Ion clustering effect of an erbium-doped ZBLAN fiber laser at a 790-nm pump wavelength

Junha Jung, Kyungtaek Lee, Jeehwan Kim, and Ju Han Lee
School of Electrical and Computer Engineering
University of Seoul
Seoul, Republic of Korea
j.h.lee@ieee.org

***Abstract*— The impact of ion clustering in Er^{3+}-doped ZBLAN fiber-based 2.8-µm laser using 790-nm pumping was theoretically and experimentally investigated. Ion clustering significantly decreased the slope efficiency due to reduced 790-nm excited-state absorption for isolated ions.**

***Keywords*— Mid-infrared, Ion clustering, ZBLAN, Fiber laser, Modeling**

I. Introduction

Mid-infrared fiber lasers have attracted huge technical attention in recent years because they provide a range of applications over environmental monitoring [1, 2], defense countermeasures [3], and medical applications [4]. However, mid-infrared wavelength requires a change in the fiber host material from silica to soft glass, such as fluoride, telluride, or chalcogenide [5, 6]. Among the soft glass materials, a fluoride glass called "ZBLAN (ZrF_4-BaF_2-BaF_2-LaF_3-AlF_3-NaF)" is one of the suitable host materials for mid-infrared wavelength operation from the perspective of optical attenuation and mechanical strength [7]. Among the rare-earth-doped ZBLAN fiber lasers with Er^{3+} ions have been intensively studied over the past few decades [8]. Also, with the technical advances, ZBLAN fibers with high doping levels of rare-earth ions are commercially available. However, most of the experimental and theoretical studies are conducted with a 980-nm pump wavelength. A 790-nm pump beam was reported to give sufficient power conversion efficiency for lasing at 2.7-µm [9]; however, this pump wavelength has been rarely used for practical laser implementations. The preference for 970-nm pumping over 790-nm pumping has been attributed to the low-cost, high-power laser diodes operating at 970 nm [10]. Low-cost, high-power 790 nm laser diodes are commercially available nowadays because of the significant advances in AlGaAs-based laser diode technologies [11]. It would be meaningful to examine this 790-nm pump wavelength for the 2.8 µm lasing from an Er^{3+}-doped ZBLAN fiber laser cavity.

In this work, we investigated the impact of ion clustering on the output performance of a 2.8 µm Er^{3+}-doped ZBLAN fiber laser at a pump wavelength of 790-nm. This investigation was mainly conducted theoretically with a modified version of our recently proposed model of Er^{3+}-doped ZBLAN fiber with ion clustering. In this model the rate equations separated for isolated and clustered ions. The model validity was verified with experimental results. It is shown that ion clustering significantly decreases the slope efficiency of the laser output.

II. Numerical Model

A. Rate equations

The dynamics of a 2.8 µm lased based on Er^{3+}-doped ZBLAN fiber was investigated by using a model with seven energy levels. The energy levels for Er^{3+} ions in ZBLAN fiber include $^4I_{15/2}$, $^4I_{13/2}$, $^4I_{11/2}$, $^4I_{9/2}$, $^4F_{9/2}$, $^4S_{3/2}/^2H_{11/2}$, and $^4F_{7/2}$ states, and are represented by N_1^S, N_2^S, N_3^S, N_4^S, N_5^S, N_6^S, and N_7^S, respectively as shown in Fig. 1. To properly include ion clustering effect, two separate rate equations for isolated and clustered ions were used. Our model assumed that the clustered ions exist only in the paired state. No more than two ions are in a cluster. No interactions between isolated ions and clustered ions were assumed to occur.

