An initial objective will be a comparison of the performance between a conventional ceramic waveguide structure (5 layers) and simple waveguide structure (3 layers). A bonding condition and a cooling effect (lasing efficiency) was investigated under high-density pumping (see Fig. 3). The structure that is effective for upsizing of the waveguide sample will be investigated in this phase.

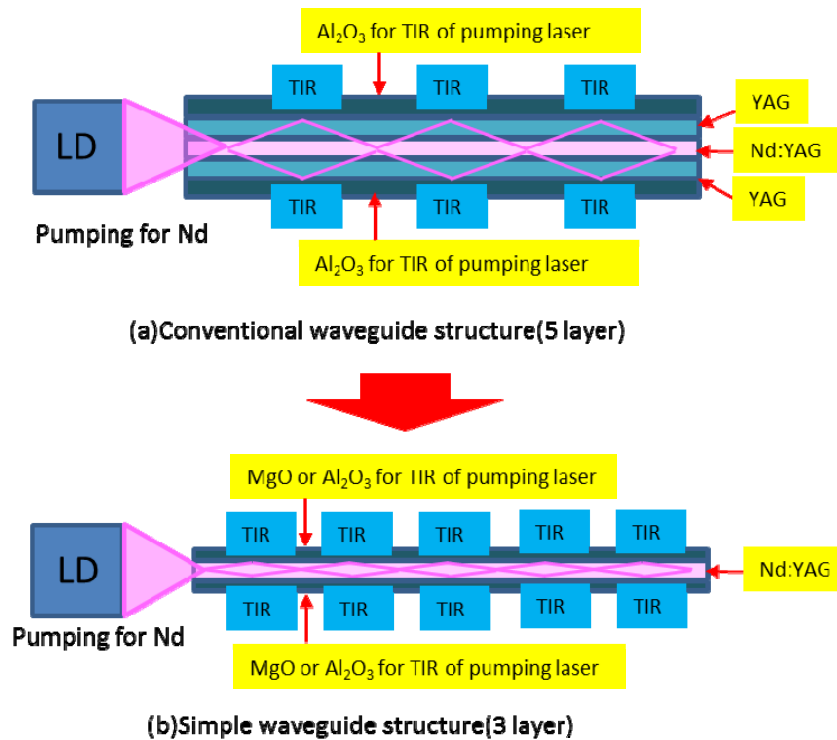


Fig 3. Comparison of the performance between a conventional ceramic waveguide structure (5 layers) and simple waveguide structure (3 layers).

Then, control of the beam profile and improving the oscillation efficiency by the homogenization of the pumping laser absorption was also investigated. A material superior in thermal conductance (Ex. ceramic YAG) for heat radiation was capped to the waveguide edges by sinter bonding technology. Nd doping profile in the core was made step-by step (Doping concentration: from low to normal concentration). As for these two structural combinations, it is considered to be advanced ceramic waveguide lasers with an ideal core structure (Fig. 4).

