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NOISE SUPPRESSION IN THE SIGNAL SPECTRAL INDUCED BY ATMOSPHERIC TURBULENCE ON THE FSO (FREE-SPACE OPTICAL) COMMUNICATIONS

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ABSTRACT

Beam wander and spatial noise that are modulated on optical propagation produce noise modulation in the signal spectral before being received by a Photodetector (PD). In order to suppress noise modulation in the signal spectral, we present an Optical Spatial Filter (OSF) method that is composed of the cone reflector and a pinhole as a detection method. A cone reflector is designed to suppress beam wander in order to minimize temporal noise that fluctuates randomly and governs reflection of the deflected focus spot into the narrow region of pinhole. The pinhole governs the Fresnel diffraction in order to suppress spatial noise in the center of focus spot that undergoes fluctuation and random frequencies as well. Through simultaneous suppression in temporal noise caused by beam wander and spatial noise using the OSF method, noise modulation in the signal spectral can be minimized optimally. We compared the OSF with the Direct-Detection (DD) method by experimentation. The results of the experiment show significant improvements for noise suppression in the signal spectral. The average values of the Signal-to-Noise Ratio (SNR) increase, namely, 37.5 dB, 38.5 dB, 38.7 dB and 39.2 dB for pinhole diameters of 50 µm, 40 µm, 30 µm, and 20 µm, respectively.

Keywords: Beam wander; Cone reflector; FSO; Pinhole; Optical Spatial Filter; Spatial noise

1. INTRODUCTION

Low-cost deployment and those offering a high rate transmision capacity are advantageous for Free-Space Optical (FSO) communications where bit-rate transmission capacity is nearly as the optical fiber communications system. The transmission rate of 2.5 Gbps has been investigated and has successfully reached an optical link distance at 4.4 Km (Nykolak et al., 1999). The FSO communications also has implemented Wavelength Division Multiplexing (WDM) which was carried at a transmission rate on the scale of Gbps (Song et al., 2000; Jeong et al., 2003; Ciaramella et al., 2009). Song et al. (200) have expanded the FSO capacity using 4 WDM channels of 4×10 Gbps and they have reached an optical link at a distance of 1.2 Km. Jeong et al. (2003) have expanded the optical link using EDFA as an optical repeater, by multiplexing 8 channels of WDM, each with a capacity at 10 Gbps, and it has successfully reached a distance of 3.4 Km. Ciaramella et al. (2009) have made a tremendous improvement in capacity by employing 40 WDM channels and they have successfully transmitted 1.28 Tbps over an optical

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link distance of 210 m.

Based on the aforementioned results (Song et al., 2000; Jeong et al., 2003; Ciaramella et al., 2009), there is a clear trend in FSO in which a high transmission rate through atmospheric turbulence, tends to shorten the propagation path length. High transmission rates over the atmosphere are very vulnerable to be induced by maximum turbulence. An optical propagation which carries n-channels of a WDM system interacts independently with atmospheric turbulence. Hence, each channel degrades maximally where the average value of the Signal-to-Noise Ratio (SNR) decreases significantly. Long distances for optical propagation path also contribute as well to higher accumulation for each channel to interact with atmospheric turbulence in random and fluctuative patterns. Each WDM channel has a specific center frequency or signal spectral, which is at a 100 GHz spacing (ITU-T G.694.1). For WDM channels that are propagated through atmospheric turbulence, and hence are based on the fourth order of the strong fluctuation theory, each signal spectral modulates noise (Prasad, 2005; Zhu et al., 2007; Weyrauch, 2007). Thus, maximum noise is accumulated depending on the scale of turbulence and optical link distance on the WDM of the FSO. The strong level of turbulence and longer distance of the optical link means maximum noise is modulated in the signal spectral. It means that the signal spectral has deteriorated, caused by this process. Thus, noise modulation in the signal spectral exhibits the lower value of the SNR for each channel of WDM (Caplan, 2007; Majumdar, 2010; Ricklin, 2006). Noise modulation in the signal spectral under the influence of atmospheric turbulence also degrades FSO performance (Pedireddi et al., 2010; Toselli, 2009; Si et al., 2012). Furthermore, these may shorten the optical link distance in the FSO.

