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The improvement of fiber-detection method to enhance the output of amplify-received relaying on FSO communications

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***Abstract*—The performance of free-space optical (FSO) communications that using an optical amplifier (OA) in the scheme of an amplify-received (AR)-relaying has a major drawback in the detection of input signal quality under the effects of turbulence. As an OA is based on a fiber-detection (FD) method to receive and delivers a signal at the amplification process stage, there is an opportunity to implement an optical spatial filter (OSF) to improve the quality of an input signal. In this paper, as the continuation of previous work on the direct-detection, the OSF is applied on the AR-relaying. The novelty proposed in this work is the improvement of FD method where the OSF is designed as the integration of cone reflector, pinhole and multi-mode fiber with an OA. The OSF produces an optical signal, the input of the OA, which minimizes the effects of turbulence, background noise and signal fluctuation. Thus, OA in AR-relaying produces signal output with high power and rise up below threshold level. Additionally, an OSF with a lower pinhole diameter produces the best quality of the signal spectral to be delivered into an EDFA. Through this implementation, the performance of optical relaying on FSO can be significantly improved.**

***Keywords*—amplify-received relaying; optical relaying network; free-space optical communications; noise suppression; optical spatial filter; scintillation**

I. Introduction

FREE-SPACE optical (FSO) communications has a great opportunity to be expanded for applications to support many platforms of telecommunication systems such as high-altitude, satellite, terrestrial, and mobile terminal [1–4]. To the best of our knowledge, FSO also has been investigated intensively for the application in deep-space communications, underwater-communications, and Li-Fi [5–7]. However, with the potential of rate capacity in the order of a gigabyte or terabyte for transmitting data or signals, FSO has faced a major problem in penetrating the barrier of atmospheric turbulence effects in order to reach the long distance of optical propagation. It has been reported that FSO in a wavelength division multiplexing (WDM) configuration of 100.8 Tbps, using the orthogonality of orbital angular momentum (OAM), successful transmitted data for a link distance of nearly 1 m [8]. Other research has reported that WDM on FSO has successfully transmitted 400 Gb over a link distance of 120 m using an OAM method with an optical amplifier (OA) using Amplify-and-Forward (AF) relaying [9]. The method of all-optical two-way half-duplex relaying (AF- and AR-relaying) has reported that FSO was successfully simulated for connecting a high-altitude platform at a link distance of 20 Km [10]. An FSO experiment with 40 Gbps successfully demonstrated reaching the path length of optical propagation at 4 Km [11].

An OA is the best option to boost the signal strength and optimize an optical propagation in order to penetrate the barrier of atmospheric turbulence. However, boosting the optical signal from a transmitter (Tx) using an OA is not the only available solution to expand the optical link distance. The strength of the optical signal that is produced from an OA does not ensure the optical propagation is immune to atmospheric turbulence effects. The long distance of optical propagation causes beam wandering, where the detection angle of optical propagation is random and there is fluctuation around the optical axis of the receiver (Rx). Due to this effect, an optical signal amplification scheme in FSO suffers from misdetection where the incoming optical signal is not optimally delivered into the amplification process stage. In the worst case of strong turbulence level, where the optical signal coming into the detection area deviates greatly from the optical axis, the OA receives more noise than signal, which leads to a significant degradation of performance. Thus, the employment of an OA in FSO requires a method that can solve the problem of misdetection and suppress the higher noise modulation before the incoming optical signal enters the amplification process stage in an OA.

Frequently, an OA that is used in FSO is an Erbium-doped fiber amplifier (EDFA) [12–15]. The other scheme of optical signal amplification in FSO uses a semiconductor optical amplifier (SOA) [16–18]. Commonly, EDFA or SOA are configured in AF-relaying in order to transmit the optical signal to reach the long distance of the destination point [19–20]. Both optical signal amplification schemes are based upon the fiber-detection (FD) method to boost the strength of optical signal. Unfortunately, the atmospheric turbulence effects of scintillation, spatial noise, and beam wandering are modulated on optical propagation [21–22]. The optical signal is boosted from the EDFA and SOA, then transmitted out over a hundred meters or several kilo meters. During the transmission, the accumulation of increasing atmospheric turbulence can also affect the signal detection. Thus, the incoming optical signal that modulates maximum noise is received by an optical fiber and then delivered into an OA. This creates two conditions. First, if

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the optical signal received falls below the threshold level of input power from an OA, then the amplification process stage does not boost the signal power as expected. Second, if the incoming optical signal exceeds the threshold level of input power from an OA, then the noise goes through the amplification. These two extreme conditions lead to performance degradation of FSO. The issue of maximum fade out of input power, induced by beam wandering and spatial noise, still exists even when an OA is configured as gain saturated. Additionally, strong turbulence level affects the detection of an optical signal in EDFA, producing the worst signal quality. Therefore, the FD method, as the fundamental technique to receive an optical signal, needs to be improved in order to enhance the performance of OA, such as AF- and AR-relaying, in reaching long distance destinations. Thus, AF- and AR-relaying need an optical method to improve the quality of the input signal to be delivered into the amplification process stage of an OA.

An optical spatial filter (OSF) was successfully developed and implemented in the receiver of an FSO as the improvement technique for the direct-detection (DD) [23]. The benefit of this approach is the optimal suppression of spatial noise, scintillation, and beam wandering, which improves the FSO performance under the influence of atmospheric turbulence. The OSF is an optical method that also has the advantage of responding quickly to suppress the noise bandwidth, in comparison to the electronics filter method. The OSF can be coupled with an OA to anticipate the maximum fade out of an optical input power caused by a strong turbulence level [24]. By implementing an OSF that is incorporated with the FD method, the received optical signal has higher signal intensity and lower noise modulation before being delivered into the amplification process stage. An OSF has been reported that successfully utilized multi-mode fiber (MMF) in suppressing the noise modulated in the signal spectral of FSO [25].