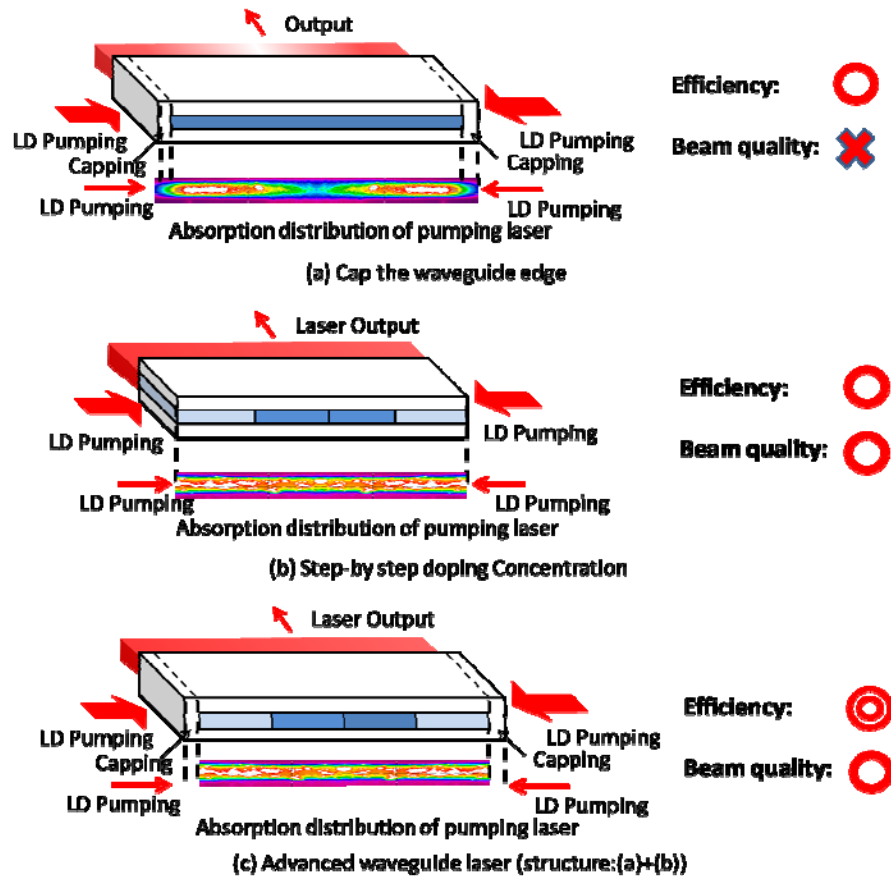


Fig 4. (a), (b), (c) Control of the beam profile and improving the efficiency by the homogenization of the pumping laser absorption to achieve an advanced waveguide laser.

2. Experiment

(A) Simplification of core and cladding structure to fabricate a large sized waveguide sample

The simple core structure is ideal to make large waveguide sample with high-quality. A comparison of the performance between a conventional ceramic waveguide structure (5 layers) and simple waveguide structure (3 layers) was performed in this work. We prepared a conventional core structure (3 layers: YAG-Nd:YAG-YAG) and simple core structure (mono layer: Nd:YAG) to evaluate a possibility of the simplification with the structure of the core. Dimension of the cores is 16 mm x 32 mm, and thickness is 1.2 mm. Simple AR coating only for pumping laser wavelengths was coated for all the edge face of the sample. After having sandwiched the waveguide core part with Sapphire, it was attached in a laser cavity. For fundamental laser oscillation, LD stack of 808 nm was used as a pumping laser. Maximum output power per one LD is approximately 400 W. The pumping laser was input from the left side of the 32 mm x 1.2 mm surface. Gradient processing (3 degree and 4 degree) was made on 16 mm x 1.2 mm surface to prevent ASE in the pumping direction. Output laser beam was oscillated from the surface of 1.2 mm x 32 mm. The mirror of 20 % of transmittance was selected as an output coupler (O. C.). The resonator length became approximately 20 mm. Then, to evaluate improvement of the chilling effect, a similar experiment was performed with the mono

layer core sample which thinned the thickness of the core to 0.6mm from 1.2mm. Moreover, we also examined the structural improvement of the TEC (Thermoelectric Cooler) unit of the heat sink and its optimal placement to improve ability for cooling of the waveguide sample.

(B) Fabrication of All Ceramic Waveguide Composite Core Sample

High purity starting powders (over 99.99% purity) were used. As shown in figure 5, Y_2O_3 and Al_2O_3 powders were mixed to get YAG composition powders, and similarly Y_2O_3 , Al_2O_3 and Nd_2O_3 powders were mixed to get Nd:YAG composition powders. Those prepared powders were used to make ceramic composite samples by advanced molding technology, followed by sintering at high temperature to achieve transparent ceramics.