In order to overcome those problems, (Priambodo et al., 2015; Darusalam et al., 2015), an OSF has been proposed for supression in signal intensity fluctuation and noise reception before PD or simply as a detection method in complementing the DD. As the continuation of the work of those researchers, in this paper, we present a preliminary study for the OSF in suppressing noise modulation in the signal spectral which has deteriorated, having been caused by beam wander and spatial noise effects. The OSF is designed to minimize bandwidth noise and fluctuation of signal intensity through suppression of beam wander and spatial noise, hence the fluctuation of temporal noise can be limited to a small area of reception which is the size of a pinhole. In order to achieve these processes, the pinhole size governs Fresnel diffraction in the near field. It is designed to minimize noise that is modulated at the focus spot. A cone reflector governs directed reflectance for a beam wandering into the pinhole where the incident angle goes into a random fluctuation. Through these processes, the OSF performs simultaneous suppression of beam wander and spatial noise in order to produce the signal spectral with minimum noise modulation. Furthermore, in order to investigate the results of filtering, we compare the signal spectral from the OSF and DD method, respectively.

2. THE OSF FOR SUPPRESSING NOISE IN THE SIGNAL SPECTRAL

The optical propagation that is induced by atmospheric turbulence is illustrated in Figure 1. It is transmitted from laser sources, with experiences of beam spreading, diffraction, absorption, and scattering that undergoes random fluctuation. These processes lead to fading effects, spatial noise, and beam wander (Priambodo et al., 2015; Darusalam et al., 2015).

The optical propagation interacts stochastically with the turbulent media which is composed of random outer- and inner-scale dimensions of the refraction index in atmospheric turbulence. When optical propagation reaches the surface of the receiver lens, it is no longer originally as when it was transmitted. Spatial noise that is caused by random scattering through atmospheric turbulence along the propagation path is modulated, which leads to noise modulation in the signal spectral. Thus, the focus spot from the receiver lens should be recovered in order to maintain the signal spectral as transmitted originally from the laser source.

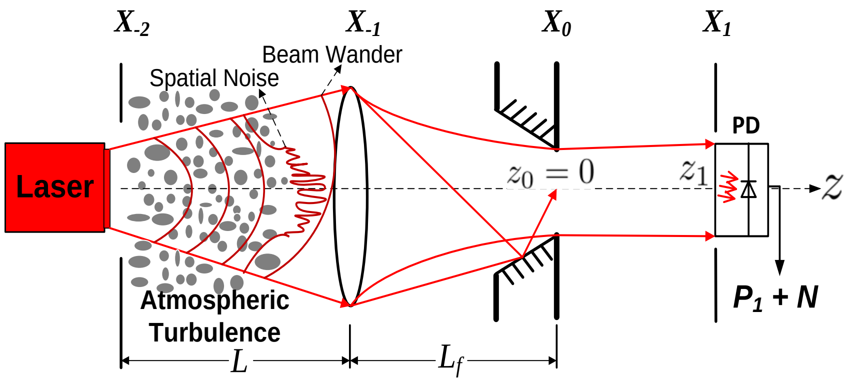


Figure 1 The optical propagation on atmospheric turbulence which modulates noise in signal spectral is suppressed by the OSF at X_0

Based on the fourth order of the strong fluctuation theory, the signal spectral of optical propagation for the path length is L and the coincidence on X_0 is (Andrews et al., 2005),

$$S_I(\omega) = \frac{4}{\omega_t}\int_0^\infty B_I\left(\frac{s}{\omega_t}, -L - L_f\right) cos\left(\frac{\omega s}{\omega_t}\right) ds \tag{1}$$

where ω_t represents the transition frequency at which the signal spectral begins to decay under weak fluctuations within the Fresnel zone and B_I is the temporal covariance function of a Gaussian beam that represents spatial noise modulation by atmospheric turbulence,

$$B_I\left(\frac{s}{\omega_t}, -L - L_f\right) =$$

$$exp\left[\frac{0.49\sigma_R^2}{\left(1+1.11\sigma_R^{12/5}\right)^{7/6}} F_1\left(\frac{7}{6}; 1; -\frac{k\rho^2\eta_X}{4L}\right) + \frac{0.50\sigma_R^2}{\left(1+0.69\sigma_R^{12/5}\right)^{5/6}}\left(\frac{k\rho^2\eta_Y}{L}\right)^{5/12} K_{5/6}\left(\sqrt{\frac{k\rho^2\eta_Y}{L}}\right)\right] - 1 \tag{2}$$

where $\rho = V_\perp\tau$ is the spatial frequency that is induced by mean wind speed at a period of temporal frequency, σ_R^2 is the Rytov variance, and $F_1$is the hypergeometric function where η_X and η_Y are the log-irradiance variances for outer- and inner-scale for a Gaussian-beam wave, respectively.

