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Paper

Light Emission in the 1550 nm Band in Single-Mode Erbium–Ytterbium Co-Doped Optical Fiber by Solar Pumping

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A single-mode erbium-doped optical fiber (SM-EDF) and a single-mode erbium–ytterbium co-doped optical fiber (SM-EYDF) were pumped using solar light. As a result, emitted light in the 1550 nm band was observed. Furthermore, we compared the emission properties of SM-EDF and SM-EYDF. The emission peak of SM-EYDF was more than twice as high as that of SM-EDF. The optimal fiber lengths for peak emission of SM-EYDF were found to be approximately 18.8 cm in the present experiment environment. This paper is the first to apply SM-EYDF to solar pumping and conduct detailed investigations, including fiber length characteristics. The possibility exists that increasing the power output and introducing oscillation systems fibers can make them applicable to long-distance optical communication light sources and amplifiers driven solely by solar light.

Keywords: Erbium-doped optical fiber, Erbium–Ytterbium co-doped optical fiber, Solar-pumped laser

1. Introduction

Solar-pumped lasers have been attracting attention recently in furtherance of efforts to realize sustainable development goals (SDGs). As its pump light source, a solar-pumped laser uses a renewable energy source: solar light. The technology, which converts incoherent solar light into a coherent, monochromatic laser, is anticipated for application to a very wide range of fields. For example, using magnesium, an abundant resource on Earth, a magnesium/magnesium oxide energy cycle has been proposed [1]. In this cycle, temperatures higher than 4000 K can be achieved using a high-power solar-pumped laser, enabling reduction of magnesium oxide using only renewable energy. Additionally, this cycle is anticipated for use in space applications including space propulsion [2], optical communications in space [3], and space solar power systems [4] that transmit energy from space to Earth.

In 1966, C. G. Young was the first to oscillate a solar-pumped laser successfully using $Y_3Al_5O_{12}$ (YAG) crystals doped with neodymium (Nd) ions and Nd-doped glass rods [5]. Since then, a great deal of research has been conducted to achieve more efficient and stable oscillation of solar-pumped lasers.

For solar-pumped lasers, the use of YAG (Nd/Cr:YAG) transparent ceramic materials co-doped with neodymium and chromium ions as a gain medium has become the mainstream. This material can realize a more efficient solar-pumped laser by allowing Cr^{3+} ions to absorb light of widely various wavelengths in the visible light region, and by acting as a sensitizer for Nd^{3+} ions [6]. In 2008, Yabe et al. reported a 100 W-class solar-pumped laser using Nd/Cr:YAG [7]. In 2018, Hasegawa et al. proposed a new solar light pumping laser configuration with a Nd/Cr:YAG gain region surrounded by Gd:YAG [8]. The new configuration achieves efficient laser oscillation with a 136 mW threshold and 25.3% slope efficiency, which is a lower laser threshold and a higher laser slope efficiency than those of the earlier uniform Nd/Cr:YAG. Additionally, in 2019, a solar tracking system with an array of small solar pumping lasers achieved over 6.5 hr continuous oscillation [9].

If this gain medium is an optical fiber, then the system is called a solar-pumped fiber laser, as first proposed in 1997 [10]. Optical fibers are thin and low-loss. For that reason, they offer better confinement of the pumping light than either transparent ceramics or glass rods, producing low-threshold, high-efficiency laser oscillation. In 2012, a 0.57 mW laser output was demonstrated using a fluoride double-clad fiber doped with Nd^{3+} ions [11]. Thereafter, by winding an Nd-doped optical fiber inside a highly reflective chamber filled with a sensitizer, they constructed and oscillated a fully planar solar light-pumped laser that needed no tracking of solar light and which was completely unfocused [12,13].

Although solar pumped lasers are expected to have various applications as described above, few reports of the literature have described attempts to apply them as light sources for long-distance optical communications. One salient benefit of using solar pumped lasers directly as a light source for long-distance optical communications is that optical communications can be realized using solar light alone in regions where power supplies are unstable, such as deserts and outer space, and when the power supply is disrupted because of a disaster. Furthermore, the system can be designed to save space and to be more easily maintained than

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systems built using photovoltaic panels. We have been working to develop a suitable solar pumped laser system for long-distance optical communications [14].