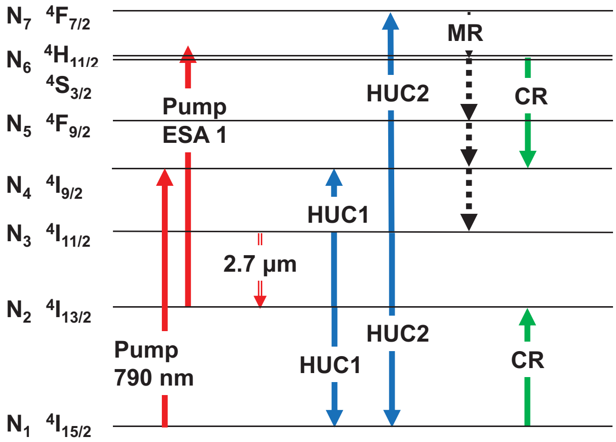

Fig. 1. Energy levels of isolated Er^{3+} ions (ESA: Excited state absorption, HUC : Homogeneous up-conversion, CR : Cross relaxation, MPR : Multi-phonon relaxation).

The rate equations for the isolated ions $N_i^S(z,t)$ and paired ions $N_i^P(z,t)$ were based on the equations for 970-nm pumping, which were presented in Ref. [12]; however, the equations for ions at $^4I_{9/2}$ and $^4I_{11/2}$ levels were properly modified for 790-nm pumping.

$$(1-mk)N_t(z,t) = N_1^S(z,t) + N_2^S(z,t) + N_3^S(z,t) + N_4^S(z,t) + N_5^S(z,t) + N_6^S(z,t) + N_7^S(z,t)\,, \tag{1}$$

$$(mk)N_t(z,t) = N_1^P(z,t) + N_2^P(z,t) + N_3^P(z,t) + N_4^P(z,t) + N_5^P(z,t) + N_6^P(z,t) + N_7^P(z,t), \tag{2}$$

k is the relative number of clusters with respect to the total ion number. The number of ions in a cluster (m) is 2 because only the pairs among clustered ions were considered in this investigation. Further details on the rate equations for 970-nm pumping will be described elsewhere.

B. Propagation equations

The pump and signal beam propagation equations were solved using the fourth-order Runge-Kutta method under the steady state condition. Also, the simulating parameters used for our model are presented in Refs. [12, 13].

III. Er^{3+}-doped ZBLAN Fiber Laser Simulation

A. Laser schematic

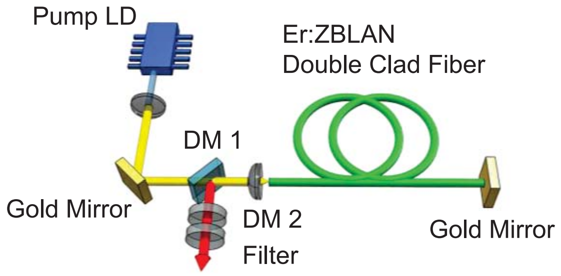

Fig. 2. Experimental schematic diagram of out built Er^{3+}-ZBLAN fiber laser (DM1 : 2800 nm dichroic mirror (R > 99%, Angle of incidence = 45º), DM2 : 2800 nm dichroic mirror (R = 52%, Angle of incidence = 0º).

The validity of numerical simulation results was examined by constructing an Er^{3+}-doped ZBLAN fiber laser based on a Fabry-Pérot cavity, as shown in Fig. 2. A 3.1-m long double-clad Er:ZBLAN fiber, which is commercially available, was used as a gain medium. The fiber had a pump absorption of 2.8 dB/m at a wavelength of 790-nm. The laser output from the DM2 was passed through a bandpass filter to suppress the residual pump power. The other parameters for the experimental setup are given in Ref. [12]