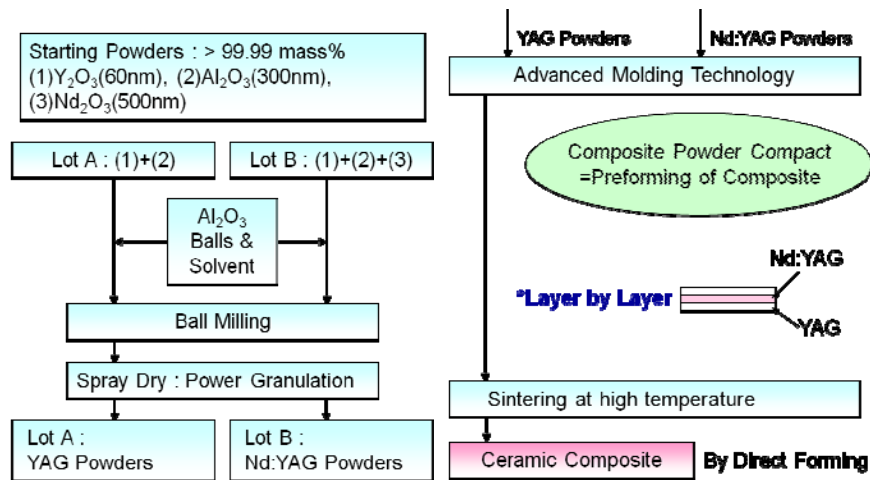


Fig.5 Fabrication chart for making ceramic composite by direct forming process.

An example of making 3-layered composite sample is shown in figure 6. We named this method as direct forming process. As a first step, YAG powders were put into a metal mold and pressed at light pressure, and then a certain amount of Nd:YAG powders were put onto it and pressed again at light pressure. Next, YAG powders were put onto it and pressed again with relatively high pressure. Then, a powder compact of YAG/Nd:YAG/YAG composite design was obtained. This performed powder compact was pressed again in CIP (Cold Isostatic Press) machine. Finally, it was sintered at high temperature to become transparent.

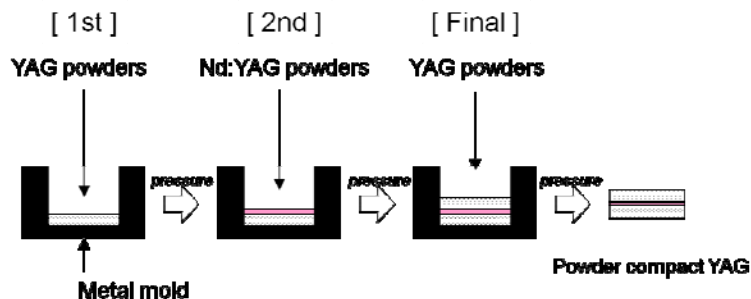
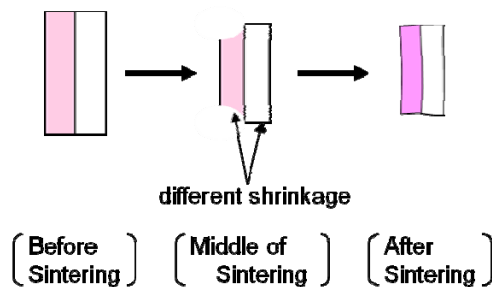


Fig.6 An example of making YAG-Nd:YAG-YAG, 3-layered composite.

This direct forming process is very simple to make composite design, compared to the conventional diffusion bonding process in which polishing and diffusion bonding are necessary and delivery time is long. However, this direct forming process also has some technical issues. When the powders with different shrinkage behavior are stacked together and sintered at high temperature, deformation occurred from the middle step of sintering and it remained till the end of sintering. (Please refer figure 7.) This caused mechanical stress in the composite sample. In some cases, pores or bubbles were trapped at the bonding interfaces, resulting not clear transparency. In the worst case, the composite sample may be cracked. Therefore, it is important to develop powders with similar shrinkage behavior although they have different chemical compositions.

