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Experimental Evaluation of Frequency Characteristics of Gain-saturated EDFA for Suppression of Signal Fluctuation in Terrestrial Free-space Optical Communication Systems

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Frequency characteristics of gain-saturated erbium-doped fiber amplifier (EDFA) are experimentally evaluated to mitigate the optical signal fluctuation induced by atmospheric turbulence in terrestrial free-space optical communication systems. Here, an acousto-optic modulator (AOM) is used to emulate optical signal fluctuations induced by atmospheric turbulence. The waveform which is generated in proportion to the refractive-index structural parameters is used to drive the AOM at various periodic frequencies. Thus, the dependence of the signal fluctuation suppression on the frequency is evaluated. The experiment is conducted using a periodic frequency sweep of the AOM driving voltage waveform and signal input power variation of the amplifier. It is observed that a low periodic frequency and high input signal power effectively suppress the optical signal fluctuation. This study evaluates the experimental results from the high-pass filter and gain-saturation characteristics of the EDFA.

Keywords : Erbium-doped fiber, Free-space optical communication
OCIS codes : (060.2320) Fiber optics amplifiers and oscillators; (060.2605) Free-space optical communication

I. INTRODUCTION

Recently, high-speed and high-capacity communication technologies are required because of the rapid increase in wireless data usage. In these circumstances, free-space optical (FSO) communication has several advantages, such as a wide bandwidth, unlicensed spectrum, high security, low SWaP (size, weight, and power), and no electromagnetic interference [1–3]. Therefore, FSO communication systems have received considerable attention in recent years. However, certain disadvantages of FSO communication systems, such as the requirement for tight acquisition owing to the narrow beamwidth, effect of ambient light, and atmospheric conditions, render the commercialization of FSO communication technology difficult [2–5]. Therefore, research to address these disadvantages has become increasingly important.

Various schemes have been proposed and demonstrated to mitigate optical signal fluctuations induced by atmospheric turbulence in terrestrial FSO communication systems [6–8]. The application of optical amplifiers is one of the simplest and most cost-effective schemes for the implementation of reliable FSO communication links [7, 8]. The gain-saturation characteristics of optical amplifiers, such as erbium-doped fiber amplifier (EDFA) and semiconductor optical amplifier (SOA) is well suited for the suppression of atmospheric turbulence-induced optical signal fluctuation. In [8], authors claimed that gain-saturated SOAs might be an appropriate solution for commercial FSO communication applications owing to their lower price and smaller size. However, the suppression of optical signal fluctuation induced by atmospheric turbulence in terrestrial FSO com-

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munication systems would be dependent on not only gain-saturation characteristics of an optical amplifier, but also a lifetime of carrier or ion for the signal amplification. It has been well known that the carrier lifetime in SOA is an order of ns while the erbium ion lifetime in EDFA is about 10 ms [9]. The carrier lifetime of ns order in SOA is too short to suppress the atmospheric turbulence-induced optical signal fluctuation efficiently. On the other hand, the long lifetime of the erbium ion provides high-pass filter characteristics in the input/output signal transfer characteristics [9]. Using this high-pass filter characteristic of the EDFA, the power spectral density (PSD) of the atmospheric turbulence-induced optical scintillation, which could be modeled using a low-pass Butterworth filter [10], was efficiently suppressed in terrestrial FSO communication systems [11]. Therefore, two characteristics of the EDFA, the gain saturation and high-pass filter characteristics were applied to suppress optical signal fluctuations.

In this study, the influence of these two characteristics was experimentally verified with an EDFA. First, we utilized a two-stage EDFA to compensate for the transmission loss and suppression of the optical signal fluctuation in terrestrial FSO systems. To emulate the optical signal fluctuation induced by atmospheric turbulence, an acousto-optic modulator (AOM) was driven by the voltage waveform calculated from the observed meteorological data. In [11], a sinusoidally fluctuating optical signal was used to examine the performance of one-stage EDFA. Here, instead of using a sinusoidally fluctuating optical signal, a random fluctuating optical signal which was generated with actual observed weather data and two-stage EDFA were used to conduct experiments closer to real conditions. The impact of the high-pass filter and gain saturation characteristics of the EDFA on the suppression of the signal fluctuation was evaluated by changing the sweep frequency of the AOM driving voltage waveform and the input power into the second-stage of the two-stage EDFA. From the results, we confirmed that the EDFA could effectively suppress atmospheric turbulence-induced optical signal fluctuations.