First, erbium-doped optical fiber amplifiers are used widely as amplifiers for signal light in the 1550 nm band used in today's long-distance optical communications. Erbium-doped optical fiber (EDF) has the property of absorbing light of 980 nm and 1480 nm wavelengths from laser diodes and then efficiently emitting light in the 1550 nm wavelength band. This characteristic enables 1550 nm signal amplification. Regarding the absorption wavelength of this EDF, it is expected to absorb light in visible light wavelength bands such as 487 nm, 521 nm, and 653 nm in addition to 980 nm and 1480 nm [15].

Secondly, a larger 1550 nm band emission is obtainable from the EDF by increasing the erbium concentration in the fiber. However, as the added erbium concentration is increased, the distance separating erbium ions in the fiber lessens, causing interaction, which in turn engenders concentration quenching. As a result, the emission efficiency in the 1550 nm band decreases.

Optical fiber in which ytterbium is co-doped with EDF is designated as erbium–ytterbium co-doped optical fiber (EYDF). The co-doping of ytterbium suppresses concentration quenching and improves the concentration limit of erbium addition [16]. Actually, EYDF has the property of absorbing light with a wide bandwidth of 800–1100 nm, which is the absorption wavelength band of ytterbium. It also emits light in the 1550 nm band, which is the emission wavelength band of erbium.

Our earlier research confirmed emission in the 1550 nm band by incident solar light on a multimode erbium-doped optical fiber (MM-EDF) [14]. However, considering construction of a resonator, single-mode is easier to handle because it requires no consideration of the phase of each mode, etc. Furthermore, when considering optical communications, single-mode is more desirable because it can be connected easily to each application.

Subsequently, we attempted to obtain emission light in the 1550 nm wavelength band by injecting actual solar light into single-mode erbium-doped optical fiber (SM-EDF) and single-mode erbium-co-doped optical fiber (SM-EYDF). For this study, we conducted a detailed investigation of the SM-EYDF length characteristics and summarized the emission properties of EYDF by solar pumping. This fundamental study examines applications such as laser oscillation and amplification of 1550 nm band light by solar pumping.

This research indicates some potential for contribution to construction of an unpowered fiber optic communication system that operates solely with solar light. This system is applicable to areas with power and communication infrastructure inadequacies, or during times when infrastructure is compromised by a disaster.

2. Optical System for Experimentation

A schematic of the actual optical system used for experimentation is presented in Fig. 1.

For this study, a Himawari solar lighting system (Himawari XD-50S/12AS; La Foret Engineering Co. Ltd.) was used to collect solar light [17]. The sun's position in the sky can be tracked automatically by this lighting system. Solar light focused by 12 lenses (134 mm diameter) is incident on 12 silica fibers, each of which carries solar light into the laboratory in two bundles of six fibers each. The power of that carried solar light was measured using a thermal-sensor-type optical power meter (visible light mode). The optical power of the solar light per fiber bundle was confirmed as 6 W (total of six cores). Because solar light is difficult to focus and because of thermal damage effects, only one of the six cores was used. A single core in the bundled silica fibers had 1 mm diameter.

Solar light transmitted by silica bundle fiber was directly incident on SM-EDF, SM-EYDF, and single-mode fiber (SMF: SMF-28; Corning Inc.). When solar light, which is incoherent light, is focused by a lens, the focal point becomes large. Furthermore, because such light has a very large loss in space, the distance necessary to focus the light (focal length) is another factor attenuating the power. Therefore, the method of focusing the light using a lens was not used for this experiment. Instead, a method was adopted to bring the bundle fiber close to the target fiber.

Solar light also includes light in the 1550 nm band, which is the emission wavelength band of the EDF and EYDF. Therefore, ascertaining how much emitted light was obtained using the EDF and EYDF effects is difficult. To resolve this difficulty, a short-pass filter (SPF, FESH1000; Thorlabs, Inc.), which cut the 1000–1580 nm wavelength band, was installed immediately before the solar light enters the various fibers. This filter enabled us to remove the 1000–1580 nm wavelength component of solar light and to observe the pure emission light obtained using EDF and EYDF. However, wavelength components longer than 1580 nm were not removable by this SPF.

