Radiation-hardened Er/Yb Co-doped Optical Fibers for Optical Communications in Space

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Intersatellite communication requires transmitters with high data transmission capacities. Optical communication has emerged as a promising solution to meet these requirements. To establish reliable communication links between low Earth orbit satellites and geostationary orbit satellites, transmitters with optical output power in the 10 W-class are required. Er/Yb co-doped optical fibers have been recognized as suitable candidates for achieving such high optical output power levels. Although radiation-hardened fibers for space applications are commercially available, we present an improved radiation-hardened Er/Yb co-doped optical fiber and demonstrate its capability to deliver a 10 W-class optical output.

1. Introduction

In intersatellite communications, conventional radio frequency (RF) communication system exhibits a large beam divergence of 0.5–30° and operates within a limited frequency bandwidth to prevent unwanted interferences[1]. The commercially available Ka-band (26.5–40 GHz) is becoming a scarce resource and increasingly constrained owing to growing demand for RF communication. Conversely, Q-band (33–50 GHz) and V-band (40–75 GHz) provide broader bandwidths, offering potential advantages for RF applications. Although both bands remain under active development, their capacity to significantly enhance communication speed appears to be limited. In contrast, optical communication typically has a beam spread angle of less than 0.006°; therefore, it has lower risk of interference compared to that faced by RF communication. Moreover, optical communication has no regulations on frequency bandwidths. Note that satellite-based optical communication transmits optical signals through a vacuum, enabling the potential for longer transmission distances and lower latencies compared to those offered by terrestrial optical fiber communication networks. Communication networks utilizing low-Earth-orbit satellites (LEOs), particularly constellations, at an altitude of 550 km are expected to offer lower latency for communication distances exceeding 3000 km[2]. For these reasons, demand for intersatellite optical communication is increasing[3][4][5]. The market for satellite-based optical communication is estimated to grow from $933.7 million in 2024 to $36.4 billion in 2034, at a CAGR of 45.4%[6].

To establish reliable communication links between satellites, especially between LEOs and geostationary orbit satellites (GEOs), 10 W-class high-power are required[7]. In addition to increasing the output power, polarization-maintaining optical fiber amplifiers could be used to separate the transmitting and the receiving signals to bring better sensitivity in signal processing on long distance communication such as between the LEOs and GEOs. Therefore, polarization-maintaining PANDA-type fibers would be required for signal amplification. Compared with LEOs, GEOs are more costly to launch and operate for longer service durations, which necessitates the use of highly reliable and radiation-hardened optical amplifiers. Because heat in space cannot be dissipated through thermal conduction as in the air atmosphere; high electrical to optical conversion efficiency must be achieved by minimizing heat generation in operation.

While the 1550 nm band is going to be applied widely for communication in both free-space and terrestrial environments, achieving a 10 W-class output power at 1550 nm with erbium-doped fibers (EDF), that most conventionally used for amplification at the band, remains a challenging issue due to the insufficient amplification ability. In this report, we present the development of a radiation-hardened erbium–ytterbium co-doped fiber (EYDF), capable of delivering 10 W-class output power.

2. Radiation-hardened Optical Fibers

Conventional single-mode optical fibers for telecommunications typically use a Ge-doped silica glass core. When such fibers are irradiated by radiation, many defects are generated owing to the presence of Ge dopants. The light propagating through the core often suffers absorption losses owing to these defects, resulting in reduced radiation resistance. To minimize the defect-induced absorption losses, the core is often made of pure silica glass, and the cladding is doped with fluorine to prevent the formation of Ge-originated defects, thereby improving radiation resistance. Furthermore, doping of additional fluorine to the core suppresses the formation of silica-derived defects, resulting in even higher radiation resistance[8][9]. Fluorine-doped core

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Abbreviations, Acronyms, and Terms.

PANDA-type fiber—Polarization-maintaining AND Absorption-reducing type optical fiber
A polarization-maintaining optical fiber with two circular stress-applying parts on symmetrically positioned relative to a core.

DCF—Double-Clad Fiber
An optical fiber with a core and a two-layer cladding, in which the refractive index is highest in the core, followed by the inner cladding, and then the outer cladding. It is mainly used as an amplifier fiber to efficiently excite rare-earth elements doped in the core. In most cases, the outer cladding is made of a low-refractive-index resin.

fibers, which demonstrate excellent radiation resistance, have been used by some facilities in the European Organization for Nuclear Research (CERN), one of the largest laboratories in the field of elementary particle physics in the world[10].