II. MEASUREMENT AND DISCUSSION

The experimental setup is shown in Fig. 1. A laser diode (LD) with a wavelength of 1,553.328 nm and output optical power of 10 mW was used as the light source. The optical signal fluctuations in the channels of the FSO communication systems were emulated using an AOM and function generator. After passing through the AOM, the power of the optical signal was set to −30 dBm with the first variable optical attenuator (VOA1) and then launched into the first-stage EDFA. We assume that the first-stage EDFA was used to compensate for the transmission loss of the optical channel. The amplified optical signal was launched into an arrayed waveguide grating (AWG1) with a center wavelength of 1,553.328 nm and a 3-dB bandwidth of 0.24 nm. Thus, the AWG1 could only pass the signal wavelength, and the amplified spontaneous emission (ASE) noise components located outside the signal wavelength band were efficiently suppressed. The input power of the optical signal into the second EDFA was adjusted using the second VOA (VOA2). By changing the input power into the second-stage EDFA, the effect of the EDFA gain saturation on the suppression of the optical signal fluctuation was evaluated. Thus, in our two-stage EDFA, the second-stage EDFA was used to suppress the signal fluctuation with an appropriate amount of gain saturation of the EDFA. Another AWG (AWG2 had the same center wavelength and 3-dB bandwidth as AWG1) was used to pass the signal wavelength only and suppress the ASE noise components. The optical power was set to −11 dBm into a photodiode (PD) with VOA3 for all the measurements. Finally, the peak-to-peak voltage of the EDFA output from the optical signal fluctuation was measured using an oscilloscope.

Figure 2 shows the measured insertion loss of the AOM as a function of the driving voltage. The optical input power into the AOM was −6 dBm, whereas the optical output power was measured using a power meter. As shown in Fig. 2, the minimum and maximum losses of the AOM were obtained as 10 and 45 dB with driving voltages of 0.7 and 0 V, respectively. As the driving voltage of the AOM was increased from 0 to 0.7 V, the insertion loss was decreased. However, the insertion loss of the AOM was increased slightly again when the driving voltage was higher than 0.7 V. From the results, we deduced that our AOM was sufficient to emulate the optical signal fluctuation by adjusting the driving voltage from 0 to 0.5 V.

To confirm the two main characteristics of the EDFA, namely the high-pass filter and gain saturation, a randomly

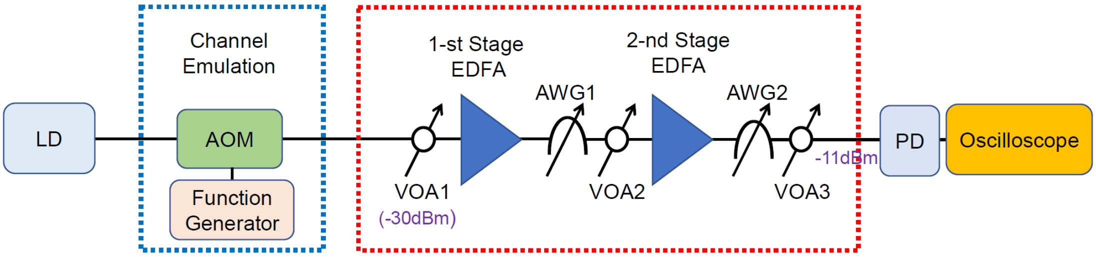


FIG. 1. Experimental setup. LD, laser diode; AOM, acousto-optic modulator; VOA, variable optical attenuator; EDFA, erbium-doped fiber amplifier; AWG, arrayed waveguide grating; PD, photo diode.

fluctuating optical signal was used to examine the performance of the amplifier. A randomly fluctuating optical signal was generated with a driving voltage of an AOM which was proportional to the refractive-index structure parameter (C_n^2). The refractive-index structure parameter is a model of the optical effect that causes changes in atmospheric conditions and is calculated as follows [5]:

$$\begin{aligned} C_n^2 &= 3.8\times10^{-8}W + 2\times10^{-15}T - 2.5\times10^{-15}U \\ &\quad + 1.2\times10^{-15}U^2 - 8.5\times10^{-17}U^3 - 2.8\times10^{-15}RH \\ &\quad + 2.9\times10^{-17}RH^2 - 1.1\times10^{-19}RH^3 - 5.3\times10^{-13}, \end{aligned} \tag{1}$$

