Direct Bonding Nd:YAG to Sapphire Wafers

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Abstract: We demonstrate chemical-assisted direct bonding of 450µm-thick neodymium-doped YAG to 660µm-thick sapphire wafers. Diced, polished and AR-coated the composite was trialed in a pump-guided free-space laser. Preliminary performance and future prospects will be discussed.
OCIS codes: (130.0130) Laser materials; (160.0160) Materials; (160.4670) Optical materials; (140.0140) Lasers and laser optics.

1. Introduction

The process of direct bonding of dissimilar materials for active devices has been proven for some time now, however there has been very little reported in the literature about how this process is actually achieved. Two companies in the US have dominated the market in producing composite structures based upon the direct bonding approach with few, if not no, other suppliers of such devices. In recent years there have been a several groups reporting room temperature bonding of various materials [1, 2] all with the aim of enhancing the optical functionality of a certain materials through the combination of key features, such as thermal or physical properties. In this work we present a chemical-assisted method for activating two oxide crystals followed by their direct bonding without any active agent to join them, rather relying upon van der Waals forces initially followed by a thermal anneal to consolidate the bond strength. In the example studied we bond together a thin 1.3at.% Nd:YAG crystal to a section of a sapphire wafer, the composite was then cut, polished, and anti-reflection coated, shaped into a format suitable for diode-end-pumping and lasing. The aim was to create a structure that would capture and guide the slow-axis-dimension of a diode-laser array (bar), and as such form a pump waveguide. While at the same time provide sufficient thickness in this axis to allow a free space laser mode to pass unfettered, essentially a 1-dimensional version of the mm-diameter crystal rods [3]. A sturdy composite structure was realized and preliminary tests undertaken to demonstrate feasibility.

2. Methodology

The versatility of direct bonding has allowed its application to a wide variety of design requirements. Here, the aim was to develop a high-strength bond, capable of resisting subsequent invasive machining. The primary mechanism behind direct bonding relies on the macroscopic dispersion van der Waals forces. Through suitable activation stages, this can be enhanced via the presence of longer-range hydrogen bonds. Post-bonding, annealing treatments can then be conducted to develop covalent bonds between surfaces, depending on the materials in question. For this project, chemical-assisted direct bonding, coupled with high temperature annealing, was chosen to maximize the potential bond strength. The presence of Alumina in both materials allows for the development of oxygen-rich surfaces through chemical activation, which in turn can be developed into high-strength, covalent bonds through annealing stages. Figure 1 (A) shows a basic representation of the bond-strengtherning process. An appropriate annealing process was determined to achieve the required bond strength and resistance to liquid for subsequent mechanical dicing and polishing processes.

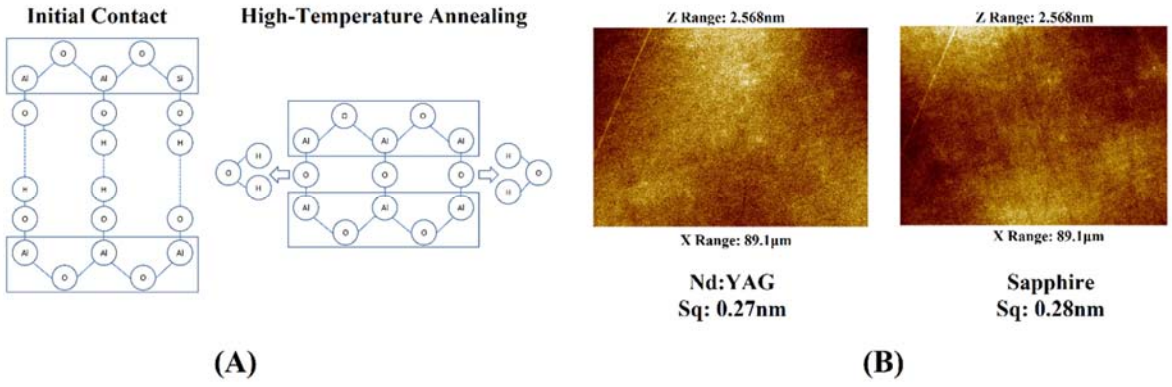

Figure 1: (A) Simplified map of the bonding process, showing the transfer from van der Waals and hydrogen bonds to covalent bonding during high temperature annealing, (B) 2D surface maps for the sapphire and YAG bonding faces, where Sq is the recorded RMS roughness