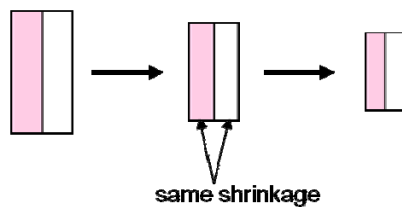
Nd:YAG + Type X (YAG)



Technical Issues

- *Stress**
- *Including pores**
- *Not clear transparency**
- *Cracking**

Nd:YAG + Type Y (YAG)



- *Important to develop starting powders with same shrinkage behavior**

Fig.7 Difficulties in direct-formed ceramic composite.

3. Results and Discussion:

(A) Simplification of core and cladding structure to fabricate a large sized waveguide sample

Laser oscillation property was investigated in a conventional core structure (3 layers: YAG-Nd:YAG-YAG) and simple core structure (mono layer: Nd:YAG). Relationship between absorbed power and output power is shown in figure 8. For a conventional core structure (3 layers), the laser output was 140 W. In contrast, higher output power of about 160 W was obtained from simple core structure. The difference of obtained output is associated with a region for Nd^{3+} doping and the focused region of the pumping laser light. The conventional core structure is three levels of YAG-Nd:YAG-YAG. The thickness of Nd:YAG layer is $400\mu\text{m}$. A region for Nd^{3+} doping Nd is restricted as compared with simple core structural Nd:YAG monolayers of 1.2mm. A high chilling effect will be obtained from the YAG layer bonded up and down of Nd:YAG layer. However, the improvement of the oscillation efficiency by the chilling effect with the YAG layer bonded up and down of Nd:YAG layer could not be confirmed at the pumping input of around

400W. On this pumping condition, high-output power is obtained in a simple core structure (mono layer: Nd:YAG) of 1.2mm.

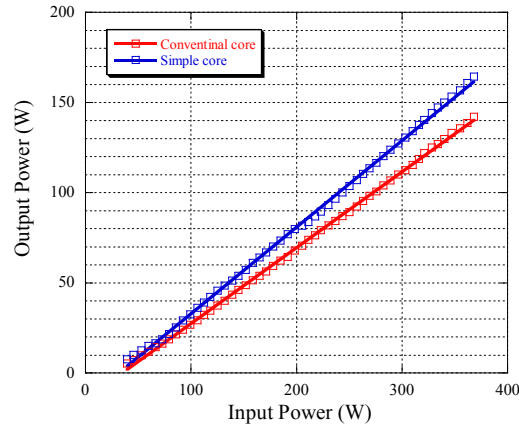


Fig. 8 Relationship between input power and output power for conventional core structure and simple core structure.

The high chilling effect is decided by the shortness of the distance between the heat sink surface and the fever part by the pumping laser absorption. For this reason, the thickness of the simple core was made 0.6mm from 1.2mm. Comparison of the laser oscillation property with the thickness of 1.2mm is shown in fig. 9. The difference of the oscillation output by the remainder of the thickness was not found in the low input power region. In the core of the thickness of 0.6mm, the efficiency of laser decreased from input power 140 W. A highly precise cavity adjusting was required at every increase of the input power. It is caused by the fact that power density of pumping laser concentrates to an incidence end at the time of 0.6mm the thickness of the core than time of the thickness of the core of 1.2mm. The influence of the change of cavity condition such as the thermal lens effect depending on input power intensity becomes remarkable in this experiment. For the current pumping focusing condition, a maintenance of the cavity adjusting is difficult in the core of thin 0.6mm which improved of the cooling effect. From these results, we fabricate the advanced waveguide sample of the simple core of thickness 1.2 mm.