where W is the temporal hour weight, T is the air temperature (in Kelvin), U is the wind speed (in m/s), and RH is the relative humidity (in %). In our measurement, a value of C_n^2 was calculated using weather observation data from the open MET data portal of the Korea Meteorological Administration (KMA) [12]. Experiments closer to real conditions were conducted because of the use of actual observed weather data. Figure 3 shows the C_n^2 waveform calculated using observational data acquired every minute from the Seoul Observatory (108) in November 2020. As expected, the calculated C_n^2 had a value of ~10^{-14}, which is similar to the values in [5]. One period of the AOM driving voltage was then generated using the calculated C_n^2. Figure 4(a) shows the output waveform of the function generator based on the calculated C_n^2 value. Using the output waveform of the function generator, the AOM was driven to generate a randomly fluctuating optical signal. Figure 4(b) shows one period of a randomly fluctuating optical output signal of the AOM measured using a PD. Owing to the saturation characteristics of our AOM, as shown in Fig. 2, the output signal variation of the AOM in Fig. 4(b) is slightly different from the output waveform of the function generator in Fig. 4(a).

Using the randomly fluctuating optical signal, the impact of the frequency and input power on the suppression of the optical signal fluctuation in our two-stage EDFA was evaluated. In our measurement, the frequency refers to the periodic frequency of the modeled waveform [Fig. 4(b)]. The

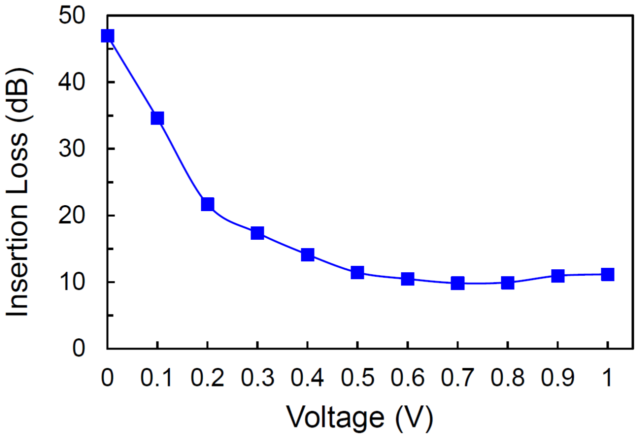


FIG. 2. Insertion loss of AOM measured as a function of driving voltage. AOM, acousto-optic modulator.

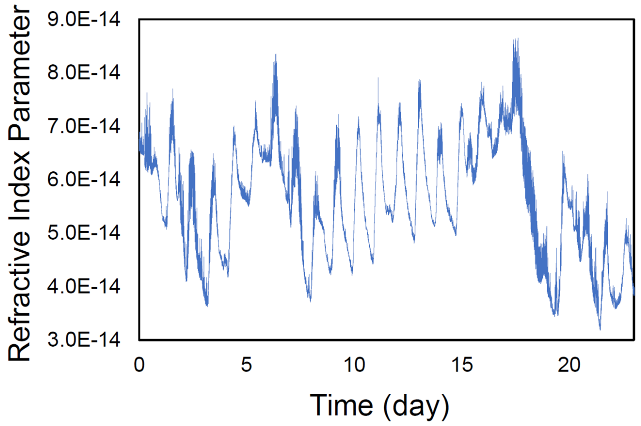
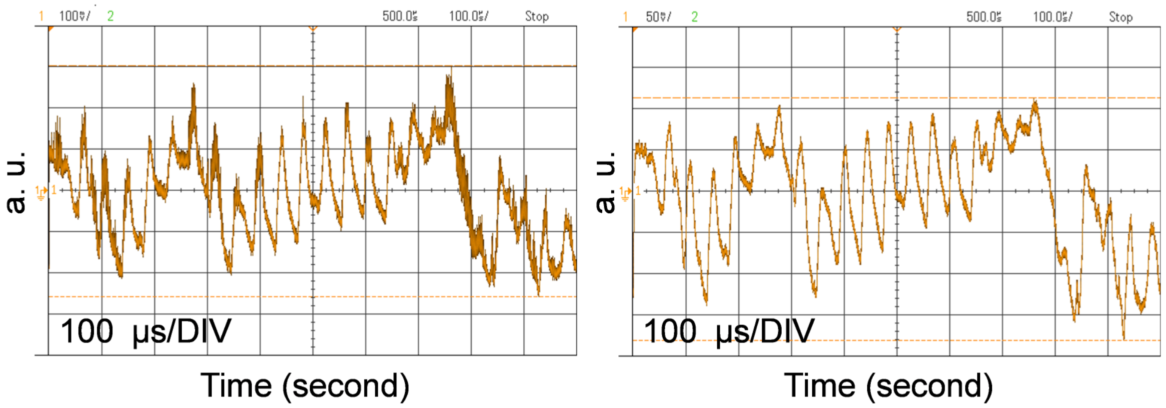


FIG. 3. Refractive-index structure parameter (C_n^2) calculated using the weather observation data.



