Attenuation and Fluorescence Characteristics of Optical Signals Propagating in an Erbium-Doped Fiber

Chien-Yuan Chen and Sien Chi

Abstract—**For a monochromatic input signal launched into an erbium-doped fiber (EDF), a broadband fluorescence spectrum will be generated with total power approximately 30 dB lower than input signal power. The forward fluorescence power decays slowly at long EDF length due to smaller absorption cross section for wavelength components away from absorption peak. Care must be taken when the conventional cutback method is used to measure the attenuation of the optical signals in an EDF. The backward fluorescence power is saturated to a constant level, and the spectrum does not change for long EDF.**

I. Introduction

ERBIUM-DOPED fibers (EDF's) will be used in optical amplifiers for future optical communication systems because of their compatibility with conventional silica-based optical fiber, high gain, broad bandwidth, and low noise figure near 1.55 μm [1]. Due to the three-level laser characteristics of the erbium ions, optical signals in 1.5-μm wavelength range suffer large attenuation in EDF when the pump power is absent. On the other hand, EDF emits fluorescence when the pump power is applied [2]. In this paper, we investigate theoretically and experimentally how the optical signal attenuates and how the fluorescence power is generated in an EDF without pump. Also, we will show that the conventional cutback method used to measure the attenuation of an EDF may yield incorrect results for a high concentration or a long EDF.

II. Theory

For the input signal of wavelength 1532 or 1550 nm, the EDF without pump can be modeled as a two-level system. A homogeneously broadened model is used, where we consider spontaneous emission power as a number of optical beams of frequency bandwidth $\Delta\upsilon_k$ centered at the wavelength $\lambda_k = c/\upsilon_k$ to resolve the spontaneous emission spectrum [3]. We use 101 points to sample the spontaneous emission spectrum from 1450 to 1650 nm, which corresponds to wavelength spacing $\Delta\lambda = 2$ nm. A step-like Er^{3+} density profile, where Er^{3+} is uniformly doped over a radius of 1 μm in the fiber core, and a Gaussian approximation for the optical mode with power spot size 3.34 μm are assumed. The spectral absorption cross section and emission cross section of the EDF used in the theory were measured from another experiment [4]. Other parameters are the spontaneous lifetime of the upper level $\tau = 10$ ms, the Er^{3+} density $n_t = 4.28 \times 10^{25}$ m^{-3}, fiber core area $A = 35$ μm^2, and the intrinsic loss of the silica-based host glass $\alpha = 0.26$ dB/km for all wavelengths, for simplicity.

III. Experiment

An experimental setup for measurement of attenuation and fluorescence of optical signals propagating in EDF is shown in Fig. 1. The signal sources are 1532- and 1550-nm DFB LD's with a side-mode suppression ratio of better than 35 dB. The polarization independent isolators with a 1.2-dB insertion loss and a 60-dB isolation are used to avoid reflections from connector ends or grating of an optical spectrum analyzer. A tunable bandpass filter, which can be tuned in the 1525- to 1575-nm wavelength range with ~3-nm FWHM and 2.5-dB insertion loss, is used to filter out the power other than the main-mode wavelength of the DFB LD. A variable optical attenuator is used to adjust the input signal launched into the EDF to a desired power level. The output light from the signal LD is coupled by a wavelength independent 3-dB coupler to the erbium-doped fiber. One arm of a 2 × 1 wavelength independent fused optical fiber coupler is used to couple the input signal into the EDF, while the other arm is used to collect the backward fluorescence power. The EDF used in this experiment has a core diameter of 5 μm, an NA of 0.24, a cutoff wavelength of 1.12 μm, and an unpumped attenuation of 8.6 and 4.4 dB/m at 1530 and 1550 nm, respectively. Components are connected by fusion splice in order to avoid reflections that may cause measurement errors. The optical signal power fed to the erbium-doped fiber is adjusted to −10 and −20 dBm at both wavelengths. The output light at the far end of the EDF, after passing through an isolator, is measured by an optical power meter or optical spectrum analyzer. A high-sensitivity optical power meter capable of measuring optical power level to −90 dBm in the 1.5-μm wavelength range is used. The EDF is cut out one meter at a time