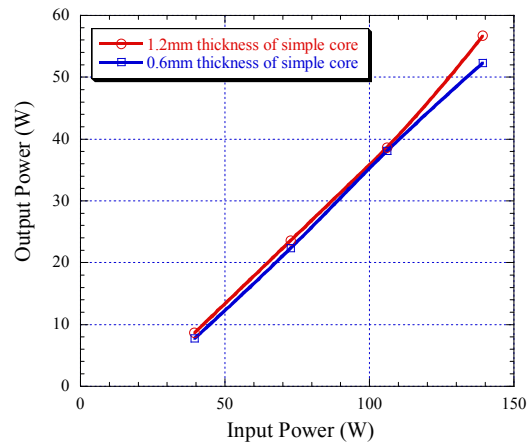


Fig. 9 Comparison of the laser oscillation property with the core thickness of 1.2 mm and 0.6 mm.

Then, the cooling efficiency of the heat sink was improved by coolability improvement and the optimal arrangement of the TECs. Heat conduction grease is used for interfacial junction of TEC (200W) and the heat sink. Thermal conductivity of the heat conduction grease is 6.5 W/mk. In this time, the interfacial junction was changed to the Indium foil of thermal conductivity 81.8 W/mk. The Indium foil of thickness 200 μm showed high coolability than conventional heat conduction grease. In the same cooling condition, a cooling temperature improved 10% (Fig. 10). The conventional laser cavity used three TECs and had coolability of 600W. By a design change of laser cavity, four TECs which a cooling capacity improved 10 % was placed on the heat sink (Fig. 11). The coolability was able to improve more than 800W from 600W. Stable experiment of the high output laser oscillation can realize by these improvement.

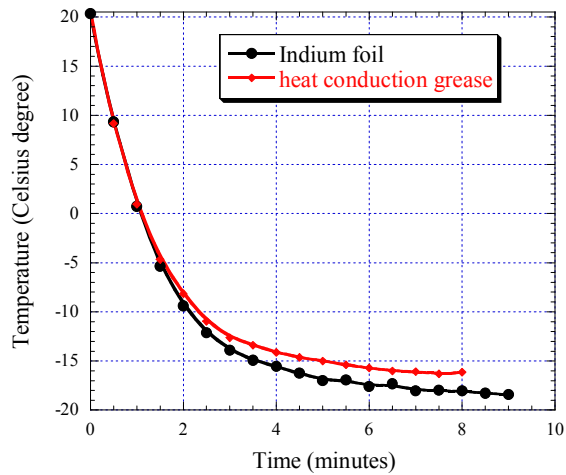


Fig. 10 Comparison of the cooling characteristics with heat conduction grease and the Indium foil.

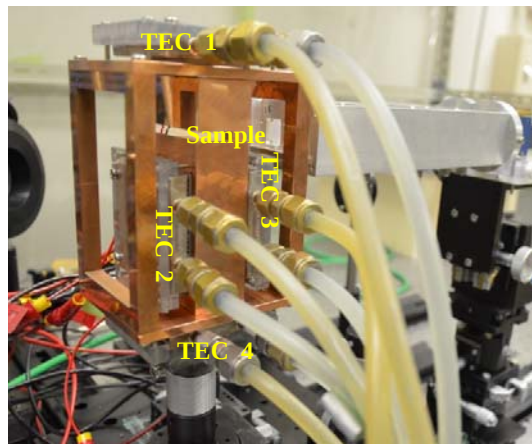


Fig. 11 Four TECs which a cooling capacity improved 10 % was placed in the laser cavity.

(B) Fabrication of All Ceramic Waveguide Composite Samples

In this work, the composite core samples with designs shown in figure 12 were demonstrated. External view of these composite samples is summarized in figure 13. Although no.1) sample is monotonic structure, it was prepared by direct forming process for stacking 5 layers of 0.6%Nd:YAG powders. Bonding condition is very perfect and bonding interstices do not exist at the bonding interfaces. Optical qualities of each ceramic composite sample were inspected in details by polarizer and optical microscope. Inspection results for no.2) core sample, YAG/Nd:YAG/YAG structure, were typically shown in this report.

