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Ceramic laser materials: Past and present

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ABSTRACT

Recently, 100 KW output power from YAG ceramic laser system has been demonstrated. It is a remarkable achievement considering that only a few milli-watt power was observed from the ceramic laser materials when first reported in the 1960s. This great improvement is mainly due to the success in high purity powder synthesis, development in new sintering technology and novel ideas in optics and device design. Additional developments have included highly doped microchip lasers, ultrashort pulse lasers, novel materials such as sesquioxides, fluoride ceramic lasers, selenide ceramic lasers in the 2–3 μm region, composite ceramic lasers for better thermal management, and single crystal lasers derived from polycrystalline ceramics. In this paper, we highlight some of these notable milestones and achievements and forecast the future in polycrystalline ceramic laser materials.

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1. Introduction

Since the first discovery of solid-state lasers in 1960 [1], much effort has been focused on developing high quality laser gain materials mainly based on single crystals. Due to high thermal conductivity, chemical stability, ease of machining, and excellence in laser energy–conversion efficiency, crystalline lasers such as yttrium aluminum garnet ($Y_3Al_5O_{12}$) (YAG) and Ti:sapphire are widely used in various industrial applications including semiconductor industry, steel industry as well as medical industry. However single crystals are generally grown from the melt, and they suffer from drawbacks such as segregation of the dopant from the host, optical inhomogeneity caused by stress during crystal growth and high cost and low productivity due to high temperature processing. It was not until 1964 that the first solid-state laser fabricated from polycrystalline ceramics using Dy:CaF_2 was reported [2]. Since then, a tremendous amount of effort has been made to realize high power lasers suitable for various commercial as well as military applications. In fact, ceramic Nd^{3+}:YAG has been recently fabricated and used to demonstrate 67 kW [3] and >100 kW [4] of output power at 1.06 μm, respectively. Although there are some remaining issues in ceramic lasers such as lack of availability of high quality commercial raw powders and immature technology for making laser-grade perfect ceramics, polycrystalline ceramics are advantageous over single crystals in many ways. The process is simple, cost effective, and typically carried out at lower temperature. More importantly, much higher doping concentrations in ceramics can be obtained without phase segregation as we often observe in single crystals [5]. In this paper, we discuss the notable achievements and progress in solid state lasing using ceramic materials.

2. History of ceramic laser materials

While the physical and optical properties of ceramic YAG have been improved so that it is now comparable, if not better, than single crystal YAG, the earlier ceramic lasers were of inferior quality and not necessarily made from YAG. The following highlights some key milestones in the development and demonstration of lasing using ceramic materials.

2.1. 1964 – the 1st ceramic laser

Hatch et al. [6] were the first to demonstrate lasing in a ceramic, in this case Dy^{2+}:CaF_2. The ceramic was made by vacuum melting the tri-fluorides, grinding the product into a powder of 150 μm particle size, hot pressing the powder in vacuum and finally reducing the product to Dy^{2+} using 0.25 MeV x-rays. The ceramic product contained relatively large grains of 150 μm, implying no grain growth, and lased at liquid nitrogen temperature upon flash lamp pumping with a threshold of 24.6 J. CaO scattering centers were identified at the grain boundaries which contributed to 2% scattering loss in the visible and subsequently limited the laser performance.

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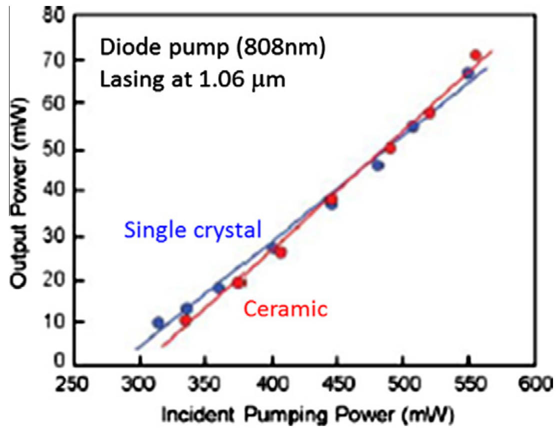

Fig. 1. Results of the first Nd:YAG ceramic laser (after [8]).

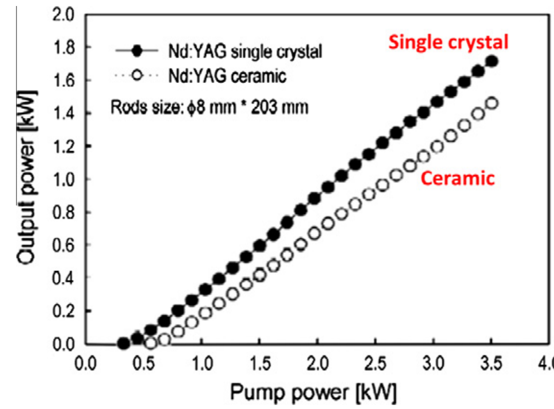

Fig. 2. Results for first Nd:YAG laser to break 1 KW output power (after [10]).

