Cr⁴⁺:YAG double-clad crystal fiber laser

Chien-Chih Lai,¹ Hann-Jong Tsai,² Kuang-Yao Huang,¹ Kuang-Yu Hsu,¹ Zhi-Wei Lin,² Kuan-Dong Ji,² Wen-Jun Zhuo,² and Sheng-Lung Huang^{1,3,*}

¹Institute of Photonics and Optoelectronics, National Taiwan University, Taipei 106, Taiwan

²Department of Photonics, National Sun Yat-Sen University, Kaohsiung 804, Taiwan

³Department of Electrical Engineering, National Taiwan University, Taipei 106, Taiwan

*Corresponding author: slhuang@cc.ee.ntu.edu.tw

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We report what we believe to be the first demonstration of a room-temperature, continuous-wave Cr⁴⁺:Y₃Al₅O₁₂ (Cr⁴⁺:YAG) double-clad crystal fiber laser grown by the codrawing laser heated pedestal growth method. The threshold is below 100 mW, which is a factor of 4 lower than previously reported Cr⁴⁺-doped lasers. A slope efficiency of 6.9% was obtained, and is in good agreement with the numerical simulation. In addition to small core diameter, the low-threshold lasing is made possible by the low propagation loss of 0.08 dB/cm and the high crystallinity of the core. © 2008 Optical Society of America

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Chromium-ion-doped laser gain media have a broadband nature because of the nonscreened electronic configurations. For future ultrabroadband fiber communication systems, a broadly tunable laser is essential to offer wavelength-on-demand, dynamic wavelength ports, and simplified inventory managements. Among all the Cr⁴⁺-doped gain media, Cr⁴⁺:Y₃Al₅O₁₂ (Cr⁴⁺:YAG) has shown a high concentration of tetrahedrally coordinated Cr⁴⁺ ions and a high emission cross section in fiber communication bands [1–4], although most reports of bulk Cr⁴⁺:YAG lasers showed lasing actions at low temperature [1,5–8] or with rather high thresholds from 0.4 to 4 W. The threshold pump power increases as the bulk temperature rises owing to the decrease in fluorescence lifetime. The fiber waveguide offers better heat dissipation because of the high surface-to-volume ratio of the gain medium [9,10]. Of particular importance, with Cr⁴⁺:YAG as the core and silica as the cladding, it has been shown that the near-infrared (NIR) ultra-broadband emission from 1.1 to 1.6 μm generated by the core can be easily guided owing to the large fractional index change at the core–inner-clad interface [3,4]. Here we show the first demonstration of a Cr⁴⁺:YAG double-clad crystal fiber (DCF) laser grown by the codrawing laser heated pedestal growth (CDLHPG) method with a lasing threshold of 96 mW and a slope efficiency of 6.9% at room temperature (RT) operation.

The sample was initially prepared from a 0.5 mol. % doped Cr⁴⁺:YAG source rod in [111] crystal orientation. With two diameter reduction steps by the laser-heated pedestal growth (LHPG) method, a 68 μm Cr⁴⁺:YAG core was grown and then inserted into a fused silica capillary with 76 and 320 μm inner and outer diameters for the codrawing process by the same LHPG system to form a Cr⁴⁺:YAG DCF. The as-grown Cr⁴⁺:YAG DCF was placed inside a Cu holder, followed by impregnating with melting Al at 780 °C to form a Cu–Al alloy. The compositions profile and microstructure of the Cr⁴⁺:YAG DCF were then examined by an electron probe microanalyzer (EPMA,

JEOL JXA-8900R) and a field-emission high-resolution transmission electron microscopy (HRTEM, Tecnai G² F20, FEI). The refractive index and Cr⁴⁺ fluorescence were measured by a homemade multiwavelength confocal microscope using a 635 nm distributed feedback laser and a 1064 nm cw Yb:fiber laser as excitations.