3. Direct bonding

2.1. Surface Quality

To facilitate direct bonding, surfaces to be joined require precision polishing to the nanometer scale. Typically, a flatness of at least λ/10 (@ 633nm) with a root mean square (RMS) roughness of ~1nm is desired for successful bonding. Sapphire and YAG surfaces were inspected using a Zescope white light interferometer. Figure 1 (B) shows 2D surface maps of the bonding faces. RMS roughness at 50x magnification was recorded for each material as 0.28nm and 0.27nm, respectively. Both values were deemed suitable for direct bonding, furthermore the small thickness and pliability of each material provides additional compensation for flatness differences.

2.2. Activation & Contact

Prior to bonding, a comprehensive cleaning and activation process was conducted in a class 1000 cleanroom. First, the sapphire and YAG samples were subjected to an extended ultrasonic solvent clean of Acetone, IPA and de-ionised (DI) water. Bonding faces were then activated using a short, two-stage plasma of oxygen and nitrogen. Nitrogen plasma has been shown to bombard bonding surfaces, removing organic contaminants and encouraging development of a hydrophilic surface state through dangling bonds [2]. Finally, samples were submerged in a 1% hydrofluoric acid bath before being thoroughly rinsed with DI Water. A pure nitrogen line was used to dry both faces before contact was completed. Figure 2 (A) shows a bonded YAG/sapphire composite. Inspection of the interface revealed a number of trapped voids from the bonding process. Further bonding attempts using the same procedure were conducted to refine this process, reducing the void quantity.

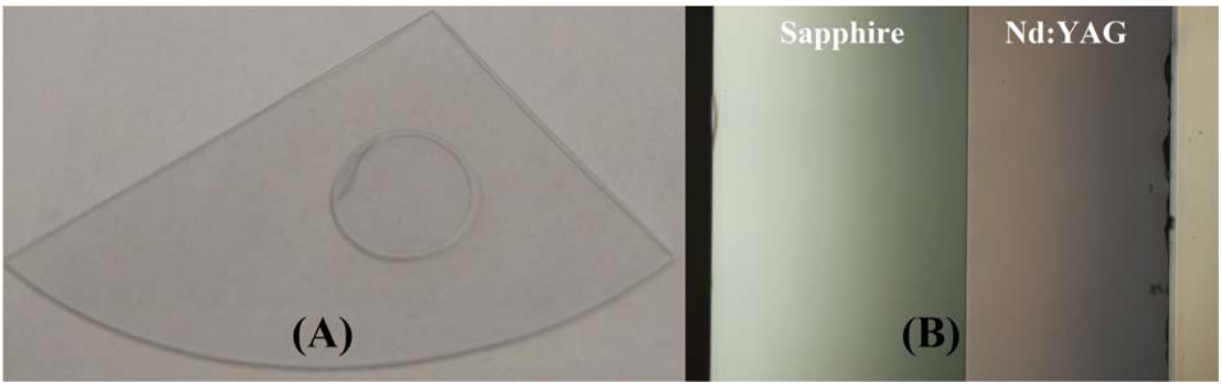

Fig 2 (A) Bonded Nd:YAG and sapphire, (B) 10x microscope inspection of the diced and coated end facets. Some chip damage is noted along the outer edges of the composite

2.3. Bond Strengthening

In order to achieve a suitable bond strength for machining, a high temperature annealing stage was required. After 24 hours under pressure, the bond was ramped to 800°C in a nitrogen atmosphere and annealed for several days. This process transfers the primary bonding mechanism from hydrogen and van der Waals forces to covalent bonds, dramatically increasing the bond strength.

3. Post-bond Machining

Following annealing, the composite was diced using a precision wafer-saw to dimensions of 8x6 mm, with a total thickness of 1.1 mm. Dicing induced some minor chip damage to the edge of the sapphire and YAG faces, however inspection of the bond interface showed no deterioration. End facets were then in-house lapped and polished in slurry using a cast iron lapping plate followed by a polyethylene plate, respectively. The bond's resistance to damage during these abrasive procedures demonstrates the excellent strength achieved from this direct bonding process. Finally, a quarter-wave anti-reflection (AR) coating of MgF_2 was evaporated onto the polished faces. Figure 2 (B) shows the polished end facets following deposition of the AR coating.