In this study, an OSF incorporated with an optical fiber was proposed to improve the performance of optical signal amplification in an EDFA since the reception of signal is based on FD method. The OSF was designed as the optical element, composed of a cone reflector, pinhole and MMF. In the experiment, the OSF was incorporated with an EDFA to anticipate the maximum fade-out of input power that frequently fell below the threshold level of input power and suppressed noise modulation in the signal spectral. The FSO experiment was performed in a laboratory using an atmospheric chamber as the turbulence media to induce the optical propagation. The FSO was configured as AF- and AR-relaying, and the OSF was installed in the FD method before the signal entered the EDFA. Thus, the novelty proposed in this work was improving the performance of optical signal amplification in AR-relaying through the installment of the OSF as the optical signal detection in order to deliver a signal with minimum of turbulence effects into an OA.

The main contribution of this work is to improve performance of FSO that is configurated in the scheme of relaying network. The optical relaying network (ORN) has an advantage to expand the link distance of optical propagation through the atmosphere without fulfilling the requirement of line-of-sight between Tx and Rx [26-27]. However, in each node of the ORN, the implementation of AF- and AR-relaying technique that uses an OA does not save from turbulence effects. For this reason, broken link is the major problem in the ORN where each node has high probability to be induced by atmospheric turbulence in random fashion. Thus, in order to minimize broken link condition in each node, there must be an improvement on FD method of an OA to ensure that received signal is minimum from turbulence effects. In this case, the OSF has an important role to be integrated with an OA to ensure that the received signal is high quality and can be enhanced optimally in the amplification process stage to be delivered out into the atmosphere to reach next node in the ORN. Thus, if each node of AR-relaying implements the OSF as the optical signal detection, optical transmission between nodes can be minimized from turbulence effects. By considering the aforementioned reasons, through integration of the OSF with an OA in AF- and AR-relaying, the performance of the ORN of FSO can be maintained in a high quality as well.

II. The Performance of Optical Signal Amplification in AR-Relaying

The optical propagation of FSO induced by atmospheric turbulence is shown in Fig. 1. The optical signal amplification in FSO for AF-relaying implements an EDFA (OA-1) in the Tx to boost the strength of the optical signal and penetrate the barrier of atmospheric turbulence. The optical propagation from the beam collimator, that undergoes scintillation, beam wandering, and spatial noise modulation, is dependent on the receiver lens. Furthermore, an optical signal is delivered into an OA-2, which is amplified in the Rx by implementing the EDFA. The OSF is composed of a cone reflector, pinhole and MMF and is implemented before the optical signal amplification process stage in AR-relaying. It performs spatial filtering on the focus spot from the receiver lens, and produces the input of signal power $\langle P_{in}^{S1} \rangle$ for the EDFA.

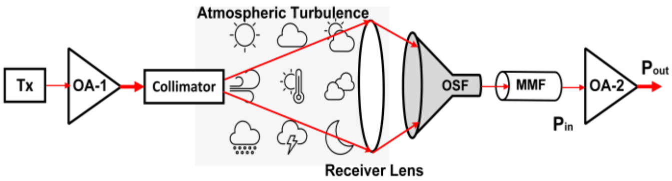


Fig.1. The optical signal amplification in the AF- and AR-relaying scheme where each one using EDFA in Tx and Rx under the influence of atmospheric turbulence as the basis of node configuration in the ORN of FSO

For optical signal amplification in the EDFA, the gain factor, G, limits output power of AR-relaying at $\langle P_{out}^{S1} \rangle$ at all times [26] and is represented by:

$$G = \frac{\langle P_{out}^{S1} \rangle + n_{sp} h v_0 B_0}{\langle P_{in}^{S1} \rangle \alpha_{SR} + \langle P_B \rangle + n_{sp} h v_0 B_0}, \quad (1)$$

where the $\langle . \rangle$ brackets denote mean value, and h, n_{sp}, v_0, B_0, α_{SR}, and P_B are Planck's constant, amplified spontaneous emission (ASE) factor, optical center frequency, optical bandwidth of the system, source-relay channel gain, and background radiation power, respectively. The gain of the EDFA depends on parameters such as the power of the pump laser, doped fiber length, and wavelength of the excitation light provided by the pump laser [27]. Thus, $\langle P_{out}^{S1} \rangle$ is kept constant when the value of $\langle P_{in}^{S1} \rangle$ is equal to or higher than the threshold level of the input signal power of the EDFA, $\left(P_{in}^{Th}\right)$. When the value of the gain has a correlation with $\langle P_{in}^{S}\rangle$ [22] it can be expressed as:

$$G = \begin{cases} \geq 1, \langle P_{in}^{S1}\rangle \geq P_{in}^{Th} \\ = 0, \langle P_{in}^{S1}\rangle < P_{in}^{Th} \end{cases}. \quad (2)$$

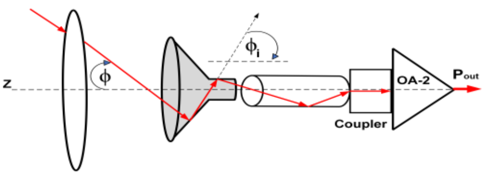
Eq. (2) suggests that, based on the three-level laser system, the optical signal amplification process is achieved when the minimum laser pumping power stimulates the population inversion of ion Er^{3+} in the upper state. Thus, the growth of the signal power increases exponentially into the saturation region, where the maximum laser pumping power is not comparable to the growth of the signal power output. The ASE is generated when the laser pumping power is equal to the level of P_{in}^{Th}. The critical condition where ASE is dominantly produced by the EDFA is when $\langle P_{in}^{S1}\rangle$ falls below P_{in}^{Th}. Thus, the growth of signal intensity is not achieved, resulting in a noise figure (NF). In the application of an EDFA as the optical signal amplification, it is important for $\langle P_{in}^{S1}\rangle$ to be higher than P_{in}^{Th} in order to achieve a $\langle P_{out}^{S1}\rangle$ that is higher than the NF.