Figure 1 shows a polished end face of a Cr⁴⁺:YAG DCF mounted in the Cu–Al alloy together with the corresponding line-scan composition profiles. The core, inner-, and outer-clad diameters are 20, 93, and 320 μm , respectively. A tremendous amount of Cu and Al ions diffuse into the inner-clad edge to form a Cu–Al alloy diffusion layer, showing the original SiO₂ outer cladding was entirely impregnated by the Cu–Al alloy, as presented in the left side of Fig. 1. This implies that the heat generated inside the DCF

Fig. 1. (Color online) Left, a polished end face of Cr⁴⁺:YAG DCF, accompanied by with the corresponding line-scan distribution of major compositions; right, an [111] HRTEM image taken in the core region. The inset shows the SAED pattern.

can be removed to improve the DCF laser performance at RT. The image in the right side of Fig. 1 is an [111] HRTEM image taken in the core region. The inset shows the corresponding selected area electron diffraction (SAED) pattern, and the sharp bright diffraction spots demonstrate that the core region has a nearly perfect YAG single crystal structure grown by the CDLHPG method, as confirmed by a measured lattice parameter $a = 12.008 \text{ \AA}$ (Joint Committee on Powder Diffraction Standards file 33-0040). Figures 2(a) and 2(b) show the corresponding refractive index and Cr^{4+} fluorescence mappings of Cr^{4+} :YAG DCF end face in Fig. 1. Figure 2(c) shows the refractive index profile of the inner cladding, corresponding to the SiO_2 concentrations from 15 to 20 wt. %. The refractive index of the core is 1.82, which is about the same as that of a single crystal YAG. The refractive index of the outer cladding is from 2.2 to 2.4, resulting from the Cu–Al alloy with 20 wt. % CuO and 80 wt. % Al_2O_3 . The fluorescence distributions in Figs. 2(b) and 2(c) show that the majority of the Cr^{4+} fluorescence is concentrated within the core region, whereas the inner cladding region has negligible fluorescence.

To investigate the lasing behavior of the Cr^{4+} :YAG DCF, a 16.5 mm long DCF was prepared. A cw Yb: fiber laser at 1064 nm was initially focused by a $10\times$ objective and then coupled into a standard single-mode telecommunication fiber (SMF-28) followed by a thin-film-based 1060/1550 coupler to monitor the lasing spectrum by an optical spectrum analyzer. The SMF-28 fiber that carried the pump beam was butt-coupled to the core of the Cr^{4+} :YAG DCF through a dichroic-coated front face. The DCF laser output and the pump beam were collimated by a 10 mm achromatic lens and further filtered by a long-wavelength pass filter before being detected by a photodetector. The lasing characteristics of the Cr^{4+} :YAG DCF la-

Fig. 2. (Color online) (a), (b) Refractive index and Cr^{4+} fluorescence mappings. (c) The corresponding line-scan profiles in (a) and (b), indicating an effective optical confinement of the excitation and NIR emission.

sers for two different output couplers are shown in Fig. 3. The threshold power increases from 69 to 96 mW when increasing the output coupler transmission from 2.5% to 3.8%. More than 10 mW of output power was achieved, and the slope efficiencies are 3.4% and 6.9% for $T = 2.5\%$ and 3.8% , respectively. At RT the 69 mW threshold power and 6.9% slope efficiency are among the record-low threshold and record-high slope efficiency reported for cw pumped Cr^{4+} :YAG lasers (bulk or fiber). The inset of Fig. 3 shows the lasing spectrum at 1421.16 nm with a side mode suppression ratio (SMSR) of 50 dB. Note that the 3 dB laser linewidth is less than 0.1 nm, which is limited by the resolution of the detection system.

To further extract parameters from the experimental data in Fig. 3, a simulation based on a four-level Cr^{4+} :YAG model was conducted. Using a lumped model, the upper-level population density, N_2 , and the intracavity photon intensity, I_c , can be expressed as [11,12]

$$\frac{dN_2(t)}{dt} = \frac{\sigma_a \lambda_p I_p}{hc} N_g(t) - \frac{\sigma_e \lambda_L I_c(t)}{hc} N_2(t) - \frac{N_2(t)}{\tau_f}, \quad (1)$$

$$\frac{dI_c(t)}{dt} = I_c(t) \left[\frac{c}{n_g} (\sigma_e - \sigma_{\text{ESA}}^{\text{sig}}) N_2(t) - \frac{c \{1 - [R_1 R_2 \exp(-2\alpha_{\text{PL}}^{\text{sig}} L_g)]\}}{2n_g L_g} \right], \quad (2)$$

where the pump intensity

$$I_p = P_{\text{in}} \eta_{\text{in}} \exp(-\alpha_{\text{PL}}^{\text{pump}} L_g) [1 - \exp(-\alpha_{p0} L_g)] / \pi r^2. \quad (3)$$

