Direct Bonding Nd:YAG to Sapphire Wafers

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Abstract: We demonstrate chemical and plasma-assisted direct bonding of 450μm-thick 1.3at.% neodymium-doped YAG to 660μm-thick sapphire wafers. Bonded composites survive extreme environments as well as abrasive mechanical processing. Diced, polished and AR-coated, the composite was trialled in a pump-guided free-space laser.

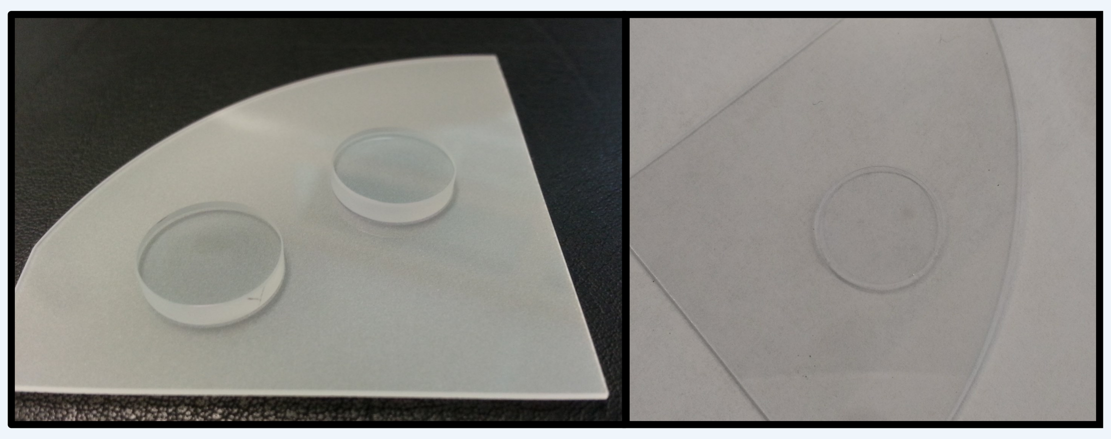


Figure 1: Bulk 4mm thick Nd:YAG and 450μm bonded to sapphire wafer

Motivation

- Investigate & develop a repeatable and resilient bonding procedure
- Join dissimilar crystals, such as YAG and Sapphire, to make a composite structure
- Demonstrate bond resistance to temperatures, physical environments and mechanical processing
- Produce an active device to show heatsinking capabilities of bonded devices

1. Why direct bonding?

- Direct bonding offers a 'universal' technique capable of joining a wide range of materials with no intermediate layer
- Direct bonding has been demonstrated between various materials[1,2,3] including glasses, crystals, metals and plastics, which enable joining of similar or dissimilar materials
- Sapphire's high thermal conductivity is twice that of Nd:YAG. A thin, heat-spreading layer of sapphire can be joined to an active Nd:YAG layer for use in high-power operation.