In addition to erbium and ytterbium, phosphorus is added typically as a third co-dopant in EYDFs to enhance the dispersion of these rare-earth elements within the silica glass core. However, when exposed to radiation, phosphorus in silica glass induces absorption loss at 1570 nm, known as the P1 defect. Figure 1 shows that the irradiation effect on absorption spectrum of P-doped silica cores at cumulative radiation dose of 100 krad, which is equivalent to the amount of radiation penetrating a 4 mm-thick aluminum-based satellite housed for over 10 years in GEO, significantly increases the radiation-induced absorption loss[11]. Irradiation of a P-doped EYDF induced an additional absorption loss of approximately 3 dB/m in the 1550 nm communication band. Although the service length of EYDF, which is an amplification fiber, is only a few meters, such loss could be significant; for example, a 7 m-long EYDF would experience a loss of over 20 dB, transmitting only about 1% of the input light, which is a level of attenuation considered critical for optical systems. Consequently, standard EYDFs are not suitable for GEOs, which require service durations of 10 years or more, owing to their high radiation-induced losses.

To address the limitations associated with EYDFs, we did propose a method to improve their radiation resistance by adding Ge to suppress P1 defects[12]. Although Ge doping introduced defects that cause absorption loss in telecommunication applications, the Ge-related loss is approximately two orders of magnitude smaller than that caused by P1 defects. In fact, owing to the competitive relationship between Ge-related and P1 defects formation, suppressing P1 defects significantly improves the overall radiation resistance. As shown in Figure 1, radiation-induced loss in the 1550 nm communication band was suppressed to below 1.0 dB/m for P-Ge-co-doped EYDFs. The EYDF developed in this study incorporates Ge doping to leverage its ability to suppress P1 defects, thereby enhancing radiation hardness.

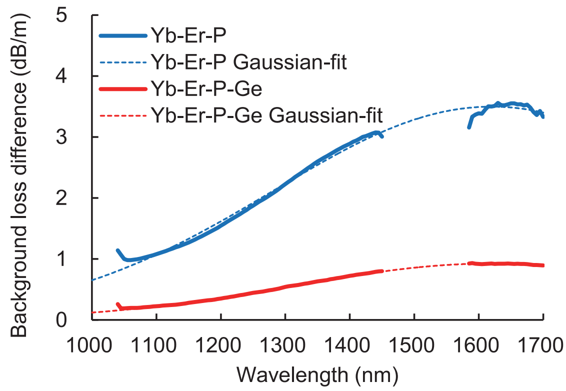

Fig. 1 Difference in background loss before and after 100 krad radiation exposure.

3. EYDF Amplification Principle

While EYDFs can amplify optical signals around 1550 nm—the telecommunication wavelength band—by exploiting the amplification wavelength band of erbium as EDFs, it exhibits much stronger absorption due to the larger absorption coefficient of added ytterbium on excitation light around 915 nm. Figure 2 illustrates the energy-level diagram of the EYDF. In the evaluation of amplification in EYDFs conducted in this study, ground state ytterbium is excited to the $^2F_{5/2}$ level by excitation light at 915 nm, and subsequently, erbium is excited to the $^4I_{11/2}$ level via energy transfer from excited ytterbium. The excited erbium then relaxes nonradiatively to the $^4I_{13/2}$ level, and the resulting population inversion between the

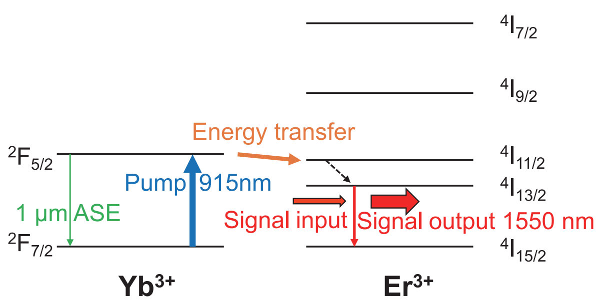

Fig. 2 Energy-level diagram of EYDF.

$^4I_{13/2}$ and $^4I_{15/2}$ levels amplifies the signal light in the 1550 nm communication band via stimulated emission.

Phosphorous must be added to EYDFs in high concentration, because phosphorus disperses erbium and ytterbium ions to prevent them from clustering, and improves the energy transfer efficiency from ytterbium to erbium[13].

In insufficient concentration of phosphorous in EYDFs reduces efficiency of energy transfer from ytterbium to erbium, and excited ytterbium undergoes a radiative transition from $^2F_{5/2}$ to $^2F_{7/2}$, producing amplified spontaneous emission (ASE) in the 1 μm band. This ASE does not contribute to optical amplification and is ultimately converted into heat. Since satellites operate in the vacuum of outer space, dissipating this heat is particularly challenging, and therefore, highly efficient amplification with minimal heat generation is required. When the 1 μm ASE band is not adequately suppressed and the amplification efficiency is low, extra heat would be generated to achieve the same target output(at 1550 nm). Therefore, it is one of the key challenges in EYDFs that higher efficient amplification by suppression of the 1 μm ASE band was achieved by optimizing dopant concentrations and core design parameters[14].