In Eqs. (1)–(3), λ_p , λ_L , σ_a , σ_e , and N_g are the pump and lasing wavelength, the pump and emission absorption cross sections, and the electron density of the ground state, respectively. τ_f , h , and c are the

Fig. 3. (Color online) Lasing characteristics of the RT CW Cr^{4+} :YAG DCF laser. Inset is the measured lasing spectrum at an absorbed pump power of 275 mW with the corresponding SMSR of 50 dB.

temperature-dependent lifetime, the Planck's constant, and the speed of light in vacuum. n_g , L_g , R_1 , and R_2 , are the refractive index of the Cr^{4+} :YAG DCF core, the crystal fiber length, and the respective input and output coupler reflectances. $\alpha_{\text{PL}}^{\text{pump}}$ and $\alpha_{\text{PL}}^{\text{sig}}$ are the propagation loss at λ_p and λ_L . P_{in} , η_{in} , and r represent the incident pump power, the input pump coupling efficiency, and the mode radius of the Cr^{4+} :YAG DCF. $\sigma_{\text{ESA}}^{\text{sig}}$ and α_{p0} are the excited-state absorption cross section at λ_L and the small-signal absorption coefficient at λ_p . The absorbed pump power, P_{abs} , is estimated by accounting the input and output pump coupling efficiency, η_{in} and η_{out} , pump light propagation loss, and excited state absorption cross section $\sigma_{\text{ESA}}^{\text{pump}}$ at λ_p . It can be expressed as follows:

$$P_{\text{abs}} = P_{\text{in}} \{ 1 - \eta_{\text{in}} \exp [- (\sigma_a N_g + \sigma_{\text{ESA}}^{\text{pump}} N_2 + \alpha_{\text{PL}}^{\text{pump}}) L_g] \eta_{\text{out}} \}. \quad (4)$$

The extracted best-fit values of σ_a and σ_e are 5.9×10^{-22} and $6.0 \times 10^{-23} \text{ m}^2$; $\sigma_{\text{ESA}}^{\text{pump}}$ and $\sigma_{\text{ESA}}^{\text{sig}}$ are 2.1×10^{-23} and $3.15 \times 10^{-23} \text{ m}^2$; η_{in} , η_{out} , and τ_f are 85%, 64%, and $3.75 \mu\text{s}$; α_{p0} , $\alpha_{\text{PL}}^{\text{pump}}$, and $\alpha_{\text{PL}}^{\text{sig}}$ are 1.0 cm^{-1} , 0.65 dB/cm , and 0.08 dB/cm ; and r , L_g , and n_g are $9.5 \mu\text{m}$, 1.65 cm , and 1.82 , respectively. These values are in good agreement with those obtained from Cr^{4+} :YAG bulk lasers [6,13–17]. Based on the extracted parameters, the slope efficiencies in terms of the crystal fiber length and output coupler reflectance are shown in Fig. 4. A mode radius r of $9.5 \mu\text{m}$ and α_{p0} of 1.5 cm^{-1} with η_{in} of 99% and η_{out} of 1% at λ_p , and R_1 of 99% at λ_L are employed in the simulations. A 10.6 cm Cr^{4+} :YAG DCF with a 42.4% output reflectance is computed for the maximum η_s of $\sim 50\%$ with a 95 mW threshold at 20°C . The simulation results indicate that the crystal fiber length is an essential factor to the laser efficiency.

Fig. 4. (Color online) Simulation of the slope efficiency η_s . A coated 10.6 cm Cr^{4+} :YAG DCF with a 42.4% output reflectance is computed for the maximum η_s of $\sim 50\%$ with a 95 mW threshold at 20°C . The black region represents no laser action.

In conclusion, Cr^{4+} :YAG crystal fiber laser with a double-clad structure has been successfully developed. The 69 mW threshold is the lowest, and the 6.9% slope efficiency is the highest as compared with previous bulk or fiber Cr^{4+} :YAG lasers at RT. The performance of this Cr^{4+} :YAG DCF laser can be further improved by optimizing the output coupler transmittance and crystal fiber length. This laser is a compact and low-cost solution for the NIR wavelength region.

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