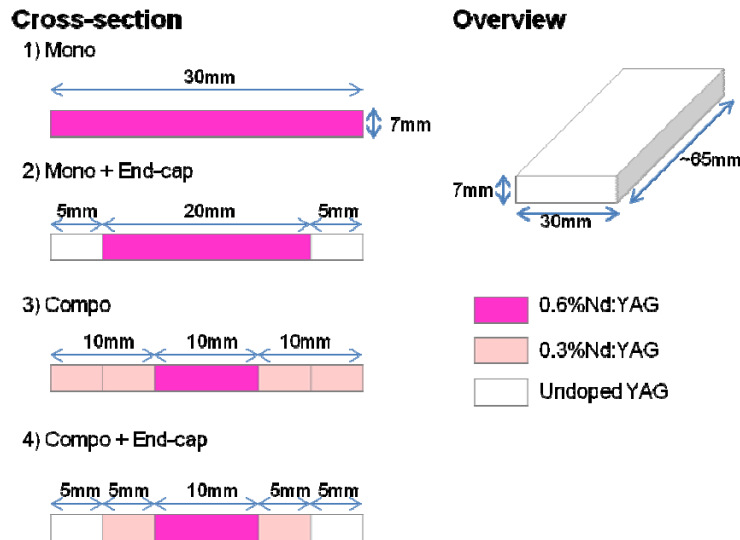


Fig.12 Design of each composite made for this work.

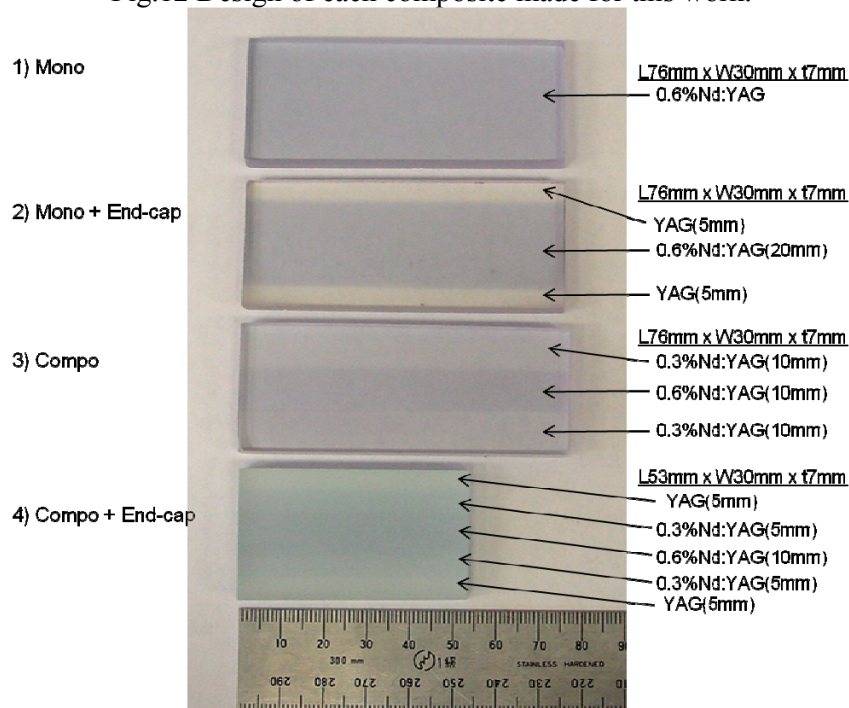


Fig.13 Demonstrated Composite Samples for this work.

Figure 14 shows the appearance of 3-layered composite core sample observed under polarizer. The round sample was included as a reference material which has optically inhomogeneous regions inside. We can easily observe optical inhomogeneity in the reference material. Fabricated composite core is highly transparent and, crack-free and stress-free conditions were observed in macro level.