2. Surface finish and bond activation

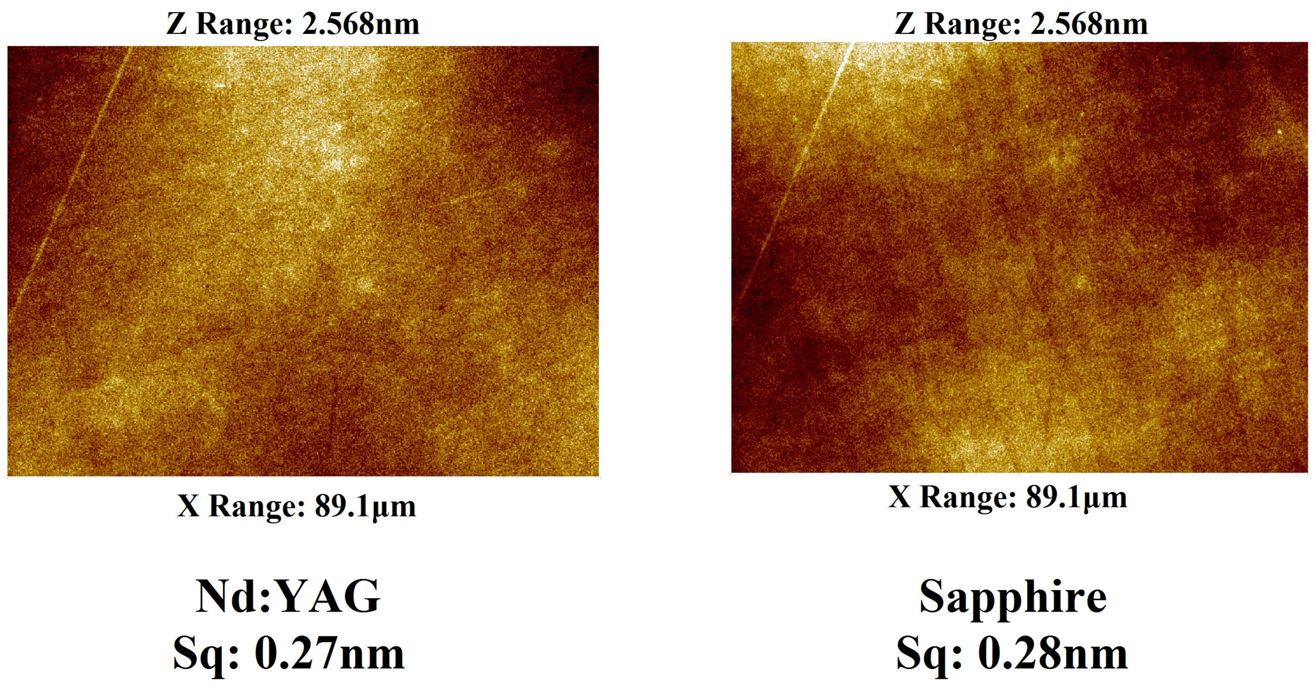


Figure 2: Surface profiles for bulk Nd:YAG and sapphire wafers used in bonding trials. S_q is the RMS surface roughness

- Direct bonding relies on short-range van der Waals forces, requiring intimate, nanometre separation
- Faces to be bonded require strict polishing to minimise roughness and maximised flatness
- Both 4mm and 0.45mm thick x 12mm ϕ YAG samples were bonded to 0.66mm thick sapphire wafers

Figure 3: (A) A diced 8x6x1.2mm composite of bonded Nd:YAG and sapphire wafer next to typical hand tweezers for scale, and (B) Microscope image of the AR-coated bond interface

- Cleaning, activation & bonding were conducted in a class 1000 clean room
- Surfaces undergo rigorous solvent cleaning
- Multiple activation routes tested, including piranha etch, plasma and HF
- Successful bonds were completed with both HF and N2/O2 plasma activation