(a)

(b)

FIG. 4. Output waveform traces measured at (a) output of function generator driven with the calculated refractive-index structure parameter and (b) output of acousto-optic modulator (AOM).

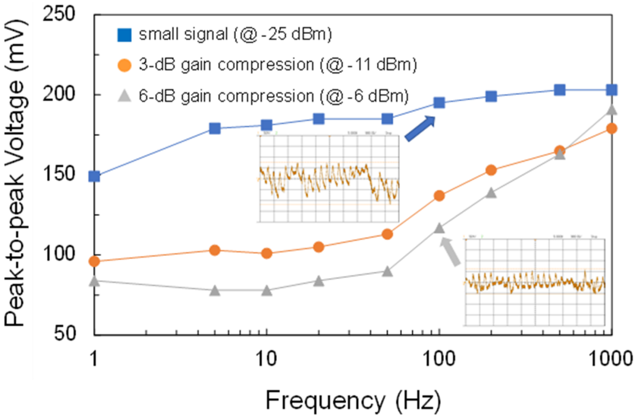


FIG. 5. Peak-to-peak voltage of optical output power of our two-stage EDFA measured using an oscilloscope and as a function of the periodic frequency. Three optical input powers, −25, −11, and −6 dBm, of the second-stage EDFA, were used to change the amount of gain saturation. Insets are the measured traces of optical output power with the optical input powers of −25 dBm and −6 dBm at the periodic frequency of 100 Hz. EDFA, erbium-doped fiber amplifier.

periodic frequency refers to how often the modeled optical signal fluctuation is launched into the two-stage EDFA. For example, a periodic frequency of 10 Hz implies that one period of the modeled waveform is input 10 times per second. Finally, the peak-to-peak voltage of the output signal power passing through the gain-saturated EDFA was measured according to the changes in the periodic frequency and input signal power. Figure 5 shows the frequency characteristics of our EDFA measured by sweeping the periodic frequency from 1 Hz to 1 kHz with three different optical input powers into the second-stage EDFA, which fluctuated, as shown in Fig. 4(b). The graph was plotted when the output signal power in the PD was −11 dBm. The peak-to-peak voltage of the output signal gradually decreased as the periodic frequency decreased, whereas the decreasing slope changed at an approximately periodic frequency of 100 Hz. Based on the input signal power, the peak-to-peak voltage of the output signal was not significantly different at a periodic frequency of 1 kHz; this difference gradually occurred as the periodic frequency decreased. At a periodic frequency of 10 Hz, the peak-to-peak voltage was 181 mV at an input power of −25 dBm (small signal gain region); However, as the input power increased to −11 dBm (3-dB gain compression point), the peak-to-peak voltage decreased to approximately half and attained 101 mV. Insets show the output voltage traces of the two-stage EDFA measured at two optical input powers, −25 and −6 dBm, into the second-stage EDFA and a periodic frequency of 100 Hz. Additionally, with an increase in the input signal power, a decrease in the peak-to-peak voltage of the output signal was observed, which supported the theoretical background of the characteristics of the gain-saturated EDFA.

III. SUMMARY

Optical signal fluctuations were suppressed based on the principle that higher input signal power results in a smaller gain when the EDFA is gain saturated. As the input signal power increased from −25 dBm (small-signal gain region) to −11 dBm (3-dB gain compression point) at a periodic frequency of 10 Hz, it was experimentally proven that the output peak-to-peak voltage was approximately half from 181 to 101 mV (based on an output signal power of −11 dBm). Because the lifetime of the erbium ions was long, the EDFA exhibited high-frequency response characteristics. Therefore, it was experimentally verified that the output peak-to-peak voltage continued to decrease as the periodic frequency decreased. Variations in actual weather conditions occur arbitrarily; However, we know empirically that variations in weather factors are unlikely to change rapidly over a short period of time. Because most weather conditions have low-frequency components, optical signal fluctuations induced by atmospheric turbulence can be effectively suppressed using a gain-saturated EDFA, as implemented herein.

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DISCLOSURES

The authors declare no conflicts of interest.

DATA AVAILABILITY

Data underlying the results presented in this paper are not publicly available at the time of publication, which may be obtained from the authors upon reasonable request.

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