Supporting Information

976 nm continuous-wave laser damage of Er:CaF2 crystal

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Figure S1. Absorption spectra of crystals with different ion doping concentrations

S2 Continuous laser damage test



Figure S2. Schematic of continuous laser damage test setup

Figure S2 shows the device used for continuous laser damage threshold testing at a wavelength of 976 nm. The pump source was a laser diode with a central wavelength of 976 nm (BWT, DS3-51512-K976AASRN). The maximum output power of the laser is 60 W (Dcore = 105 µm, N.A. = 0.22). The operating modes included continuous wave, single pulse, and multiple pulses. In practical applications, the single-end pumping method using laser laser diode is typically employed for simplicity of construction, good beam quality, and favorable spatial mode. This experiment also utilized the single-end pumping technique. A beam attenuation system was added to the collimation section, and an equivalent optical path, separated by wedge prisms, was employed in the optical path. The beam profile was measured using an Ophir and Spiricon beam analyzer. The spatial distribution of the laser beam approximated a Gaussian distribution, with a 1/e2 beam diameter of 160 µm at the focal point. The experiment was conducted in the air, where the pump light focused on the crystal surface through a coupling system consisting of two lenses. To determine the damage threshold of crystals under practical conditions, the crystal was wrapped in thin indium foil and mounted in a copper heat sink module with a circulating water maintained at a constant temperature of 12°C. During the experiment, the incident and transmitted power were recorded, and surface changes in the material were observed using a CCD camera. The temperature of the pumped end face of the crystal was monitored using an infrared thermal imager.

When the crystal is damaged, The absorption of light by the crystal is greatly increased by the creation of cracks, at which moment the power of transmitted light drops significantly. The FLIR detects a sharp rise in temperature of end face, indicating damage, the crystal is irradiated for 60 s (Thermal equilibrium of crystals irradiated by lasers with different pump powers for this duration) and then the irradiation is stopped to check if any damage has occurred. Given the dramatic effect of temperature gradients on material stress, it is important to allow the crystal to cool completely before increasing the incident laser power and repeating the test until damage occurs at a specific pump power level.

S3 Finite element calculation model



**Figure S3.** Modeling of high-power continuous laser irradiated crystals

A coupled thermal-mechanical physical model was established, allowing for the calculation of temperature distribution and stress distribution in the crystal at different time points, as shown in Figure S3. The laser is focused on the surface of Er:CaF2, with the laser beam vertically incident on the sample surface (Z = 0), and the center of the laser beam coincides with the center of the sample. The dimensions of the CaF2 model are 3×3×8 mm3.

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| **Property** | **Value** |
| Density (Kg/m3) | 3180 |
| Specific heat (J/kg**·**K) | 911 |
| Young modulus (Gpa) | 110 |
| Poisson ratio | 0.29 |
| Thermal conductivity [W/m**·**K] | 9.71 |
| Linear expansibility (K-1) | 18.85**·**10-6 |
| Melting point (K) | 1635 |
| Compressive strength (MPa) | 300 |
| Tensile strength (MPa) | 34 |

Table S1. CaF2 Parameters used in finite-element numerical calculations[1]



Figure S4. The maximum temperature of 2 at.% Er:CaF2 crystals, as a function of time at a pumping power of 8 W, was obtained through calculations using a (a) finite-element model and (b) measurements using a thermal imager.

S5 Pump face temperature profile



Figure S5. The three-dimensional finite-element simulation model is used to calculate the temperature profile on the pumping end face of crystals with different doping concentrations, ranging from 4.17 W to 16.50 W in the x-axis direction.

Temperature along the x-direction on the crystal surface for different pump powers is show in Figure S5. When the pump power increases from 4.17 W to 16.50 W, the center temperature on the pump face of 1 at.% Er:CaF2 rises from 43 °C to 104 °C, while the center temperature of 2 at.% Er:CaF2 crystal on the pump face increases from 73 °C to 218 °C. It can be observed that the temperature gradient also increases continuously as the pump power increases. The temperature gradient serves as the direct cause of thermal stress generation, and its increase indicates a continuous rise in stress levels.

References

1. C. Li, X. Kang, W. Han, W. Zheng, and L. Su, "Nanosecond laser-induced surface damage and material failure mechanism of single crystal CaF2 (111) at 355 nm", Applied Surface Science 480, 1070-1077 (2019).