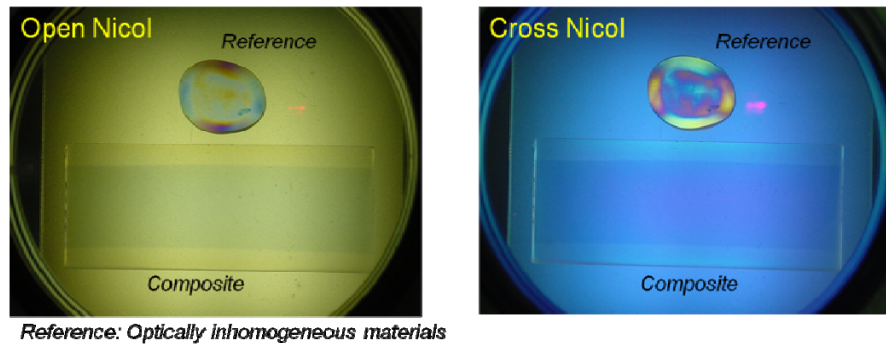


Fig.14 Observation under polarizer for 3-layered composite in macro level.

In addition, we also observed the homogeneity in micro level by using transmitted polarized optical microscope. Results are summarized in figure 15. Optical homogeneity at five different positions was observed: 1) upper YAG layer region, 2) lower YAG layer region, 3) inside Nd:YAG region, 4) upper YAG/Nd:YAG boundary region, 5) lower YAG/Nd:YAG boundary region. Optically inhomogeneous parts such as secondary phases or optical stress were not observed in all positions.

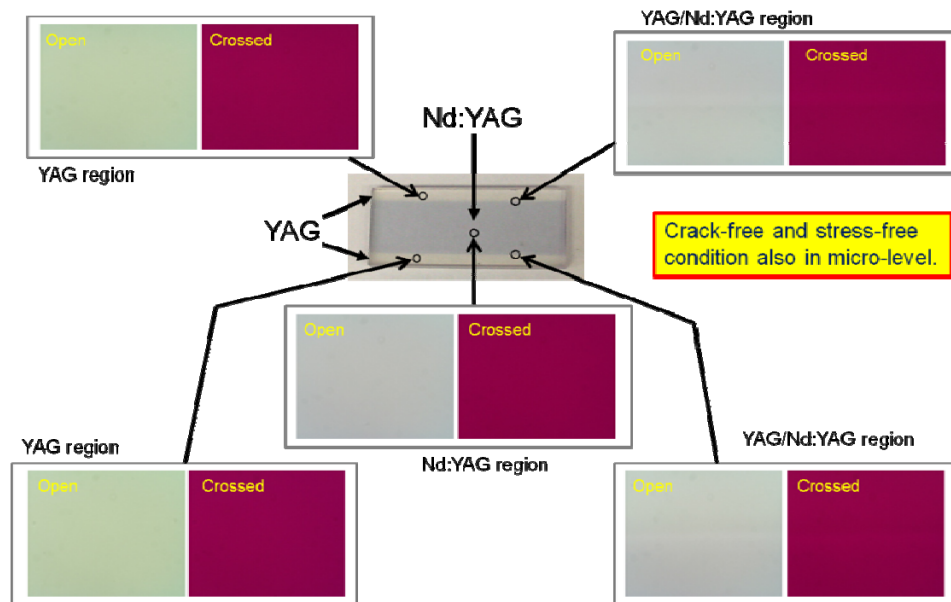


Fig.15 Observation by transmission and polarizing microscopy.

The microstructure of the fabricated composite core sample was also observed at five different positions as shown in the above. The sample was thermal etched at high temperature for a short time. Then it was observed under reflecting optical microscope. Results are summarized in figure 16. Uniform grains (ca. several tens of μm) were observed.

Neither interstices nor cracks due to incomplete bonding were observed at the bonding regions. Power scaling studies will be performed in the advanced waveguide lasers up to pumping power of 1.6 kW.