The SM-EDF (ER110-4/125, Liekki; Thorlabs, Inc.) used for this experiment has absorption of 68 dB/m in the 975 nm wavelength band and 110 dB/m in the 1530 nm band, which is the erbium emission wavelength band. The SM-EYDF (DF1500Y; Humanetics (Fibercore)) used an optical fiber with absorption of 1000 dB/m in the 975 nm band and 20 dB/m in the 1530 nm band. Compared to EDF, EYDF has about 15 times greater absorption in the absorption wavelength band at 975 nm because of the ytterbium co-doping effect. Furthermore, less loss occurs in the emission wavelength band. The numerical aperture (NA) and mode field diameter (MFD) were, respectively, 0.2 and 6.0–7.0 μm for SM-EDF, and 0.20–0.24 and 5.3–6.8 μm for SM-EYDF, and 0.14 and 9.9–10.9 μm for SMF. Various measurements were made by monitoring the solar light power from the bundle fiber while keeping it constant. In addition, solar light was captured on a clear day around noon. All optical spectra were measured using an optical spectrum analyzer (OSA: Q8381A; Advantest Corp.).

Power measurements were taken by replacing the OSA in Fig. 1 with a fiber input type optical power meter (MA9423; Anritsu Corp.), and then passing solar light emitted from the silica bundle fiber through an SPF and into the SMF. The result yielded 3.2 μW. This value includes losses attributable to the diameter difference between the bundle silica fiber and the SM core, in addition to losses caused by the space necessary for SPF insertion.

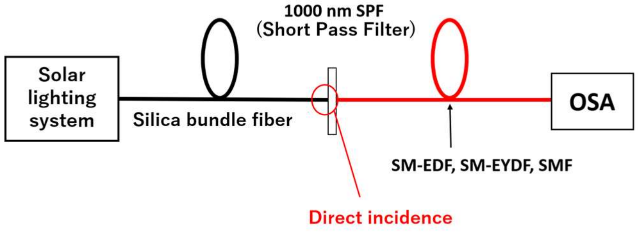
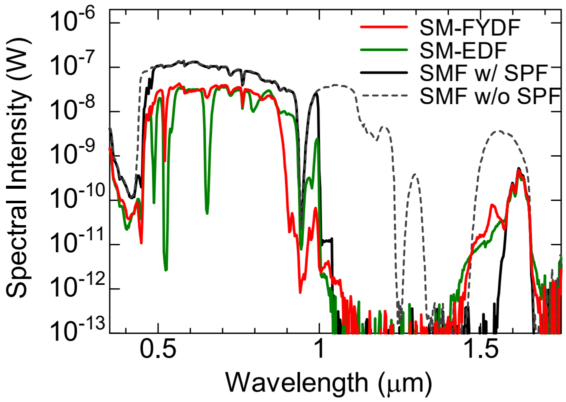


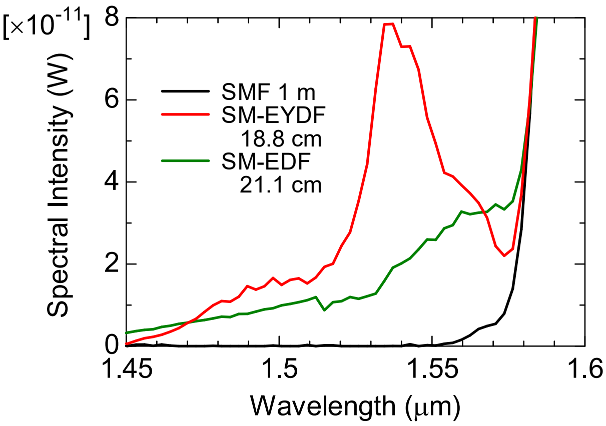
Fig. 1. Schematic diagram showing the optical system experiment.