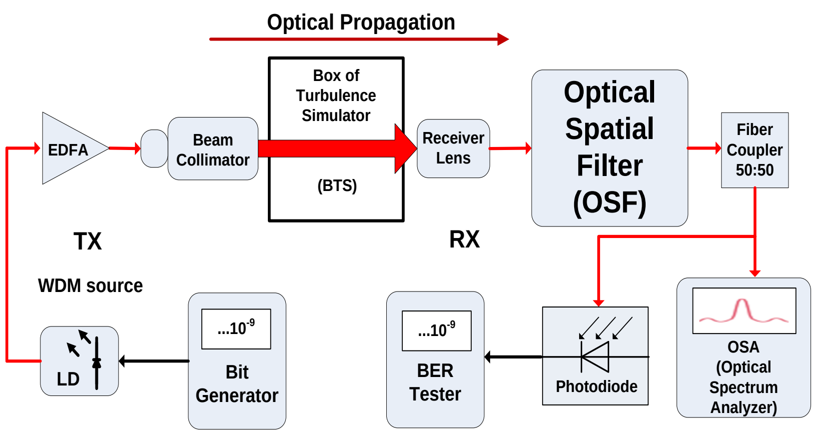
The OSF is designed to suppress beam wander and spatial noise effects, where fluctuation of noise in the signal spectral is limited to pinhole diameter. Through localization of random spatial and temporal noise in pinhole diameters, noise modulation in signal spectral can be minimized. The duration of noise bandwidth B_I as shown in Equation (1) is suppressed by directed reflectance by the cone reflector into the pinhole diameter. The mean irradiance for the signal spectral, as the output of OSF, is stated below (Priambodo et al., 2015; Darusalam et al., 2015),

$$\langle I_1(\mathbf{r_1}, z_1 \approx 0, \phi_i)\rangle = \frac{1}{4} I_{-1}^0(0, -L_f)\frac{W_G^2}{W_0^2}\, SR \exp\left(-SR\frac{2(\Delta r_0)^2}{W_0^2}\right)\cos(\phi_i)\,[1 - 2\cos(v)\;\; J_0(v) + J_0^2(v)] \tag{3}$$

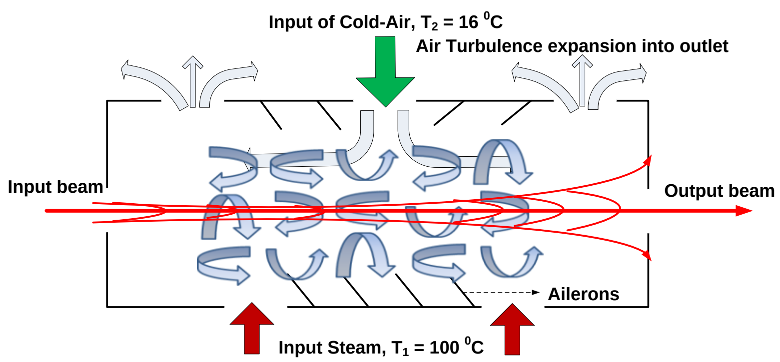
where the brackets $\langle . \rangle$ denote mean value, r_0 is the radius coordinate at X_0, W_G is the effective aperture radius of the receiver lens, W_0 is the focus spot radius, ϕ_i is the reflectance angle for beam wander from the cone reflector into the pinhole diameter with respect to the optical axiz Z as shown in Figure 2, J_0 is the Bessel function of the first kind, $I_{-1}^{0}(0, -L_f) = W_{-2}^2/W_{-1}^2$ is the free-space irradiance of optical propagation that is incident on the receiver lens of X_{-1} where W_{-2} is the transmitted light radius from the laser source on X_{-2} and W_{-1} is the incident light radius on the receiver lens, $SR = 1/\left(1 + 1.63\, \sigma_R^{12/5}(L)\, \Lambda_{-1}\right)$ is the Sthrel ratio, $\Lambda_{-1} = 2L/kW_{-1}^2$ is the effective beam parameter of incident light, $\sigma_R^{12/5}(L) = \left(1.23\, C_n^2\, k^{7/6}\, L^{11/6}\right)^{6/5}$ is the Rytov variance for the propagation path length L, $v = [2\pi\Delta r_0/\lambda z_1] r_1$ is the spatial frequency at radius r_1 on X_{-1} as the function of spacing distance z_1, and $k = 2\pi/\lambda$ is the wave number, respectively. Based on Equation (1), ω_t, which represents the noise bandwidth in the signal spectral, is minimized by the cone reflector and the pinhole. Thus, the signal spectral is assessed in parallel with the minimum noise modulation.