3. Developing a resilient bond

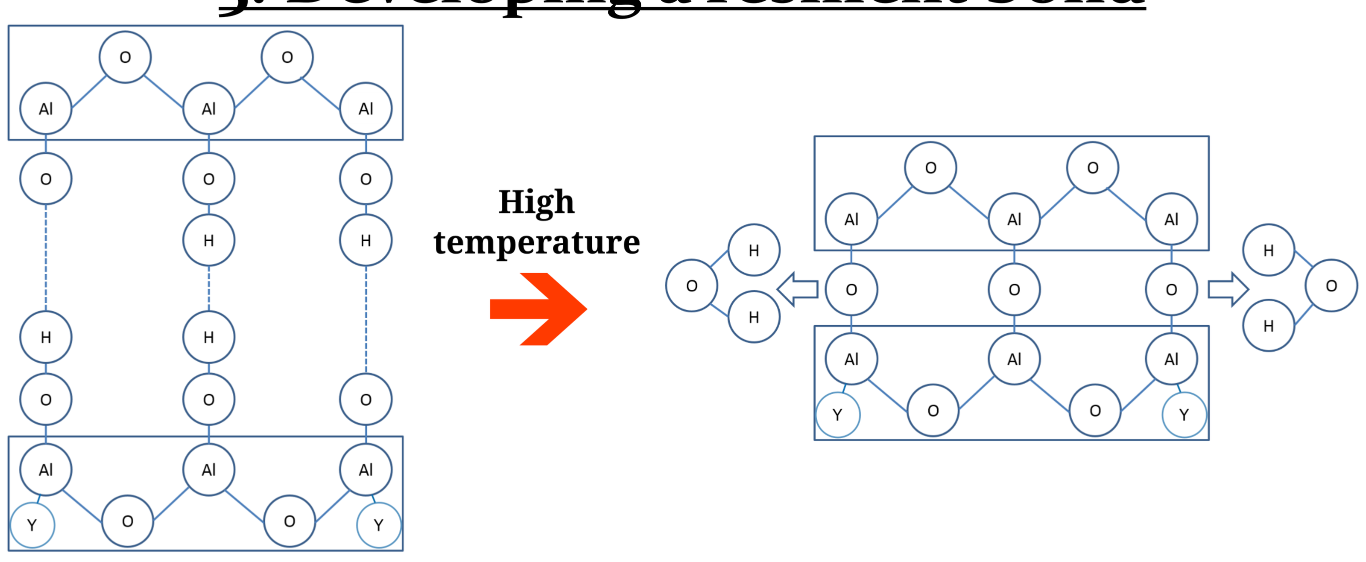
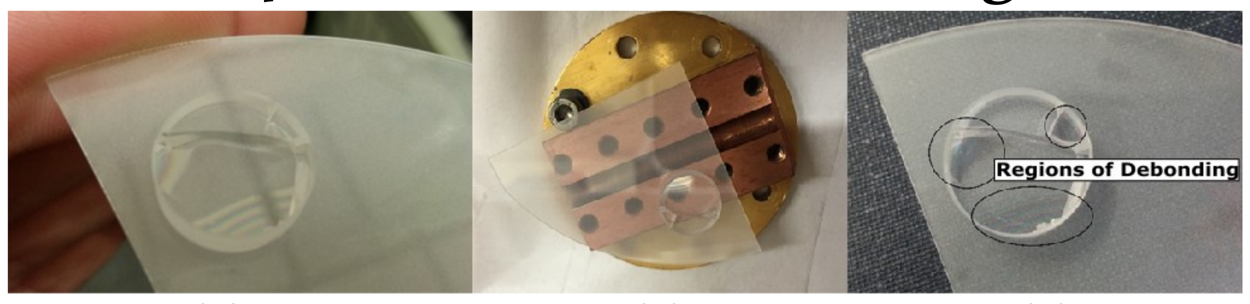


Figure 4: A simplistic representation of the bond transfer during high-temperature annealing

- The bond is strengthened through extended (50+hr), high-temperature (800°C) annealing
- As temperature increases, hydroxyl groups disassociate from the surface, transferring the transient hydrogen and vdW bonds to rigid covalent bonds
- Bond strength is increased to survive submersion, ultrasonic treatment, dicing and cryogenic cooling

4. Environmental testing



(A) (B) (C)

Figure 5: A bonded YAG/Sapphire composite with debonded regions (A) before cooling, (B) mounted on the cryo holder, and (C) after cryo cooling

- Imperfectly bonded composites were tested in a series of environmental trials. Ultrasonic solvent submersion as well as elevated temperatures produced no change to the bonds, showing strong resilience
- A YAG to sapphire bond which showed interference patterns in certain regions was cooled in a vacuum chamber to −180°C and left for several days. Despite these regions being potential failure points, no change was noted in the bond interface