B. Laser Output Measurement and Calculation

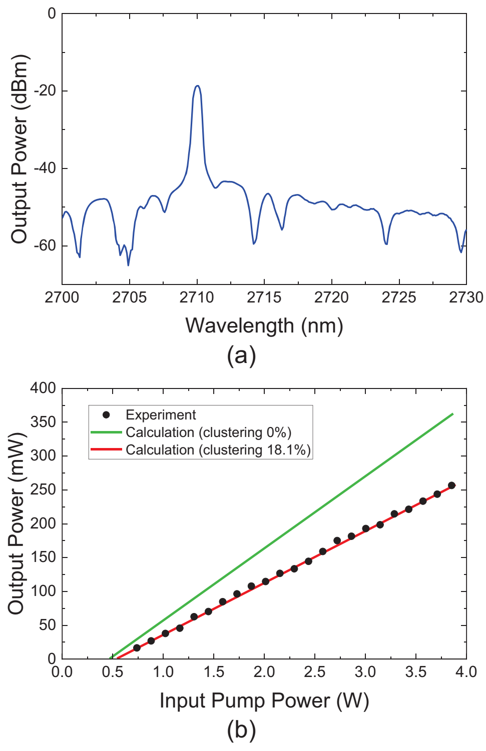

Fig. 3. (a) Experimentally measured output optical spectra for 790-nm pumping. (b) Experimentally measured laser output power v.s. pump power, together with the theoretically calculated results. The theoretical calculations were conducted for two different relative ion clustering levels: k = 0 and 18.1%.

Fig. 3(a) presents the measured output optical spectra for 790-nm pumping at a pump power of 1.2 W. The center wavelength of the laser output was ~2710 nm. Next, the laser output power was measured as the pump power was enlarged. The measured results are illustrated in Fig. 3(b), together with the theoretically calculated results. The theoretical calculations were conducted for various values of the relative number of clusters (k), it was found that the experimentally results are in good agreement with the theoretical ones in the case of k=18.1%. This indicates that the Er^{3+}-doped ZBLAN fiber used for this investigation had a significant number of clustered Er^{3+} ions. From Fig. 4(b), the slope efficiency of the experimentally measured data was estimated at 8.09%, while the calculated slope efficiencies were 13.2% and 8.21% at k = 0 and 18.1%, respectively. It is evident from the results that ion clustering significantly decreases the laser output efficiency.

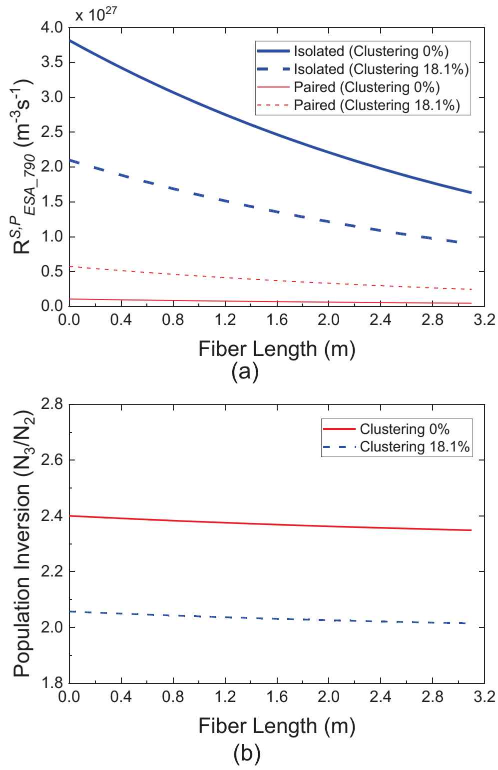

Fig. 4. (a) Calculated 790-nm ESA values ($R^S_{ESA\_790}$, $R^P_{ESA\_790}$) for isolated and paired ions, and (b) population inversion along the Er^{3+}-doped ZBLAN fiber, for two different relative ion clustering levels: k = 0 and 18.1% at a pump power of 3 W.

Fig. 4(a) shows the calculated 790-nm ESA values ($R^S_{ESA\_790}$, $R^P_{ESA\_790}$) of the isolated and paired ions along the Er^{3+}-doped ZBLAN fiber for two different relative ion clustering levels of k = 0 and 18.1% at a pump power of 3 W. The occurrence of 790-nm ESA at $^4I_{13/2}$ for the isolated ions was found to be significantly hindered by ion clustering. The reduction of 790-nm ESA at $^4I_{13/2}$ for the isolated ions resulted in a significant decrease in population inversion, as shown in Fig. 4(b). On the other hand, the 790-nm ESA at $^4I_{13/2}$ for paired ions slightly increased simply due to the increase in paired ion population at a relative clustering level of 18.1%. The 790-nm ESA value for paired ions was relatively small compared to the 790-nm ESA value for isolated ions, and its contribution to the overall population inversion was not significant.