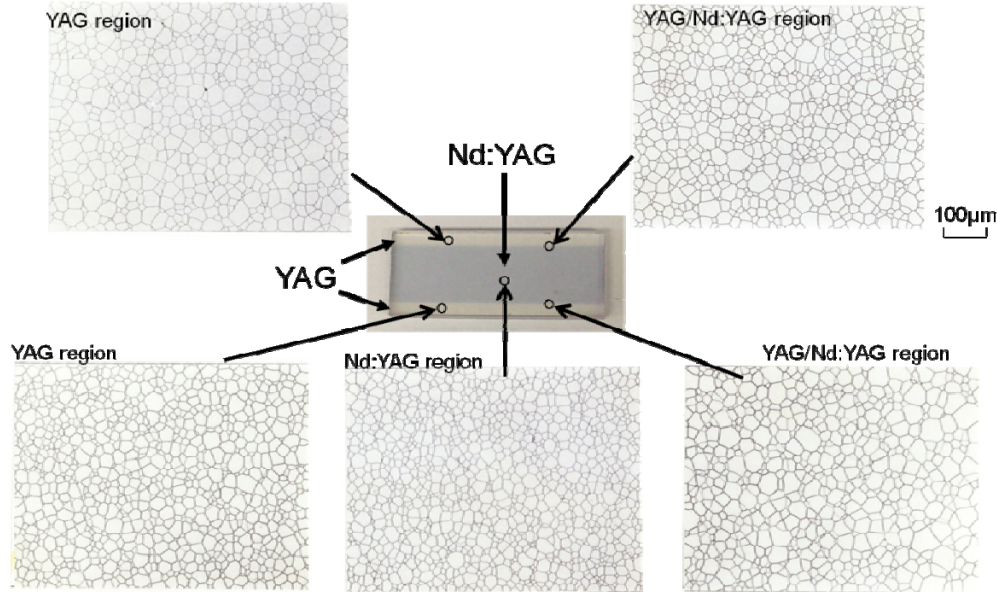


Fig.16 Microstructure observed by reflecting microscopy.

7. Conclusions

Advanced waveguide lasers based on optically transparent polycrystalline materials for power scaling studies is investigated in this research. For this purpose, simplification of the waveguide structure and improvement of the ability for cooling of the heat sink were performed in this work. Conventional core structure (3 layers: YAG-Nd:YAG-YAG) and simple core structure (mono layer:Nd:YAG) was prepared to evaluate a possibility of the simplification with the structure of the core. Dimension of the cores is 16 mm x 32 mm, and thickness is 1.2 mm. A higher output power of about 160 W was obtained from simple core structure compared with that of conventional core structure. The thickness of the sample compared 1.2mm and 0.6mm about a simple core. In the current pumping condition, the optimum thickness of the sample was found to be 1.2mm. From these results, we fabricate the advanced waveguide sample of the simple core of thickness 1.2 mm. Then, the cooling efficiency of the heat sink was improved by coolability improvement and the optimal arrangement of the TECs. 10% of coolability was improved by using the indium foil for junction of TEC. By a design change of laser cavity, four TECs which a cooling capacity improved was placed on the heat sink. The coolability was able to improve more than 800W from 600W. Stable experiment of the high output laser oscillation becomes able to realize by these improvement.

The advanced waveguide core which is available for a high performance oscillation and beam quality control were demonstrated. “Mono”, “End-cap + Mono”, “Composite”, and “End-cap + Composite” types of simple core were successfully fabricated in this work. Although “Mono” type core is monotonic structure, it was prepared by direct forming

process for stacking 5 layers of 0.6%Nd:YAG powders. Bonding condition is very perfect and bonding interstices do not exist at the bonding interfaces. Optical qualities of each ceramic composite sample were inspected in details by polarizer and optical microscope. We can easily observe optical inhomogeneity in the reference material. Fabricated composite is highly transparent and, crack-free and stress-free conditions were observed in macro level. Power scaling studies will be performed in the advanced waveguide lasers up to pumping power of 1.6 kW.

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