Unfortunately, due to atmospheric turbulence effects in optical propagation, the input of signal power produced from the OSF is sporadic due to spatial noise, beam wandering and scintillation. This condition also produces the background noise received by the EDFA in AR-relaying. Thus, in Eq. (1), the gain of the optical signal depends upon three important variables, $\langle P_{in}^{S1}\rangle$, $\langle P_B\rangle$ and ASE, which can enhance the performance of optical signal amplification from the EDFA in the FSO for AR-relaying.

The modified optical system of the OSF [23], that suppresses the atmospheric turbulence effects on the optical propagation of FSO, is shown in Fig. 2. The OSF is composed of a cone reflector, pinhole and MMF that is coupled into an EDFA. The configuration of the optical system is composed of the receiver lens plane, $\boldsymbol{X_{-1}}$, OSF plane $\boldsymbol{X_0}$, and MMF plane, $\boldsymbol{X_1}$. In practice, $\boldsymbol{X_0}$ and $\boldsymbol{X_1}$ are coincidence where $z_1 \approx 0$ [23–25]. The optical signal power input resulting from the OSF and MMF is stated as:

$$\langle P_{in}^{S1}(\boldsymbol{r_1}, z_1 \approx 0, \phi_i)\rangle = \frac{\pi}{2}\frac{W_G^2}{W_0^2}\, SR\, I_{-1}^{0}(0, -L_f)\, \exp\left(-SR\frac{2r_0^2}{W_0^2}\right)\cos(\phi_i)\ B, \quad (3)$$

where $\boldsymbol{r_0}$ is the radial coordinate of the pinhole on $\boldsymbol{X_0}$; $I_{-1}^{0}(0, -L_f)$ is the free-space irradiance; W_0 is the effective aperture radius of the receiver lens; W_G is the focus spot radius; and ϕ_i is the incident angle with respect to the optical axis Z at the output of the pinhole at $\boldsymbol{X_0}$ and $\boldsymbol{X_1}$, SR is the Strehl ratio, and B is the circular aperture function. The Strehl ratio SR is $1/\left(1 + 1.63\, \sigma_R^{12/5}(L)\, \Lambda_{-1}\right)$, where the Rytov variance for the distance of optical propagation, L is $\sigma_R^{12/5}(L) = \left(1.23 C_n^2 k^{7/6} L^{11/6}\right)^{6/5}$, the effective beam parameter is $\Lambda_{-1} = 2L/kW_{-1}^2$, and the wave number is $k = 2\pi/\lambda$.



F

Fig. 2. The optical system of the OSF as the improvement for FD method, composed of cone reflector, pinhole and MMF delivering the optical signal into an EDFA by a coupler

The circular aperture function [23] is represented by:

$$B = \left\{\frac{r_1^2}{2} - \left[\frac{2A^2 r_1^2}{3}\cos(Ar_1)\, J_0(Ar_1) + \frac{A^2 r_1^2 \sin(Ar_1) - Ar_1\cos(Ar_1)}{3} J_1(Ar_1)\right] + \left[\frac{A^2 r_1^2}{2}\left(J_0^2(Ar_1) + J_1^2(Ar_1)\right)\right]\right\}, \quad (4)$$

where $A = [2\pi(D_P/2)/\lambda z_1]$ is the spatial frequency of the focus spot that is localized in the pinhole diameter of D_P at $z_1 \approx 0$; r_1 is the core radius of MMF; and J_1 is the Bessel function of the second kind.

In Eq. (1), the input of signal power $\langle P_{in}^{S1}\rangle$ resulting from the OSF remains higher under the influence of atmospheric turbulence. The beam wandering, that causes the incident optical propagation to become random, is collected radially by the cone reflector and guided into the pinhole diameter. The spatial noise that is modulated on optical propagation is filtered out by the pinhole. Under turbulence effects, the OSF maintains higher $\langle P_{in}^{S1}\rangle$ in order to minimize the optimum fade-out condition, where the optical signal power input falls below P_{in}^{Th} of the EDFA. Thus, the treatment of optical signal by cone reflector and pinhole produces minimum noise and high signal intensity to be delivered into MMF and goes through to EDFA via fiber coupler.

The background noise and ASE in Eq. (1) can be explained based on previous studies [26–28]. Factors for AR-relaying can be composed of background radiation DC current and noise variance, relay-destination background radiation beat noise, and ASE-ASE DC current and beat noise. Thus, background noise and ASE can significantly decrease the performance of optical signal amplification. Through using the OSF in the configuration of FD, the background noise can be optimally minimized by the circular aperture function of B, by filtering the optical signal in a localized region of the pinhole diameter. Thus, the optical signal, with minimum scintillation and noise, is guided to the core of MMF and delivered into the amplification process stage of the EDFA.

The optical signal amplification in the EDFA will achieve high performance based on the ability of the OSF mechanism to suppress the turbulence effects on the optical propagation. The OSF improves the output of signal power $\langle P_{out}^{S1}\rangle$ from the EDFA when the input of the optical signal power is higher than P_{in}^{Th} under turbulence effects. This condition produces optical signal power with minimum noise and ASE as well, $\langle P_{out}^{S1}\rangle \gg n_{sp}$. In other words, based on the mechanism of the signal amplification process in the EDFA, the growth of $\langle P_{out}^{S1}\rangle$ is higher than the value of NF. The background noise is also filtered out by the OSF, thus minimizing the noise power that is modulated on optical propagation under the turbulence effects. This condition is beneficial for the performance of optical signal amplification, where background noise is minimized before the amplification process stage in the EDFA.