IV. Conclusion

We have investigated the impact of ion clustering in Er^{3+}-doped ZBLAN fiber-based 2.8-µm laser using 790-nm pumping. It was shown that ion clustering significantly degraded the laser slope efficiency since ion clustering significantly hindered the occurrence of 790-nm ESA at $^4I_{13/2}$

for the isolated ions and resulted in a significant decrease in population inversion.

V. ACKKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (NRF-2021R1A5A1032937 and NRF-2021R1A2C1004988).

REFERENCES

[1] B. I. Vasil'ev and O. Mannoun, “IR differential-absorption lidars for ecological monitoring of the environment,” *Quantum Electron.,* vol. 36, no. 9, pp. 801, 2006.

[2] J. J. Scherer, J. B. Paul, H. J. Jost, and M. L. Fischer, “Mid-IR difference frequency laser-based sensors for ambient CH_4, CO, and N_2O monitoring,” *Appl. Phys. B,* vol. 110, pp. 271-277, 2013.

[3] H. H. P. T. Bekman *et al.*, “Development of a midinfrared laser for study of infrared countermeasures techniques,” *in Proc. SPIE,* vol. 5615, pp. 27-38, 2004.

[4] D. Halmer, S. Thelen, P. Hering, and M. Mürtz, “Online monitoring of ethane traces in exhaled breath with a difference frequency generation spectrometer,” *Appl. Phys. B,* vol. 85, pp. 437-443, 2006.

[5] M. C. Falconi *et al.*, “Design of an efficient pulsed Dy^{3+}:ZBLAN fiber laser operating in gain switching regime,” *J. Light. Technol.*, vol. 36, no. 23, pp. 5327-5333, 2018.

[6] S. D. Jackson and R. K. Jain, “Fiber-based sources of coherent MIR radiation: key advances and future prospects (invited),” *Opt. Express*, vol. 28, no. 21, pp. 30964-31019, 2020.

[7] S. D. Jackson, “Towards high-power mid-infrared emission from a fibre laser,” *Nature Photon.*, vol. 6, no. 7, pp. 423-431, 2012.

[8] X. Zhu and N. Peyghambarian, “High-power ZBLAN glass fiber lasers: Review and prospect,” *Adv. OptoElectron.*, vol. 2010, 2010, Art. ID 501956.

[9] B. Srinivasan, R. K. Jain, and G. Monnom, “Indirect measurement of the magnitude of ion clustering at high doping densities in Er:ZBLAN fibers,” *J. Opt. Soc. Amer. B*, vol. , no. 2, pp. 178-181, 2000.

[10] A. Szerling, P. Karbownik, A. Laszcz, K. Kosiel, and M. Bugajski, “Low-resistance p-type ohmic contacts for high-power InGaAs/GaAs-980 nm CW semiconductor lasers,” *Vacuum*, vol. 82, no. 10, pp. 977-981, 2008.

[11] M. A. Ladugin *et al.*, “Laser diode bars based on AlGaAs/GaAs quantum-well heterostructures with an efficiency up to 70%,” *Quantum Electron.,* vol. 47, no. 4, pp. 291-293, 2017.

[12] J. Jung, J. Lee, K. Lee, and J. H. Lee, “Modeling of an Er^{3+}-doped ZBLAN fber laser with ion clustering effect,” *J. Light. Technol.,* vol. 41, no. 1, pp. 265-274, 2023.

[13] J. Li, and S. D. Jackson, “Numerical modeling and optimization of diode pumped heavily-erbium-doped fluoride fiber lasers,” *IEEE J. Quantum Electron.*, vol. 48, no. 4, pp. 454-464, 2012.