3. Results and Discussion

3.1 Emission of 1550 nm band light in SM-EDF and SM-EYDF by solar pumping Using the system for experimentation presented in Fig. 1, the SM-EDF and SM-EYDF light spectra obtained when solar light is incident on them are presented in Fig. 2(a). A magnified figure of the spectrum in the 1550 nm wavelength band at that time is presented in Fig. 2(b). The spectra of solar light incident on the SMFs are shown as black lines, those on the SM-EYDF as red lines, and those on the SM-EDF as green lines. The solar light spectrum directly incident on the SMF without the SPF from the optical system of Fig. 1 is shown by the dashed line. When removing the SPF, the incidence distance and position from the bundle silica fiber to each fiber were maintained. Each measurement was conducted at approximately the same time on the same day. The lengths of fibers used for this experiment were 18.8 cm for SM-EYDF and 21.1 cm for SM-EDF. These fibers were prepared to have similar lengths to compare the emitted light intensities. The SMF length was chosen arbitrarily because the only reasons for connecting the SMFs were to ensure that the 1550 nm band spectrum in solar light was blocked by the SPF and to confirm the pure emission of the 1550 nm band by the SM-EYDF and SM-EDF. Consequently, 1 m length was used for this experiment. It is noteworthy that the SPF filtering effect fades as the wavelength increases from 1560 nm to longer wavelengths, leaving the solar light spectrum in the measurement results.



(a) Full measurement wavelength spectra



(b) Enlarged view of emission wavelength range

Fig. 2. Light spectra of solar light incident on SM-EDF, SM-EYDF, and SMF in the optical system used for experimentation shown in Fig. 1.

Results demonstrate that both SM-EDF and SM-EYDF emit 1550 nm band light when solar light is incident on SM-EDF and SM-EYDF. Hereinafter, we describe a comparison between the case of solar light incident on the SM-EDF and the case of solar light incident on the SM-EYDF.

Regarding the absorption wavelength band, EDF showed better absorption properties in the visible light region than EYDF did. This finding demonstrates that Er^{3+} has absorption wavelengths not only in the infrared region but also in the visible light region, as described in Section 1 [15]. Figure 2(a) shows attenuation in spectral components of 487 nm, 521 nm, and 653 nm wavelengths, which was not observed when only SMF was connected. This result is consistent with the absorption wavelength of Er^{3+} in the visible light region. In SM-EYDF, a large absorption effect was observed over a wide wavelength range of 850–1000 nm, which is the absorption band of ytterbium ions. The 940 nm attenuation in the solar light spectrum, which is also apparent when only SMF was connected, results from absorption by atmospheric water vapor. The emission peak in the 1550 nm band attributable to solar pumping was more than doubled for SM-EYDF compared to that for SM-EDF. Fiber properties show that SM-EYDF absorbs about 15 times more in the absorption band at 975 nm than SM-EDF does. In addition, the absorption loss in the emission wavelength band is 90 dB/m lower for SM-EYDF. However, the absorption effect in the visible region was less in EYDF than in EDF. In the EYDF, Yb ions are pumped to the $^2F_{5/2}$ level by pumping light in the 800–1100 nm band, leading to energy transfer to Er ions and pumping Er ions to the $^4I_{11/2}$ level. Er ions that were pumped to the $^4I_{11/2}$ level relax to the $^4I_{13/2}$ level via non-radiative processes, thereby forming an inverted population between the $^4I_{13/2}$ and $^4I_{15/2}$ levels and emitting light in the 1550 nm wavelength band [16]. Therefore, when EYDF was used, although absorption in the visible region characteristic of Er decreased, a considerable amount of absorption was observed across the broad near-infrared absorption wavelength range characteristic of Yb. The solar light also includes a spectral component in the near-infrared region at 975 nm. The 975 nm wavelength band has better conversion efficiency to the 1550 nm band than the visible light wavelength region. Furthermore, EYDF showed a wider spectral range of absorption than EDF in the 975 nm wavelength band, which is sufficiently wide compared to the absorption loss at 940 nm caused by atmospheric effects. These properties, which exceed the visible light absorption of SM-EDF, are thought to contribute to the large peak power obtained with SM-EYDF.