The OSF is coupled with the EDFA to keep the input of signal power higher than P_{in}^{Th}, optimally minimize background noise, and achieve an optimal signal-to-noise-ratio (SNR). The SNR [29] is represented by:

$$\langle SNR\rangle = \frac{\langle P_{out}^{S1}\rangle}{Fh\nu\Delta\nu}, \quad (5)$$

where F is the noise factor, and $\Delta\nu$ is the bandwidth of the signal. For the binary on-off-keying (OOK) modulation, the performance of bit-error rate (BER) can be expressed as a Q-factor [29], represented by:

$$\langle Q\rangle = \sqrt{\frac{2\langle SNR\rangle \Delta v}{B_S}}, \quad (6$$

$$\langle BER\rangle = \frac{1}{\sqrt{2}}\frac{exp(-Q^2/2)}{Q}, \quad (7)$$

where B_S is the bandwidth of the electrical signal. When the OSF optimally suppresses noise before the optical signal enters the amplification process stage in the EDFA, the noise of the electrical signal can be minimized. Therefore, the Q-factor can also be improved. Thus, the performance of optical signal amplification in the EDFA of FSO can be optimally improved by implementing an OSF to receive an optical signal under the influence of atmospheric turbulence.

III. SETUP OF EXPERIMENT

The schematic diagram of the experiment and laboratory setup for FSO in the AF- and AR-relaying schemes using two optical amplifiers (EDFA-1 and -2) are shown in Figs. 3 – 4, respectively. FSO is configured in forward optical propagation through an atmospheric chamber called a box of turbulence simulator (BTS) which has the length of 4 m [23–24]. The optical parameters on Tx and Rx such as the beam diameter from collimator and diameter of lens receiver are implemented in the experiment based on [23-24]. The optical signal is generated by a laser diode (LD) in the Tx with a wavelength of 1555.08 nm. The data rate at 1 Gbps is set-in as the bandwidth of electrical signal, B_S for Tx. The electrical signal from the Tx is modulated in OOK by an optical modem, then coupled into an OA, EDFA-1. The high output of signal power from the EDFA-1 is collimated and the optical propagation is transmitted to the BTS. The optical propagation, modulated by turbulence media on the BTS, reaches the receiver lens and is then focused into the OSF. The OSF that is integrated with MMF is coupled into the EDFA-2 via fiber coupler. The output of optical signal amplification from the EDFA-2 is measured by optical instruments such as an optical signal analyzer (OSA), BER Tester (BER-T), and optical power meter (OPM). The experimental setup of the BTS is based on the strong turbulence level (α_{BTS}) used to induce the optical propagation. The properties of AF- and AR-relaying on FSO in optical terms are shown in Table I.

TABLE I
THE OPTICAL PROPERTIES OF AF- AND AR-RELAYING IN FSO SYSTEM

Parameters	Quantity
P_{Tx}	$0\ dBm$
G (EDFA-1 and -2)	$23\ dB$
B_S	$10^9\ bps$
P_{in}^{Th}	$-25\ dBm$
α_{BTS}	$30\ dB$

In the experiment, based on Table I and Fig. 3, the optical signal power from laser source LD is $P_{Tx} = 0$ dBm, and this signal is amplified to 23 dBm by the EDFA-1. The optical signal power from the EDFA-1 is transmitted out to the turbulence

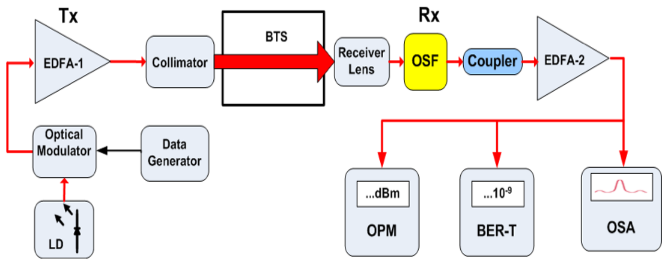


Fig. 3. The schematic diagram of experimental setup for FSO in the AF- and AR-relaying scheme using two optical amplifiers, EDFA-1 and EDFA-2 in the Tx and Rx, respectively

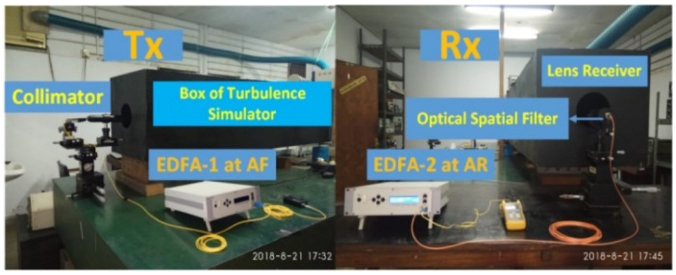


Fig. 4. The experimental setup for FSO in laboratory using BTS as the atmospheric chamber for optical propagation where Tx is the main device of EDFA-1 as AF-relaying, and Rx consists of the OSF and EDFA-2 as AR-relaying

media of the BTS under strong turbulence conditions, where the parameter of loss is $\alpha_{BTS} = 30\ dB$.

For the OSF, the design of the cone reflector and pinhole [23-25] is integrated with MMF. In the experiment, four OSFs are used with different pinhole diameters, D_P; $D_{P1} = 50\ \mu m$, $D_{P2} = 40\ \mu m$, $D_{P3} = 30\ \mu m$, and $D_{P4} = 20\ \mu m$. Each OSF is coupled with an MMF (NA of 0.22), core diameter of $62.5\ \mu m$, and optical fiber length of $2.0\ m$. The output of optical signal power from MMF becomes the input of the optical signal for the EDFA-2, and is coupled with minimum loss because the coupler converter (MMF to SMF) is also used. The main consideration to use MMF as the interface to the SMF of EDFA is NA able to receive larger angle from cone reflector when beam wandering incoming to the OSF. The loss of power conversion from MMF to SMF is about $1\ dB$ but it is not significant since the OSF produces signal with minimum noise and lower fluctuations as well. The higher-order mode from the OSF that is delivered into EDFA via SMF is no issue since the output of signal power from EDFA is directed into the atmosphere as the optical transmission to reach a next node or directly received by photodiode (PD).

