Room-temperature watt-level and tunable ~3 μm lasers in Ho3+/Pr3+ co-doped AlF3-based glass fiber

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A room-temperature watt-level CW-output power mid-infrared multimode fiber laser operating at λ~3 μm is demonstrated using a Ho3+/Pr3+ co-doped AlF3-based glass fiber as a gain fiber. This fixed-wavelength laser had maximum output power of 1.13 W with a slope efficiency of 10.3% and a long-term operating stability of >40 minutes without any additional packaging or active thermal management. A fiber laser with tunability from 2.842 to 2.938 μm showed a maximum output power of 110 mW.

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Fiber lasers have attracted significant research interest because of their high efficiency, low threshold, good beam quality, superior thermal management, a simple and compact structure, and capability to operate in harsh environments. The mid-infrared (MIR) region around the wavelength λ~3 μm includes many important molecular absorption bands including water. A MIR laser source in this wavelength range has important applications in laser surgery, sensing and materials processing, and has been a research hotspot in last three decades [[1-9]](#A1). However, increasing output powers to watt levels is an ongoing challenge.

Many efforts have been done to get high MIR laser outputs. Fiber lasers at λ ~3 µm usually rely on the Ho3+:5I6→5I7, Er3+:4I11/2→4I13/2, and Dy3+: 6H13/2→6H15/2 transitions and have mainly focused on the ZrF4-BaF2-LaF3-AlF3-NaF (ZBLAN) glass host. Dy3+ offers wider wavelength coverage but lower outputs, while Er3+ offers higher powers. In 2003, Jackson reported continuous-wave Dy3+-doped ZBLAN fiber laser at λ~2.9 µm with a maximum output power of 0.275 W[[10]](#A10). In 2007, Zhu *et al.* reported a tunable Er3+ -doped ZBLAN MIR fiber laser with 2 W output and a 2.7–2.83 µm tunability range [[11].](#A11) In 2010, Tokita *et al.* reported a tunable Er3+ -doped ZBLAN fiber with 10 W output and a 2.77–2.88 μm tunability range [[12]](#A12). In 2016, Majewski *et al.* demonstrated a tunable Dy3+ -doped ZBLAN fiber laser with a tuning range from λ~2.95 to 3.35 µm[[13]](#A13). In 2018, the same group demonstrated a MIR Dy3+ -doped fluoride fiber laser with a tunable range of 0.573 μm[[14]](#A14). In 2018, Aydin *et al.* reported an Er3+ -doped (7 mol%) ZBLAN fiber with a 41.6 W MIR laser output at λ~2.82 µm[[15]](#A15). Compared with Er3+, Ho3+ doped fibers could provide longer emission wavelengths, which result in a better overlap with the water absorption band. Thus, Ho3+-doped fiber lasers offer a wider range of applications, such as surgery. Under pumping at λ~1.15 μm, Ho3+-doped fiber lasers have potentially a higher Stokes efficiency limit than Er3+ doped fiber lasers. However, the lifetime of Ho3+:5I7 (~12 ms) is longer than Ho3+:5I6, meaning that the Ho3+:5I6→5I7 transition is self-terminating process. To obtain an efficient laser at λ~3 µm, it is essential to deplete the lower level by co-doping with Pr3+. In 2015 Crawford *et al.* demonstrated a tunable Ho3+/ Pr3+ co-doped ZBLAN fiber laser with a 7.2 W output, and a 0.15 μm tuning range from λ~2.82 μm to 2.97 μm[[16]](#A16).

ZBLAN has been considered the most promising glass host for MIR fiber lasers[[17-20],](#A17) for its low loss (0.2 dB/m for λ~0.2–4.5 µm) and mature manufacturing process. However, ZBLAN fibers exhibit easy deliquescence because of the NaF content, which restricts their real applications. AlF3-based glasses have better corrosion resistance [[21, 22]](#A21), and a higher glass transition temperature (~ 370 °C) than ZrF4- or InF3-based glasses which in turn offers the potential for higher power mid-infrared fiber lasers and better performance in harsh environments, especially those with high humidity. Compared with the ZBLAN wide application in mid-infrared laser, AlF3-based glasses are still in the development stage because of their higher loss. In 2018, Jia *et al.* showed a 2.87 µm Ho3+ -doped AlF3-based glass fiber laser with a maximum output of 57 mW and a slope efficiency of 5.1%[[23]](#A23). In 2020, Wang *et al.* reported a 2.9 µm Ho3+/Pr3+ co-doped AlF3-based glass fiber laser with an output power of 173 mW and a slope efficiency of 10.3%[[24]](#A24).