5. 869nm pumped 1.064μm laser

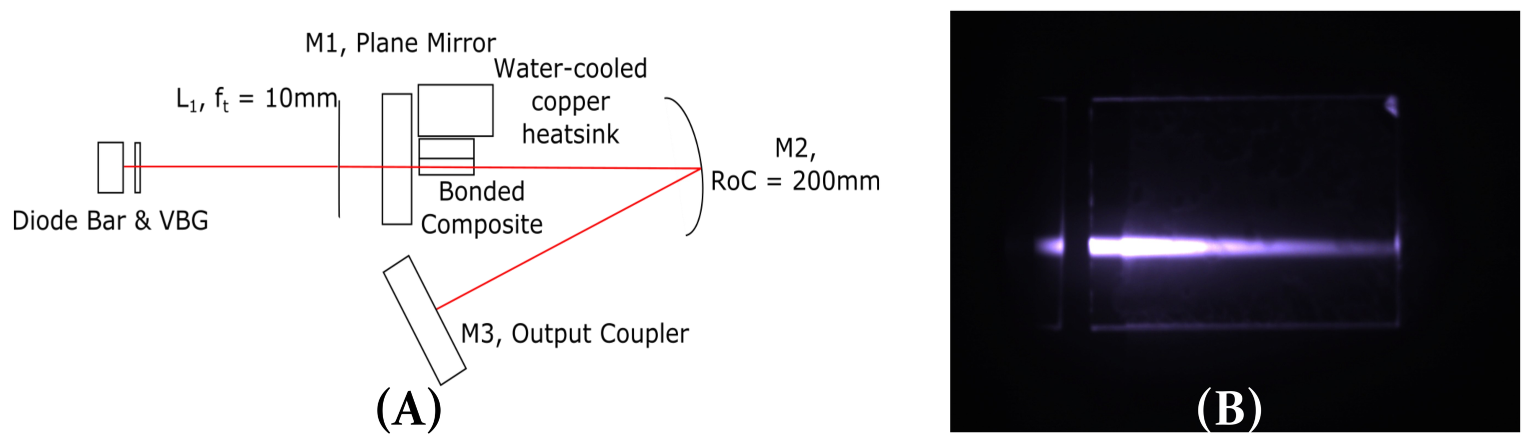


Figure 6: (A) Setup diagram for the 1.064μm laser and (B) Fluorescence from the top of the composite, whilst lasing, viewed through a long-pass filter

- The sapphire layer was soldered to a liquid-cooled copper heatsink
- Planar structure guides the slow-axis of the diode pump laser beam, with free-space propagation for the other. The pump was focussed to 390μm x 1mm, with slow axis waist positioned at the facet
- Laser cavity optimised for a 145 micron mode radius in the composite
- Laser performance was characterised with and without pinhole to isolate the diffraction-limited portion

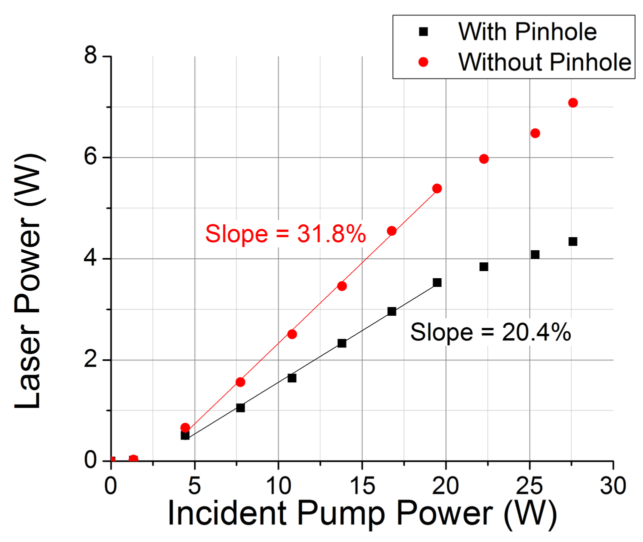


Figure 7: Slope efficiencies recorded for the laser output with and without a pinhole around the central beam

- Slope efficiencies recorded showed that 34% of the power was diffracted out from the fundamental mode
- This was believed to be due to warped end facets of the YAG leading to diffraction losses, which also limited the laser performance
- 3D surface profiles were recorded across the coated end facets showing clear aberrations across the surface of P-V 450nm. This was present on both end facets
- This would distort the beam during multiple cavity trips, resulting in power diffracted outward
- Stricter polishing standards are required for both end facets before coating for laser experiments