The measurements of FSO performances are optical signal power, optical signal-to-noise-ratio (SNR), and BER rate. The optical instruments used are an OPM, OSA, and BER-T, as shown in Fig. 3. In the experiment, the BTS is configured for a strong turbulence level with a higher scintillation index ($\sigma_I \gg 1$). Subsequently, the optical propagation from the collimator that interacts with turbulence media inside the BTS goes through the OSF. The output of optical signal power from the OSF is measured as $\langle P_{in}^{S1}\rangle$ in dBm, and this becomes the input signal power to the EDFA-2. Thus, as the result of optical signal amplification from the EDFA-2, the output of signal power $\langle P_{out}^{S1}\rangle$ is produced.

IV. RESULTS AND DISCUSSION

The results of the experiment are analyzed in the parameters of SNR and BER, and the comparison is based upon signal power from the OSF and EDFA-2 for two conditions; non-turbulent and turbulent, as outlined below in sub-section 4.1. The signal spectral as the indicator of signal quality is also presented in this section, as outlined below in sub-section 4.2.

A. *The Performance of FSO in the AR-relaying Scheme*

The measurements produced in the experiment by the OSF and EDFA-2 are shown in Figs. 5 – 6. In Fig. 5, in the presence of strong turbulence, the optical signal power input produced by FD is much lower where $< P_S^1 > = -32\ dBm$. This value also falls below the P_{in}^{Th} of the EDFA-2. The optical signal power input in the BTS produced by the FD method for non-turbulence, or the absence of strong turbulence, is higher where $P_S^0 = -15\ dBm$. The OSF is installed to improve the FD method in the case of strong turbulence on the BTS. The optical signal power input is further improved for $< P_S^1 >$, as shown by the results of $< P_{in}^{S1} >$ as the function of D_P. The OSF minimized the turbulence effects modulated on optical propagation, thus suppressing beam wandering, spatial noise, and as well as scintillation. Through this mechanism, the optical signal intensity is directed by the OSF onto MMF as an input of the OA, EDFA-2. $< P_{in}^{S1} >$ is also higher using the OSF beyond P_{in}^{Th}. Under the influence of strong atmospheric turbulent, $< P_{in}^{S1} >$ produced by the FD method in the AR-relaying scheme frequently falls below the value of P_{in}^{Th}. This condition decreases the performance of optical signal amplification because the signal detection used to implement the FD method at the input of the optical signal fades out. However, by using the OSF as the optical signal detection before the amplification process stage in the EDFA-2, the optical signal power input remains higher as it as approaches P_S^0. The OSF shows a trend that the output of optical signal power tends to be higher as D_P goes lower. This is confirmed by the $< P_{in}^{S1} >$ values from D_{P3} and D_{P4}. The benefits of the lower diameter of the OSF are the optimal suppression of spatial noise, beam wandering, and scintillation.

In the experiment, P_{in}^{Th} of EDFA-2 is $-25\ dBm$ where this is the case for an OA characteristic that available in the market. Perhaps another proper designed of an OA such an EDFA has lower of P_{in}^{Th} than the one used in the experiment. However, the point of this experiment is to improve the signal intensity that is fade-out caused by turbulences effects. Even though, if the lower of P_{in}^{Th} on EDFA-2 is applied for AR-relaying without implement the OSF, as in example in the value of -30 dBm or even lower, still FD method cannot anticipate beam wandering and noise modulation. The lower value of P_{in}^{Th} does not guarantee for an OA receives the best input signal quality to be processed into the amplification process stage. Therefore, in the experiment the value of P_{in}^{Th} is the case for the commercial of OA. Thus, this work does not generalize all optical amplifiers in the market has the same value of P_{in}^{Th}. The key point is FD method in the reception of signal input for an OA is degraded and need to be improved to optimize the amplification process stage of optical signal within.

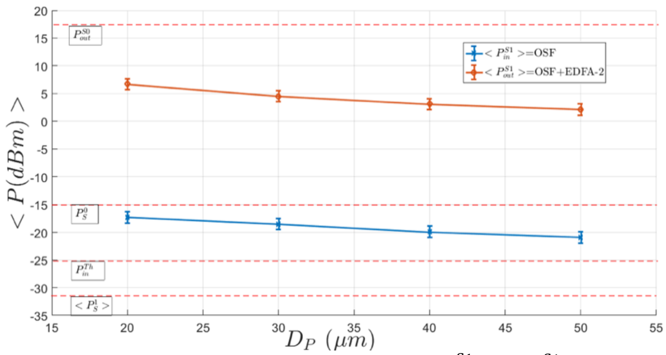


Fig. 5. The input power of optical signal amplifier, $\langle P_{in}^{S1} \rangle$ and $\langle P_{out}^{S1} \rangle$ vs. pinhole diameter of the OSF, D_P

In Fig. 5, the output of optical signal amplification produced by the EDFA-2 is higher. $\langle P_{out}^{S1} \rangle$ for all D_P is higher and tends to approach the output of optical signal amplification in the absence of turbulence. The output of optical signal amplification through the FD method with turbulence fades out. $\langle P_{in}^{S1} \rangle$ for the OSF method is higher with strong turbulence, and the noise is optimally suppressed. Therefore, the background noise is filtered out in order to deliver a signal intensity with minimum noise into the amplification process stage. The optical signal amplification in the EDFA-2 grows optimally through this process and does not compete with NF caused by the optical signal intensity. NF is beyond P_{in}^{Th} and has characteristics of minimum of noise modulation. Thus, the EDFA-2 predominantly produces the optical signal power rather than noise under the influence of strong turbulence. As $\langle P_{in}^{S1} \rangle$ from the OSF for all D_P is produced higher, $\langle P_{out}^{S1} \rangle$ produced by the EDFA-2 is also higher. $\langle P_{out}^{S1} \rangle$ also exhibits a trend of higher $\langle P_{in}^{S1} \rangle$ when D_P becomes smaller.