In this letter, a room-temperature watt-level laser at λ~3 μm and a tunable laser within the range λ~2.842-2.938 μm are demonstrated using a 28 cm long Ho3+/Pr3+ co-doped AlF3-based glass fiber. This is the first demonstration on room-temperature watt-level laser output at λ~3 μm in AlF3-based glass fibers, which shows the potential of this glass host in high power MIR lasers.

The fiber used in these experiments was fabricated by using the rod-in-tube method on the matrix glass composition of AlF3-BaF2-CaF2-YF3-SrF2-MgF2-LiF-ZrF4-PbF2. The core glass was codoped with 2 mol% Ho3+ and 0.2 mol% Pr3+. The fiber had a 230 μm outer cladding, a 9 μm core diameter and a numerical aperture (NA) of 0.28. The background losses at λ∼793 nm and λ∼2.87μm were measured by the cut back method and resulted to be ∼1.9dB/m and 3.9 dB/m, respectively. The absorption coefficient of the fiber at 1150 nm pump wavelength is ~ 0.58 cm-1.

The experimental setup used for the experiments is shown in [Fig. 1](#B1), a Raman fiber laser at λ~1.15 μm with a maximum output of 20 W was used to pump 28 cm of fiber through a commercial HI1060 standard fiber with a fiber collimator at the end. The pump beam was launched into the fiber core through a lens (*f*=5 mm, NA=0.16) and a dichroic mirror (DM) (high transmittance 95% at λ~1.15 μm and high reflectance 99.8% at λ~2.9 μm). In the watt-level laser experiment, the laser cavity was formed exploiting the DM and the Fresnel reflection (~4% at 2.868 μm) of the fiber end, which was cleaved perpendicular to the fiber axis. The fiber was butted against the HR surface of the DM. The fiber was placed on a heat sink with a V-shape groove, to protect the fiber. A filter (T< 0.1% at 300- 2200 nm) was used when detecting the output power.