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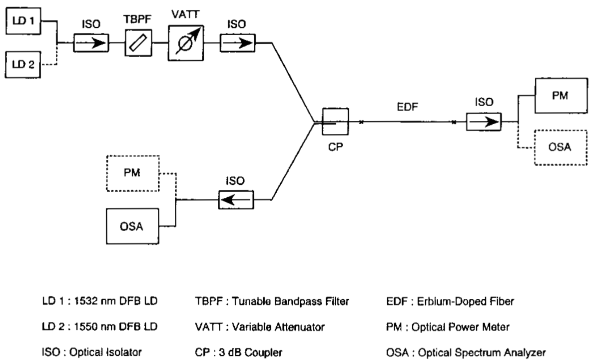

Fig. 1. Experimental setup for measurement of attenuation and fluorescence characteristics of optical signals in EDF.

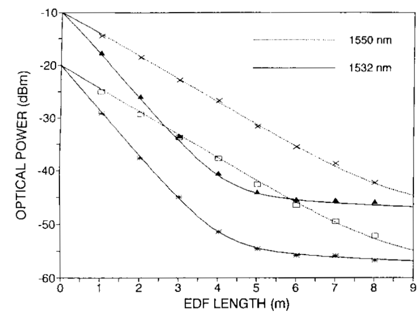

Fig. 2. Forward optical power versus EDF length for −10- and −20-dBm input signal power at 1532 and 1550 nm wavelength. Labeled data points are measured by experiment, and the curves are numerical results from theoretical model.

then fused again, and the measurement procedures are repeated.

IV. Results and Discussion

Fig. 2 shows the optical power measured by the optical power meter versus EDF length for an input signal power level of −10 and −20 dBm at 1532 and 1550 nm. The labeled data points are measured experimentally, and the curves are numerical results that fit the experiment results well. These results indicate that the optical power measured by the optical power meter decreases more slowly at long EDF length. This is especially true for an optical signal at 1532-nm wavelength, which has a larger absorption cross section in EDF. Thus, if the attenuation of the optical signal at a wavelength near the absorption peak of EDF is measured by the cutback method with an optical power meter, one may obtain smaller attenuation per unit length at a longer EDF length.

This behavior of optical signal attenuation in the EDF is due to the fact that at longer EDF length the output power is dominated by fluorescence power generated in the EDF, as shown in Fig. 3. It can be seen that the input signal decays drastically along the EDF length, whereas the fluorescence power grows rapidly at short EDF length to a power level about 30 dB lower than the input signal and then decays slowly at the longer EDF length. This reveals the fact that the input signal, though at a fairly low power level, acts as a pump source that excites the erbium ions from ground state to metastable states. Thus, the input signal is absorbed and turns into fluorescence powers emitted uniformly in each direction. Only those fluorescence powers within the numerical aperture of the EDF can be captured, and these are approximately 30 dB less than the input signal power.

The reason why the fluorescence power decayed slowly at the longer EDF length can be explained by Fig. 4, where the numerical results of forward fluorescence power spectra at various EDF lengths for a −10-dBm input signal power at 1532 nm is shown. It can be seen that in addition to the signal power, a broad spectrum fluorescence (the solid curve) is generated. At the longer EDF length, the fluorescence power in the proximity of the absorption peak decays drastically, while the fluorescence power far from the absorption peak survives. The experiment results observed on the optical spectrum analyzer verify this point.