In the absence of turbulence, the signal-to-noise-ratio, SNR^0, and bit-error rate, BER^0, achieve higher and lower results, respectively, as shown in Fig. 6. Those parameters show the best performance because turbulence effects are not modulated on optical propagation. In the presence of strong turbulence, $\langle SNR^1 \rangle$ and $\langle BER^1 \rangle$ produced from the FD method are extremely degraded and fall below the performance of SNR^0 and BER^0. The OSF that is installed for AR-relaying keeps $\langle P_{in}^{S1} \rangle$ higher than P_{in}^{Th}; thus, $\langle P_{out}^{S1} \rangle$ produced by the EDFA-2 is higher with minimum noise. Therefore, the performances of $\langle SNR \rangle$ and $\langle BER \rangle$ for all D_P of the OSF are also higher. The values of $\langle SNR \rangle$ and $\langle BER \rangle$ of the function D_P are also better than SNR^1 and BER^1, approximating the values of SNR^0 and BER^0. They also show a trend when $\langle P_{in}^S \rangle$ is kept higher by the OSF, with the performances of $\langle SNR \rangle$ and $\langle BER \rangle$ improving significantly as D_P decreases.

Based on the results in Figs. 5–6, as estimated in previous reports [21,22] the improvement of optical signal amplification through the implementation of the OSF in the AR-relaying scheme on FSO is achieved by the cone reflector and pinhole that work simultaneously to collect the random beam wandering and spatial noise into a small area of signal detection, the pinhole diameter. Through this mechanism, the random dancing of the focus spot that frequently causes maximum deflection around the optical axis of Z can be optimally suppressed. Thus, each random movement of the focus spot is directed radially by the cone reflector into the pinhole diameter in order to be guided by MMF into the amplification process stage in the EDFA-2, as illustrated in Fig. 2. The optical signal input directed by the OSF into the EDFA-2 has higher intensity and less noise modulation than a signal received through FD method. The OSF facilitates optical signal amplification to anticipate the fade out condition, where the input signal intensity frequently falls well below P_{in}^{Th} of signal intensity required by the EDFA-2 to achieve the growth of signal intensity under population inversion by laser pumping. The OSF also suppresses the spatial noise in order to minimize the background noise that frequently passes into the amplification process stage in the EDFA-2. Minimizing the background noise in the EDFA-2 allows for the growth of optical signal amplification that does not compete with NF. Additionally, through the enhancement of optical signal intensity by the OSF, ASE does not dominate the amplification process stage. This means that the OSF maintains higher optical signal intensity and minimizes the background and spatial noises. Hence, the output of optical signal power from the EDFA-2 is higher than the performances of $\langle SNR \rangle$ and $\langle BER \rangle$ are improved, as shown in Fig. 6.

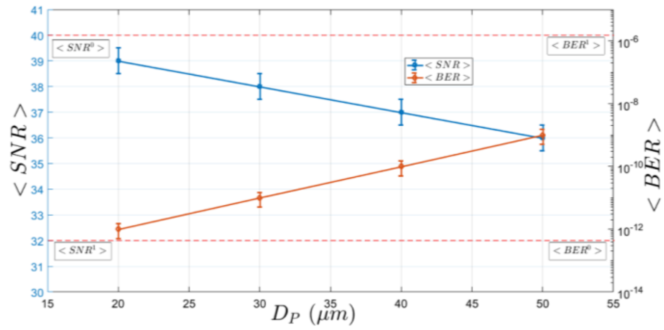


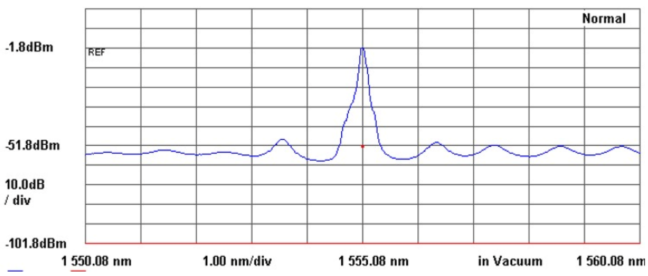
Fig. 6. The performance of AR-relaying on FSO as the function pinhole diameter of the OSF integrated with EDFA-2, D_P as the improvement of FD method

The improved performance in AR-relaying of FSO can be seriously degraded by the presence of strong atmospheric turbulence. The integration of the OSF with an OA such as EDFA, has the potential to be implemented in the AR-relaying scheme of FSO in order to expand the capacity of the ORN for connecting remote destinations at longer distances. For example, in multi-hop transmissions or the cooperative diversity technique, where AF- and AR-relaying of FSO are implemented [30–32], the OSF can be installed with an OA in each relay node to ensure that the system can reach the long-distance destination of optical propagation and penetrate the atmospheric turbulence barrier. Another advantage of implementing the OSF in each relay node is that background noise can be minimized where the pinhole diameter performs a low-pass optical filtering. Thus, in each node of optical signal detection for multi-hop transmissions, the turbulence effects of beam wandering, scintillation, and noise modulation can be optimally suppressed before an optical signal enters the amplification process stage in an OA. These advantages enhance the growth of optical signal intensity in an OA of each node to produce signal power output that dominates ASE and NF. It is expected that the implementation of the OSF in each relay node can minimize background noise and turbulence effects, as well as anticipate the broken link condition where the fade out of the optical signal is a major threat.

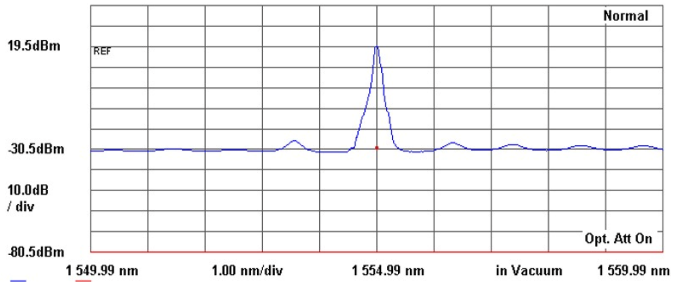
The OSF is an optical method that has the benefits of fast response and real-time processing, compared to the electronics filter method in PD. This improved time response mitigates the fading effect of optical propagation, improves noise filtering, and overcomes limited bandwidth. Aside from the benefit of improved performance, the OSF optical method of FSO also supports for a low-cost communications platform.