4. Amplifier Evaluation System

As shown in Figure 3, the amplifier evaluation system used in this study was a backward-excitation type using 915 nm excitation light. The seed light with a wavelength of 1550 nm was amplified by a preamplifier, and its power amplitude was adjusted to approximately 50 mW before being injected in EYDF through a forward coupler. The 915 nm excitation light was injected into the entire glass cladding region of the EYDF through a double-clad fiber (DCF) from a backward pump combiner, and output intensity of the amplified light was delivered through a single-mode fiber. The 1 μm ASE, generated because of the low energy-transfer efficiency from ytterbium to erbium, was measured with a power meter by selectively extracting the light propagating in the core through the forward coupler.

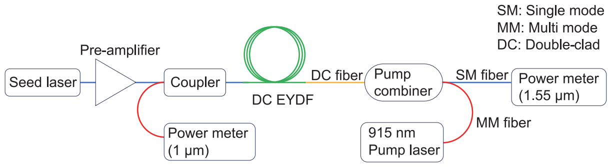

Fig. 3 Amplifier evaluation system.

5. Amplifier Evaluation Results

Table 1 shows the specifications of the developed EYDF and commercially available radiation-hardened EYDF (Exail Technologies, France). No significant differences were observed in the basic parameters, such as core diameter and absorption. However, the birefringence of the developed EYDF estimated from the cross-sectional structure such as the diameter and position of the stress-applying part was found to be higher than that of the catalog value of the product. This suggests that the EYDF developed in this study may have better polarization-retention performance than reported EYDF. Further verification of polarization-retention performance under target operating conditions, such as a 10 W output typically used by amplifier users, is necessary to provide more accurate indicators for amplification.

Figure 4 shows the evaluation results obtained before and after irradiation of the EYDF-based amplifier at cumulative radiation dose of 100 krad. The amplifier achieved a high output power of 10.1 W at 25 W of excitation light before irradiation. The output power under excitation of 25 W was reduced by only 14.5% from 10.1 W at initial to 8.7 W after irradiation, which is less than the target output power loss of 20%. The 1 μm ASE did not appear even at 25 W of excitation light before irradiation and increase slightly but below 0.2 W even after irradiation. Experimentally achieved maximum output power was 10.8 W at 27 W irradiation due to the limit of the evaluation setup used in this report. Taking into account of the good linearity of output to excitation and low ASE, higher output exceeding 10 W-class, or 10 W-class amplification even after irradiation aging would be achieved by increase of excitation power.

Table 1. Specifications of EYDFs[15]

Parameter	This report	Other company (Exail Technologies, France) IXF-2 CF-EY-PM-12-130-RAD
Dopant for Radiation Hardness	Ge	Ce
Core Diameter	13.8 μm	12±1 μm
Cladding Diameter	125 μm	125±3 μm
Polarization Maintaining Structure	PANDA	PANDA
Birefringence	2.0×10^{-4}	$> 1 \times 10^{-4}$
Cladding Yb absorption	4.33 dB/m (915 nm)	2.6 ± 0.6 dB/m (915 nm)
Core Er absorption	32.2 dB/m (1530 nm)	50 ± 10 dB/m (1536 nm)

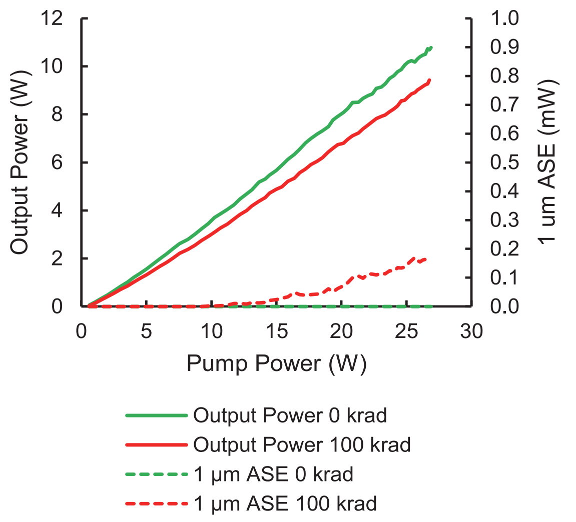

Fig. 4 Change in amplification characteristics before and after 100 krad radiation exposure.

6. Conclusion

We developed an EYDF with high amplification efficiency, achieving output power of 10.1 W under excitation light intensity of 25 W. The EYDF co-doped with Ge, which enhanced its high radiation resistance, was limiting the output power degradation to only 14.5% even after exposure to radiation equivalent to that experienced by GEO over 10 years. Future work will focus on evaluating the polarization-maintaining performance of the EYDF at 10 W output power to confirm its stability under practical amplifier operating conditions. Additionally, we also plan to develop radiation-resistant EYDFs for low-power amplification of several watts, tailored for LEOs where the market demand for EYDFs would be relatively high.

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