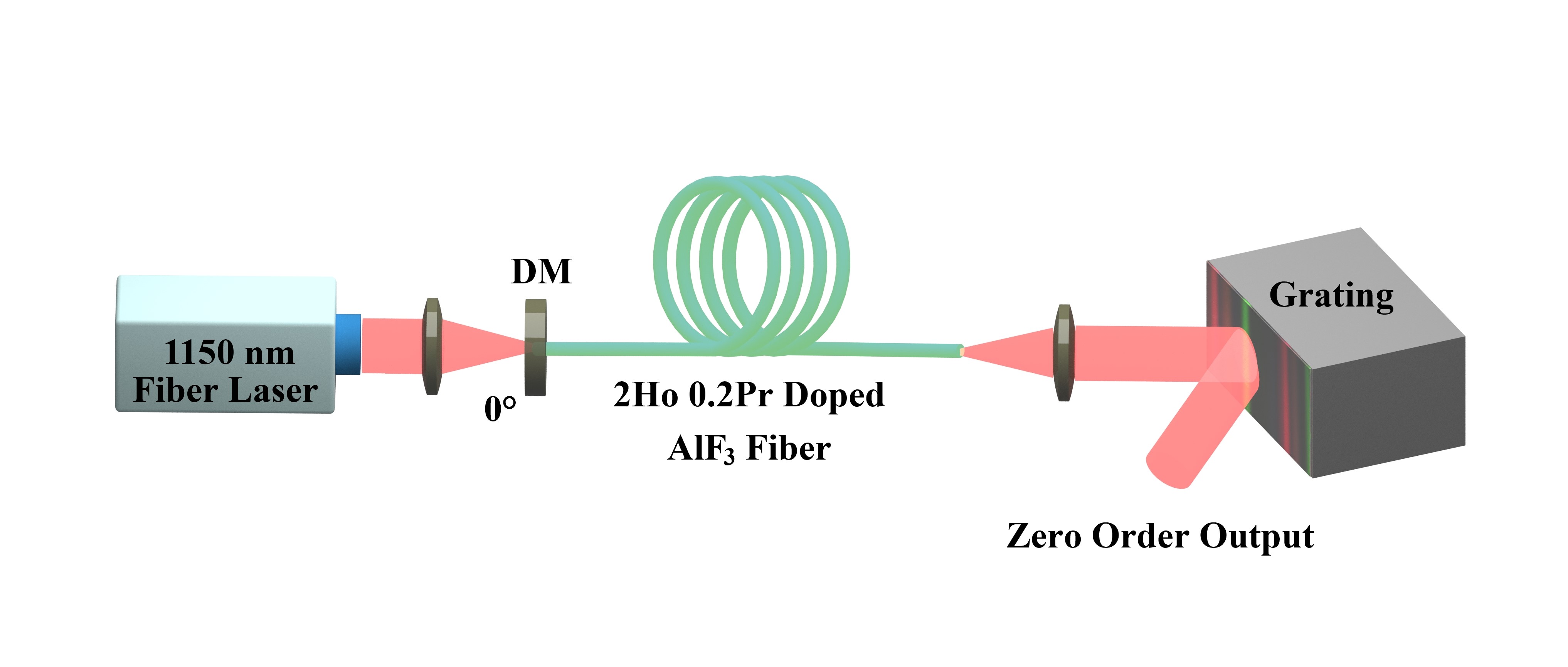


Fig. 1. Schematic of the experimental set-up. In the watt-level laser the grating was not used.

The coupling efficiency of the laser system was determined to be 80%.As the pump power was increased to 52 mW, lasing at λ~2.844 μm was observed. When the pump power was further increased, the lasing wavelength shifted. [Fig. 2](#B2) shows the fiber laser output power at λ~2.87 μm as a function of absorbed pump power. The maximum output from the 28 cm long fiber was 1.13 W with a 10.3% slope efficiency: slope efficiency reached 14.3% at low pump powers (below 1 W). The laser spectrum was monitored with an optical spectrum analyzer (OSA) (YOKOGAWA AQ6377) with a resolution of 0.2 nm.



Fig. 2. Laser output power at λ~2. 87 μm as a function of absorbed pump power at λ~1.15 μm. The blue line represents the linear fit.

[Fig. 3](#B3) shows the dependence of the laser wavelength on the output power. The inset shows the laser spectrum at 969 mW output, and this is a multi-wavelength laser output due to the wide band reflection (HR at 2.9 ± 0.1 μm) of the dichroic mirror. When the laser output is below ~500 mW, the central wavelength of the laser output shifts monotonically to longer wavelengths for increasing pump powers. Above ~500 mW, the central wavelength fluctuates around 2.872 μm. This phenomenon could be mainly explained by the change in temperature. The fiber core temperature rises at first and then fluctuates around the average value for increasing pump powers. At higher temperatures, the energy gap of the Ho3+:5I6→5I7 transition narrows, thus resulting in the red-shifting of the laser central wavelength. When the laser output is above ~500 mW, the fiber core temperature stabilizes and so does the central wavelength.



Fig. 3. Dependence of laser wavelength on output power. Inset: laser spectrum at 969 mW output.

The output laser beam quality was characterized with a beam propagation analyzer (Ophir Photonics NanoModeScan). A 6 mm focal length ZnSe lens (Innovation photonics) was used to collimate the ~2.9 µm laser, while a 100 mm focal length planoconvex CaF2 lens focused the beam along the optical axis of the beam propagation analyzer. Figure 4 shows the beam width as a function of the Z position; the inset presents the beam profile at Z=0. These measurements provided M2 ~1.2 in both X and Y directions.



Fig. 4. Beam quality measurement (M2) for X and Y axes. The inset shows the beam profile at Z = 0.

[Fig. 5](#B5) shows the temporal dependence of the maximum output power over a period of 45 minutes, measured using a power meter with a response time of 0.3 s. The inset shows the experimental set-up. As the heat sink is an aluminum plate without active cooling, the temperature of the gain fiber increased and reached ~50 °C within 45 minutes, while the DM reached ~60 °C. Damage to the fiber ends was not observed at the maximum power, which in turn proved the long lifetime stability of the AlF3 fiber under high power operation. The rising temperature changes the coupling position between focused pump laser and the fiber tip, thus resulting in poor stability of the laser output.