B. *The Signal Spectral Analysis*

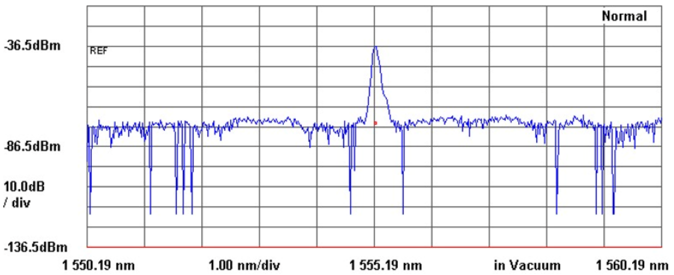
The results of the signal spectral analysis are shown in Fig. 7. Measurements were taken from the original laser source, Tx, and Rx for different conditions on the BTS. In Fig. 7 (a), the signal spectral produced by the laser source in the Tx is very original, whereas the DFB laser is smooth and peaks at 1555.08 nm with the power of -1.8 dBm. Second side modes for this original spectral are at 1553.64 nm and 1556.52 nm, both with the power of -46.58 dBm. This original signal spectral is amplified by the EDFA-1 for the AF-relaying scheme with a power output of 19.5 dBm, as shown in Fig. 7 (b). The signal spectral from the EDFA-1 is almost the same as the source, where it has not yet interacted with turbulence media in the BTS. When the signal spectral from the EDFA-1 is transmitted to the BTS with a strong turbulence condition inside, the signal spectral that is received by PD via the FD method is the poorest. As seen in Fig. 7 (c), the signal spectral fluctuates from its original center of wavelength to 1555.19 nm. The signal spectral in Fig. 7 (c) also optimally modulates noise because the turbulence effects in the BTS induce optical propagation during strong turbulence. The strength of the signal also drops under P_{in}^{Th}, where $\langle P_{out}^{S} \rangle = -36.5\ dBm$ is delivered into PD via the FD method. To suppress this condition, the OSF is applied in AR-relaying. The results of the signal spectral from the OSF as the function of D_P are shown in Figs. 7 (d) to (g). The signal spectral that is produced by the OSF has the least noise modulation and lower center wavelength fluctuation. Figs. 7 (d) to (g) also demonstrate a trend that lower D_P of the OSF produces the best quality of signal. Fig. 7 (g) shows that the signal spectral from D_{P4} is quite high and $\langle P_{out}^{S} \rangle = -15.3\ dBm$, similar to the original source shown in Fig. 7 (a). The signal spectral from D_{P1} is low where $\langle P_{out}^{S} \rangle = -21.8\ dBm$, and the noise modulation is higher than that produced by D_{P4}. However, the signal spectral quality from D_{P1} is better than the FD method or without the OSF.



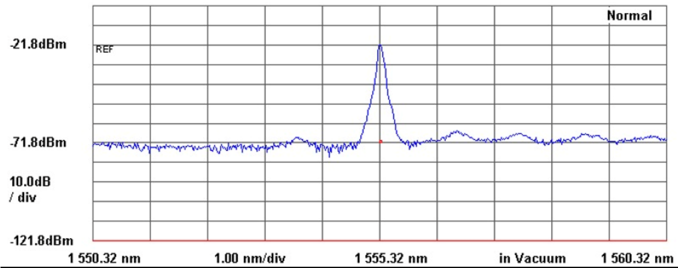
(a)



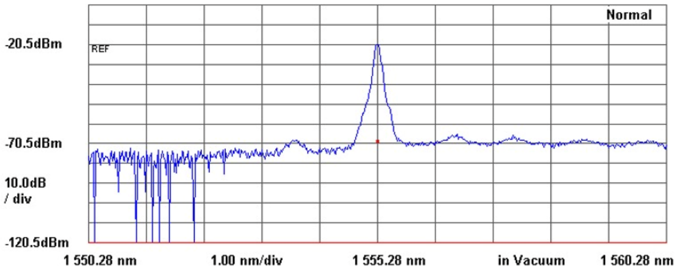
(b)



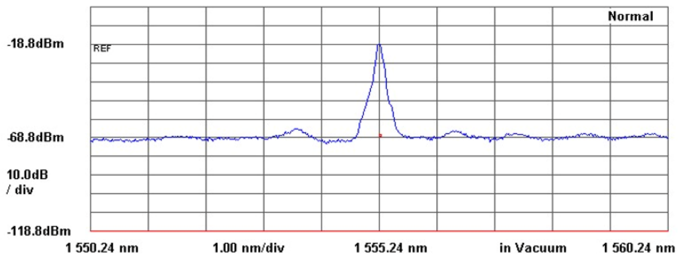
(c)



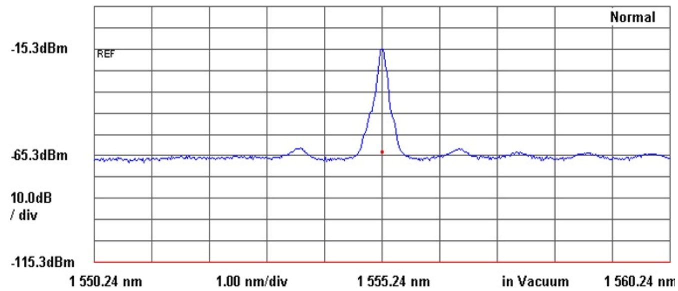
(d)