3.2 Characteristics of SM-EYDF length We investigated emission light-fiber length characteristics in the 1550 nm band using the optical system for experimentation described above and SM-EYDF. Furthermore, SM-EYDFs with lengths of 4.8 cm, 8.8 cm, 12.0 cm, 18.8 cm, 38.8 cm, and 54.5 cm were used. The relation between the maximum emission spectra in the 1550 nm band observed when solar light was incident on the SM-EYDF at each length is depicted in Fig. 3. Results show that the optimal fiber lengths for SM-EYDF were approximately 18.8 cm long for the present experiments. Greater fiber length is associated with a greater pumping effect of the doped rare earth ions, but with greater loss inside the fiber. Lesser fiber length is associated with a smaller pumping effect of the doped rare earth ions. Therefore, if the solar power incident on the EYDF can be increased by improving the focusing system and by increasing the focusing lens size, then the pumping effect of the rare earth ions will outweigh the fiber loss. The optimum fiber length might be longer.

Peak values of the emission obtained from the 18.8 cm SM-EYDF were slightly different in Figs. 2 and 3. This result might be attributable to different atmospheric conditions of the different measurement dates, such as solar altitude and meteorological conditions.

We attempted to evaluate not only the maximum peak value but also the spectral width. However, it was difficult to calculate the pure spectral width because of the filtering range of the SPF. For future studies, we plan to conduct evaluation using spectral width by introducing an appropriate SPF.

Exploring the optimal coupling method between the bundled silica fiber and the SM-EYDF, and scaling up of the solar lighting system are necessary to achieve greater output power. Currently, we are considering approaches to enhance the incident solar light intensity on each fiber using multiple solar lighting systems and to adopt a multi-mode pump combiner.

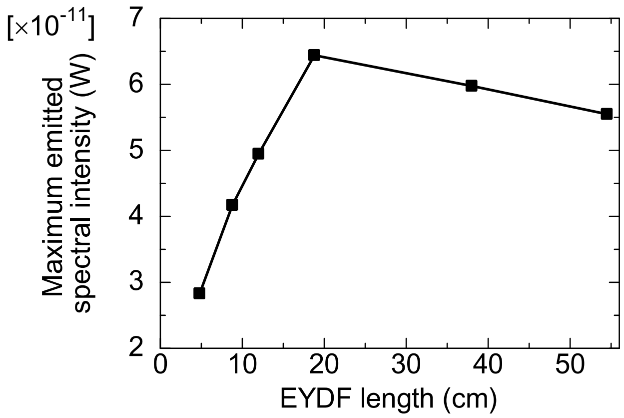


Fig. 3. Characteristics of maximum spectral intensity of the emitted light relative to SM-EYDF length.

4. Conclusion

A single-mode erbium-doped optical fiber (SM-EDF) and a single-mode erbium–ytterbium co-doped optical fiber (SM-EYDF) of similar length were exposed to solar light. Emissions in the 1550 nm band were observed for both fibers. Comparison of the emission spectra obtained by solar pumping in SM-EDF and SM-EYDF demonstrated that the peak emission value of SM-EYDF was more than two times greater than that of SM-EDF. Subsequently, we observed the emission spectral maximum of the SM-EYDF at several fiber lengths. Results show that the optimal fiber lengths for SM-EYDF were confirmed as approximately 18.8 cm long in this experiment environment.

By increasing the output power and by introduction of oscillation systems, future applications might include long-distance optical communication light sources and amplifiers that are driven solely by solar light. To increase output power, optimal coupling methods between bundled silica fibers and SM-EYDFs must be explored, as well as scaling up of solar lighting systems. We plan to continue developing and researching these systems.

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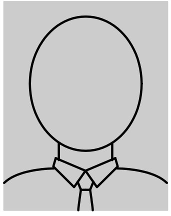

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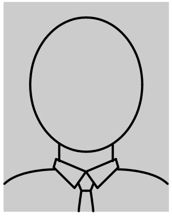

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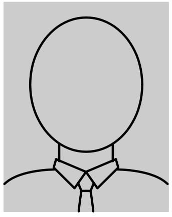

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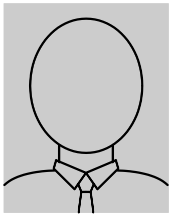

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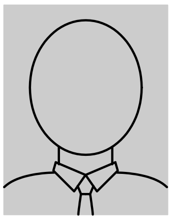

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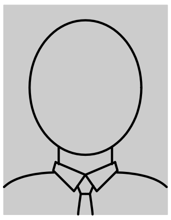

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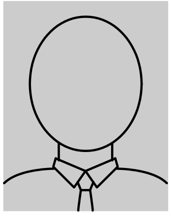

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