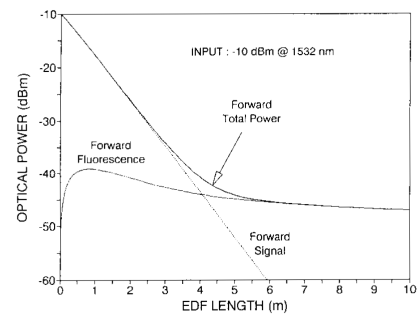

Fig. 3. Forward total power consists of forward fluorescence power and signal power for various EDF lengths with −10-dBm input signal power at 1532 nm.

Fig. 5 shows the numerical results of the fluorescence power spectrum in the backward direction. In contrast to the forward fluorescence power spectrum, its wavelength spectrum does not change for EDF longer than 3 m. This shows that only a negligible amount of backward fluorescence power is contributed by EDF longer than 3 m, due to high attenuation of optical signals propagating in the EDF. This point is also verified by the experiment results.

Fig. 6 shows how the forward and backward fluorescence power grows and decays at various EDF length for −10- and −20-dBm input signal powers at 1532- and 1550-nm wavelengths. It can be seen that the forward fluorescence power decays along the EDF length, while the backward fluorescence power maintains at a power level approximately 30 dB lower than the input signal power for an EDF length longer than 3 m.

V. Conclusion

Attenuation and fluorescence characteristics of optical signals propagating in an EDF are investigated theoreti-

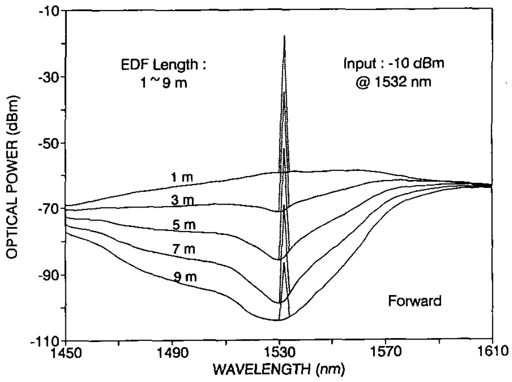

Fig. 4. Forward fluorescence power spectra at various EDF lengths for a −10-dBm input signal power at 1532 nm launched into the EDF, where the signal power is shown in the dashed curve and a broad spectrum fluorescence generated is shown in the solid curve.

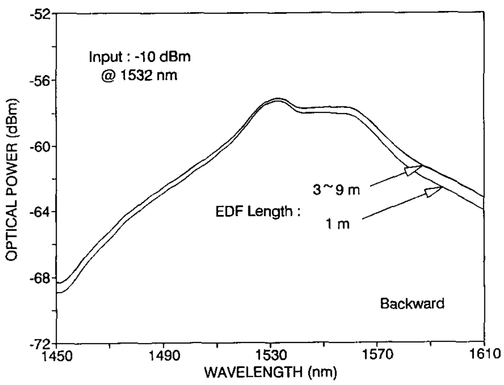

Fig. 5. Fluorescence power spectra in the backward direction for various EDF lengths, with −10-dBm input signal power at 1532 nm.

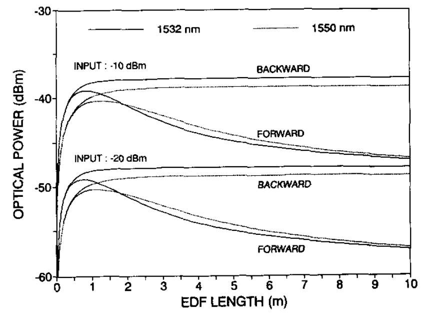

Fig. 6. Forward and backward fluorescence power at various EDF lengths for −10- and −20-dBm input signal powers at 1532- and 1550-nm wavelengths.

cally and experimentally. A broadband fluorescence spectrum will be generated in EDF even when a monochromatic light source is used. Care must be taken when the conventional cutback method is used to measure the signal attenuation in an EDF. The forward fluorescence power decays slowly at long EDF length, while the backward fluorescence power and power spectrum do not change for the long EDF.

References

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