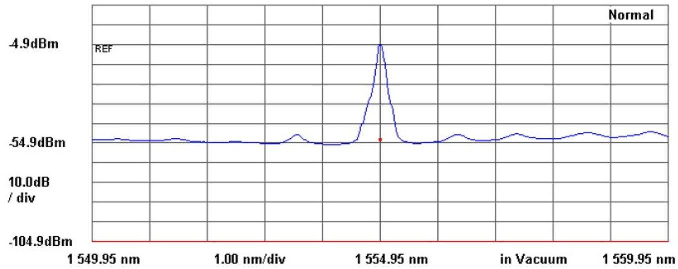
(e)



(f)



(g)



(h)

Fig. 7. The signal spectral measurements in FSO from Tx to Rx with two variations of conditions in BTS, non-turbulent and turbulent for all D_P. **(a)** The original signal spectral from TX laser source. **(b)** The signal spectral from EDFA-1 as the AF-relaying into BTS. **(c)** The signal spectral as the result of FD method with strong turbulence condition in BTS. **(d)** The signal spectral from OSF with $D_{P1} = 50\ \mu m$. **(e)** The signal spectral from OSF with $D_{P2} = 40\ \mu m$. **(f)** The signal spectral from OSF with $D_{P3} = 30\ \mu m$. **(g)** The signal spectral from OSF with $D_{P4} = 20\ \mu m$. **(h)** The sample of signal spectral from EDFA-2 as the AR-relaying for $D_{P3} = 30\ \mu m$

The signal spectral that is produced by the OSF is then delivered into the EDFA-2 as the AR-relaying. This sample of a signal spectral is shown in Fig. 7 (h), with minimum noise modulation and a fluctuation of center wavelength not quite as high as the FD method. The OSF suppresses noise modulation, which could degrade the quality of the input signal before it is delivered into the EDFA-2. The OSF maintains the signal beyond P_{in}^{Th} and minimizes noise modulation. Thus, using the EDFA-2 as the second booster to transmit the optical propagation into the next turbulence medium can work suitably to amplify the signal. Also, by implementing the OSF as a detection method before the EDFA-2, the fade out condition can be avoided. If the EDFA-2 receives a signal below P_{in}^{Th}, as shown in Fig. 7 (c), the amplification process in the EDFA-2 does not work properly. Under this condition, the EDFA-2 does not produce a high signal power or black-out. The amplification process of the signal will compete with noise amplification under moderate turbulence levels. In this case, the signal intensity received by the FD method is higher than that delivered into the EDFA-2. This means the EDFA-2 also has an opportunity to amplify the noise. For this reason, the OSF should be installed before the signal is received by the EDFA-2 in the AF-relaying scheme to suppress the noise modulation and deliver a signal spectral with the best quality to enter the amplification process.

Based on the experiment results, as shown in Figs. 5–7, the OSF has an opportunity to improve the FD method by implementing AR-relaying in the ORN scheme. The OSF can suppress noise modulation and minimize scintillation, beam wandering and fluctuation of the signal spectral before the optical signal amplification process stage, as discussed in previous research [23][33]. These advantages provide a benefit for the implementation of FSO in WDM, where some channel frequencies are multiplexed into a single light transmission of optical propagation. Based on previous research [25], the fluctuation of the signal spectra, caused by turbulence effects, has a probability of occurring in dense wavelength division multiplexing (DWDM) on the ORN of FSO where the spacing frequency is 0.2 – 1.6 nm. Particularly, the ORN of FSO which carry several channels through many nodes of optical transmission is very vulnerable to the turbulence effects. This condition leads to inter-channel cross-talk (ICC) where every signal spectral in many frequency channels randomly fluctuates [34]. This is proven by the results in Figs. 7 (c) to (h), where a single channel frequency of 1555.08 nm fluctuated in random fashion from its origin of center wavelength. The shifting of the center wavelength is higher when a strong turbulence level induces the optical propagation. It can be deduced that ICC is caused by the effects of forward scattering on optical propagation when a linewidth of signal interacts with a random media [35]. However, ICC is not the main issue in this research, and perhaps further research is required to investigate this problem. Thus, if this condition exists in DWDM on FSO, every frequency channel has only a very brief opportunity to randomly overlap with others in the spacing frequency channel. Therefore, this condition also leads to performance degradation of DWDM on FSO. For this reason, the OSF can be implemented in DWDM of FSO in the scheme of ORN with the DD or FD method in the case of signal detection. Thus, the integration of the OSF with an OA bring benefit to produce the best signal spectral quality before being received by PD or FD method to be delivered into the amplification process stage.

Conclusion

The performance of optical signal amplification in the AR-relaying scheme on FSO has been improved by configuring the integration of OSF with the EDFA to deliver an optical signal with a minimum of turbulence effects modulation. The optical signal from an OA is strong enough to reach the long-distance of optical propagation path lengths, but is not immune to effects from turbulence. Therefore, the OSF can be implemented in the optical signal detection of the OA to improve the FD method. The OA is based upon fiber technology, thus, integrating the OSF with the EDFA can improve the optical signal amplification and enhances the performance of AF- and AR-relaying on the ORN of FSO. The advantages of FSO include suppressing the turbulence effects, minimizing background noise and minimizing the fluctuation of the signal spectral delivered into the amplification process stage within the EDFA. Therefore, the OSF has a capability to improve the signal spectral quality to be delivered into an OA. Thus, the amplification process stage in the EDFA-2 can optimally produce a signal with characteristics of high signal power, minimum noise, and low signal spectral fluctuation. From the experiment, the OSF with pinhole diameters of D_{P1} to D_{P4} have demonstrated performance improvement for optical signal amplification in the EDFA-2 where the output of signal power from each D_P is produced higher beyond threshold level. Also, the OSF at lower pinhole diameter, D_{P4} produces the best signal quality for the EDFA-2 in AR-relaying. Finally, the OSF that is integrated with the EDFA has a good opportunity to expand the link distance of an FSO destination through the ORN scheme that frequently implements an OA in each node of optical transmission.

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