4. 869 nm pumped 1.064 μm laser

To further test the bonds capabilities, a 1064nm oscillator was constructed, using the bonded Nd:YAG as a gain medium. The sapphire surface of the bonded composite was soldered to a copper heatsink. The structure was end-pumped using a 50 W diode-laser-bar, (19 emitters, 50% fill-factor 9.5 mm bar-width), wavelength locked to 869 nm

via a Volume Bragg Grating to match the zero-phonon line of Nd:YAG. Figure 2 (A) shows the setup. The fast- and slow-axis (FAC/SAC) collimated diode-laser output was focused by an aspheric cylindrical lens (NA = 0.55), L1, f = 10mm, through the in-coupling dichroic mirror M1, into the 450 μm-thick Nd:YAG layer, which has a numerical aperture of 0.47. Defining the tangential axis as the one guided in the YAG layer, the sagittal axis was unconditioned after the FAC, that is it was allowed to propagate 200 mm before reaching the medium, with a ~1 mm second-moments full-width in the sample. The position of the bonded composite to optimize the pump-launch, and a simple V-cavity configuration configured with M2, the turning mirror, angled at ~17 ° in the tangential plane, and which had a 200 mm radius of curvature. A flat 85% reflective output coupler mirror, M3, was positioned in order to maximize the lasing output. This preliminary configuration, was primarily configured to test the quality of the bond and realise laser output. Lasing on the dominant 1064nm line, the beam at the output coupler, was reimaged via a telescope system onto a CCD camera, enabling the cavity modes to be assessed. The bonded composite showed no signs of deterioration with over 40W of incident pump power, for which over 90% was expected to be absorbed. Over 5W of output power was recorded. Figure 3 (B) shows the lasing composite, viewed through an RG1000 longpass filter. The 1064nm fluorescence is clearly visible within in the Nd:YAG layer.

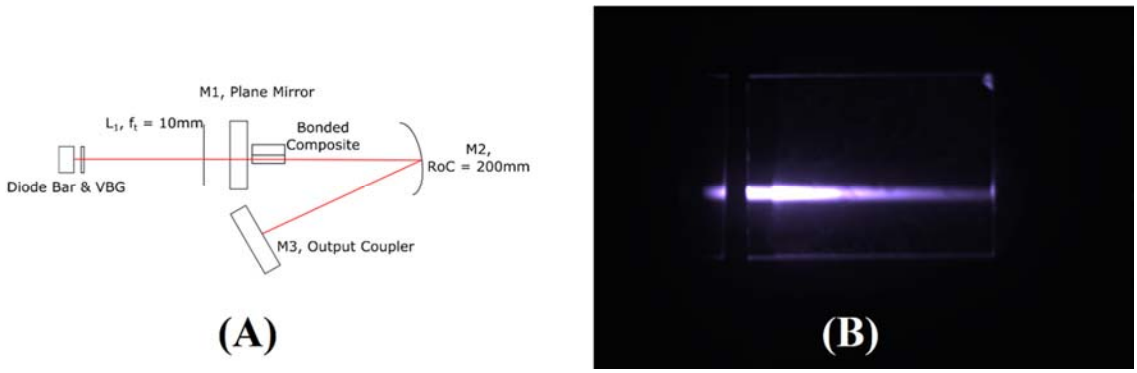

Fig 3 (A) Setup for the bonded composite laser, (B) 1064nm fluorescence visible from the lasing Nd:YAG layer

4. Conclusions

We successfully demonstrate a robust direct-bonding of Nd:YAG to sapphire through a chemical-assisted approach. The strength of the bonded composite is proven through its resistance to subsequent mechanical processing steps and AR coating, showing that the bond is both rigid and resistant to liquid exposure. A pump-guided 1064nm free-space laser-oscillator was constructed using the composite as the gain medium, extracting heat from the Nd:YAG layer through the bonded sapphire substrate. The bond is resilient to >40W of incident pump-power coupled into a cross section of 0.45 mm x 1 mm. Further characterization of the thermal lens and performance of the laser system are ongoing and will be presented along with further power scaling prospects.

5. References

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