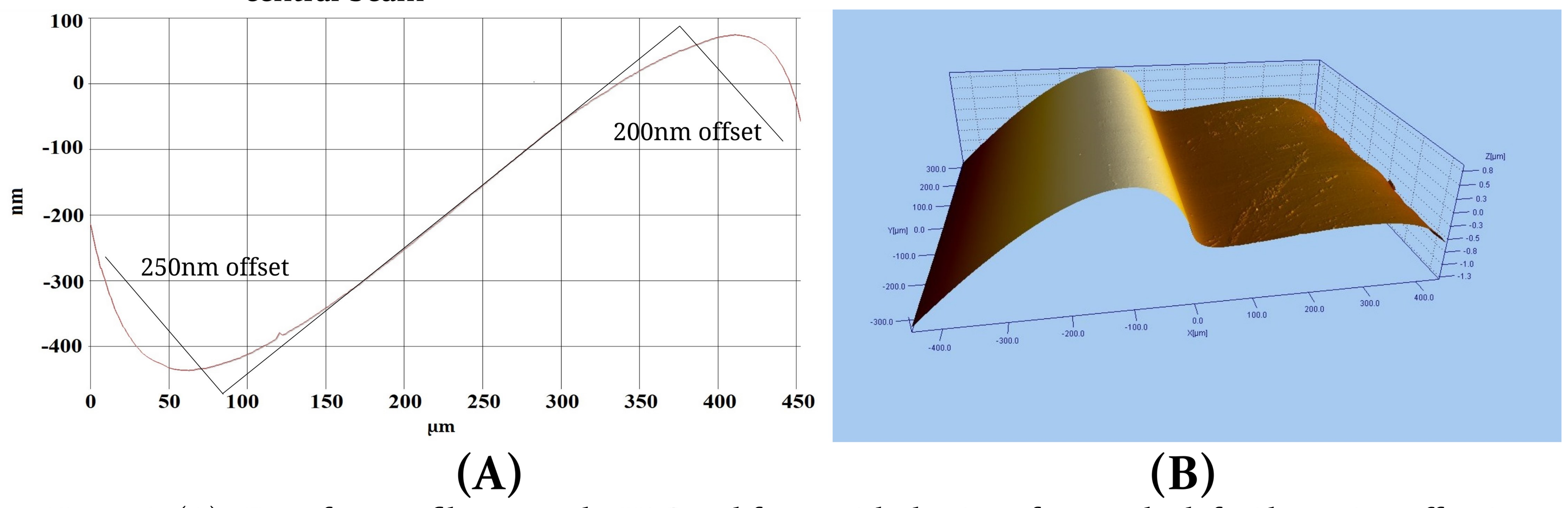


Figure 8: (A) 2D surface profile across the YAG end facet, with the interface on the left. Aberration offset is shown at each edge. And (B) a 3D surface profile of the YAG and sapphire end facets. The sapphire is raised due to slower abrasion rate when polishing

6. Summary

- We have successfully bonded Nd:YAG and sapphire using both wet chemical and plasma activation.
- The bonded composites were tested in a variety of environments, surviving temperature extremes and abrasive mechanical processing
- A diced and polished composite was built into a diode-pumped laser oscillator
- No evidence of damage observed for an incident irradiance of 6.75kW/cm², or thermal loading density of 4.74kW/cm³

References

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[2] L. Zheng, A. Kausas, and T. Taira, "Drastic thermal effects reduction through distributed face cooling in a high power giant-pulse tiny laser" *Optical Materials Express*, 7(9), 2017.

[3] D. Li, H-c. L, S. K. Meissner, D. J. Meissner, and H. E. Meissner, "Adhesive-free bond (AFB) true crystalline fiber waveguides and walk-off compensated nonlinear crystal stacks: optical components for high performance lasing and frequency conversion," *Optical Materials Express*, 7(8), 2017