Fig. 5. Temporal dependence of output power over a period of 45 minutes. The inset shows the experimental set-up.

The single cladding fiber used in these experiments has a 9 µm diameter and a very high power density (~ 1011 W/m2) at the fiber input end-facet, when the 1150 nm fiber laser was set at ~ 10 W. Further increases of the pump power can easily cause surface damage on the fiber end-facet. It is worth pointing out that the fiber end was flat cleaved using a fiber cleaver (Vytran LDC401A) and had a good surface quality. Fiber end facets with higher quality, a perfectly match between the focused beam and the fiber core would help to further enhance the output power, if active thermal management was used. In the future work, a water-cooled heat sink, a double-cladding fiber and fiber Bragg gratings, and all-fiberized components could be used to increase the output power and improve the laser stability performance further.

The glass thermal stability ΔT can be evaluated from the value of Tx-Tg, where Tx is the onset glass crystallization temperature, and Tg is the glass transition temperature. For the AlF3 fiber core ΔT~84 °C, comparable with ZBLAN, as previously reported in [[24].](#A24) The good thermal stability of the AlF3-based glass, along with a higher acid and water durability, a higher mechanical strength and a higher glass transition temperature compared with ZBLAN [[22],](#A22) indicate a strong potential for adoption in high power fiber lasers operating in the MIR.

The experiments on the tunable laser system were performed with the setup shown in [Fig. 1](#B1), which includes an external cavity. In this system, the fiber input facet was flat cleaved, while the output facet was angled cleaved at 4 degrees. The laser output from the fiber facet was collimated using a ZnSe lens (Innovation Photonics, NA=0.17 *f*=6 mm, maximum beam diameter~2 mm). The external cavity was completed by a ZnSe lens and a diffraction grating (Thorlabs GR 2550-45031) in the Littrow configuration to provide wavelength-selective feedback. The zero-th order of the grating was used as output coupler of the fiber laser. The grating was blazed for 3.1 μm operation and had measured reflectivities of ~86% (when the incident beam was polarized perpendicularly to the grooves), ~22% (parallel to the grooves) and ~54% on average. The CW laser damage threshold for the grating is 2.5 W/mm2. The collimated laser output was set at 289 mW in the tunable laser experiment. By changing the feedback angle of the grating, a tunable wavelength range of ~0.1 μm, ranging from λ~2.84 μm to λ~2.94 μm was obtained. [Fig. 6](#B6) shows the selected laser spectra in the tuning range. The typical full-width-at-half-maximum (FWHM) for the laser spectra is ~0.7 nm, which is mainly determined by the spectral selectively of the external cavity. A longer focal-length collimating lens or a diffraction grating with smaller pitch or a gain fiber with a single-mode core could be used to reduce the bandwidth further. [Fig. 7](#B7) shows the tunable fiber laser output power as a function of wavelength. Lower output powers at longer wavelengths are mainly the result of OH- absorption and smaller gain factor of the doped fiber. The lower maximum output power of the tunable laser (110 mW) compared with the fixed-wavelength laser (289 mW) is due mainly to the losses in the external grating feedback cavity and the OH- absorption in the gain fiber. Besides manufacturing high quality fibers, reducing lens aberrations, using gratings with higher reflectivity and depositing coating antireflection films on collimating lenses and fiber output facets can increase the coupling efficiency of the external cavity.



Fig. 6. Selected laser spectra in the λ~2842-2938 nm wavelength region.



Fig. 7. Tunable fiber laser output power as a function of wavelength.

In conclusion, this work demonstrated a room-temperature watt-level ~3 μm CW fiber laser and a tunable laser using 28 cm of Ho3+/Pr3+ co-doped AlF3 multimode fiber. Under a Raman fiber laser pumping at λ~1.15 μm, the fiber produced a maximum laser output power of 1.13 W with a slope efficiency of 10.3% and a long-time operating stability of 45 minutes without any additional packaging or active thermal management. The tunable fiber laser employed a diffraction grating and was tuned over a wavelength range of ~0.1 μm from 2.84 to 2.94 μm, with a maximum output power of 110 mW. This demonstration may pave the way for a powerful and ultra-stable mid-infrared fiber laser with emission between 3 and 4 μm.

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