2.2. 1973 – the 1st oxide ceramic laser

It took about another 9 years for the second demonstration of lasing using a ceramic [7]. This was based on 1%Nd_2O_3 doped Yttralox (10%ThO_2–89%Y_2O_3), whereby the ThO_2 was used to control grain growth. Greskovich and Chernoch [7] synthesized submicron powder ($\leqslant$0.1 µm) using co-precipitation of oxalates and then sintered the powders under hydrogen gas at 2170 °C. The ceramic had large sized grains (130 µm) and high scattering loss of 5–7 cm^{-1} attributed primarily to index inhomogeneity since the pore volume was relatively low (1 ppm) and the pores were only 1 µm. Despite this, the flashlamp pumped ceramic lased with a slope efficiency of ~0.1%.

2.3. 1995 – 1st ceramic YAG laser

Ikesue et al. [8] were the first to demonstrate lasing in YAG ceramic doped with 1.1 atomic percent Nd. They synthesized pure, submicron oxide powders (Y_2O_3 – 60 nm, Al_2O_3 – 400 nm, and Nd_2O_3 – 500 nm) with <100 ppm-wt impurity content and performed a thorough analysis of the densification dynamics via vacuum sintering. Several recommendations came out their work. Examples include the use of 320 ppm SiO_2 sintering aid, ball milling with high purity alumina balls, spray drying the powders, and sintering at 1700 °C to get full densification and complete conversion of the starting oxides into the YAG phase ($Y_3Al_5O_{12}$) via the intermediate $Y_4Al_2O_9$ and $YAlO_3$ phases. They also recommended rapid quenching to prevent impurity phase segregation at the grain boundaries. Their process is often called "Reactive Sintering" since they started with the individual oxides and converted them to YAG during sintering. The ceramic grain size was ~50 µm, with pores less than 5 µm in diameter, a total pore volume estimated at 200 ppm and measured scattering loss of 0.9%/cm. Continuous wave (CW) lasing was observed at 1.06 µm with a slope efficiency of 28% using GaAlAs diode laser pumping at 808 nm (Fig. 1). The efficiency was similar to the value obtained for their single crystal sample. The ceramic also possessed very similar physical, mechanical and optical properties to the single crystal sample.

2.4. 2001 – Nd:YAG ceramic laser using precipitated powder

Lu et al. [9] diode pumped a 1%Nd:YAG ceramic and demonstrated lasing at 1064 nm with an output power of 72 W and slope efficiency of 24.8%. This result was obtained using submicron 1%Nd:YAG powder that was synthesized by Konoshima Chemical Co. via a co-precipitation process followed by calcination, ball milling, slip casting and vacuum sintering. Their ceramic had a small grain size with 1 nm grain boundaries, a pore volume of only 1 ppm and the thermally induced birefringence observed at high pump power similar to a single crystal.

2.5. 2002 – breaking the 1 KW output power barrier

In 2002, a group led by Ueda, in collaboration with Toshiba and Konoshima Co., achieved a milestone by demonstrating an output power of 1.46 KW using a Nd:YAG ceramic [10]. The slope efficiency was 42% and only slightly lower than the 49% obtained for a single crystal (Fig. 2). The rod was 8 mm in diameter and 203 mm long. The high quality of the rod was attributed to improvements made in powder synthesis and sintering.

2.6. Microchip lasers

Dong et al. [11] have studied heavily Yb-doped YAG ceramics. For example, they demonstrated a slope efficiency of 52% for 1-mm-thick YAG ceramic doped with 20 atomic percent ytterbium ions. Heavy-doped Yb:YAG ceramic is more suitable for a thin disk laser than a single-crystal with the same Yb^{3+}-ion lasants. They have also improved upon this and demonstrated up to 61% efficiency. In another example, they demonstrated a decrease in efficiency with increasing Yb content, albeit a 10% doped sample had an efficiency of 85% (Fig. 3). The decrease of slope efficiency at higher Yb-doping concentration (10% versus 20%) was caused by the increase of the thermal population at the terminated lasing level and the thermal lens effect. The serious heat generated in the highly doped gain medium is the main factor to limit the laser performance at room temperature without sufficient cooling for the samples.

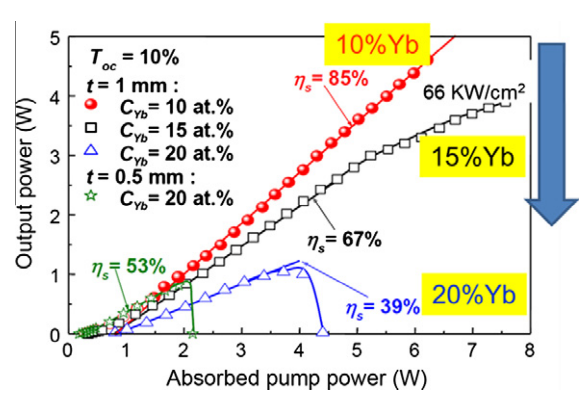

Fig. 3. Highly doped Yb:YAG ceramic lasers (after [11]).