3. EXPERIMENTAL SET-UP

A single channel of 1554.9 nm (ITU-G.694.1) is used on the FSO where the set-up experiment implements full duplex transmission, TX to RX as shown in Figure 2. Bit rate capacity at 1 Gbps is transmitted via the Laser Diode (LD). The signal power of -2.6 dBm of LD is amplified by an Erbium-Doped Fiber Amplifier (EDFA) at +23.5 dBm. Then, it is coupled into a beam collimator, henceforth the light diameter of the signal at 4 cm is transmitted through turbulent media in the Box of a Turbulence Simulator (BTS), as an atmospheric chamber, as shown in Figure 2.



(a)



(b)

Figure 2 (a) FSO set-up experiment using channel 1554.9 nm as WDM source with full duplex of TX and RX, which is designed to investigate the results of filtering by the OSF; (b) BTS providing turbulent media for optical propagation

The optical propagation is received by the receiver lens and focused onto the OSF which is connected to the fiber coupler. Then, it is received by the Optical Spectrum Analyzer (OSA). The SNR measurement uses the OSA (Anritsu MS9740A). The threshold level of photodiode P_{Th} of -30 dBm is used as the reference for signal detection.

The turbulent media provided by BTS has a three-dimensional volume of 4 m × 0.5 m × 0.5 m (Figure 4). BTS is conditioned to receive the propagation media at a strong turbulence level. In order to achieve this, an intake of cold air from an Air Conditioning (AC) unit at $T_2 = 16^oC$, at a laminar speed of 6 to 7 m/s, and steam, at $T_1 = 100^oC$, flows into the BTS. This mixing process of laminar flow is broken into turbulence by ailerons. By using these processes, the turbulent media is produced and it fills the volume of the BTS to induce optical propagation. Hence, optical propagation at a diameter of 4 cm is transmitted from the beam collimator and it will interact optimally at a 4 m length with the turbulent media inside the BTS.

4. RESULTS AND DISCUSSION

The analysis of the four signal spectral measurements from the (SNR) are shown in Figures 5–6. First is the original signal spectral measurement or one directly taken from the output of the EDFA. Second is the signal spectral measurement after propagation on the BTS at a non-turbulent level. Third is the signal spectral measurement for the DD method at a level of strong turbulence. Fourth is for the OSF at a level of strong turbulence as well.

4.1. Original Signal Spectral

The original signal spectral that is coupled into the beam collimator is shown in Figure 3. The peak of the signal spectral is 1554.99 nm and its power is +19.5 dBm. It is very clear that there is no spectral noise because the signal has not yet been propagated in the turbulent media. The value of the SNR is quite high and constant at 39.23 dB. The second peak at 1553.55 nm is very low and the Side-Mode Suppression Ratio (SMSR) is 45.79 dB.

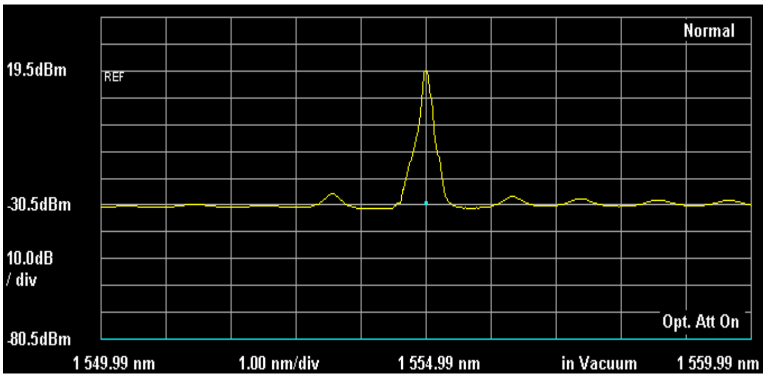


Figure 3 Original signal spectral from the output of EDFA

4.2. Signal Spectral in Non-Turbulent Media in BTS

The original signal spectral as shown in Figure 3 is transmitted by a beam collimator into the BTS in a non-turbulent condition. The signal spectral is regulated by an attenuator of 6 dB which is used in the OSA. The signal power decreases at -1 dBm and the center changes to 1555.22 nm. The SNR is quite high also because the turbulent media is not present in the BTS. The value of the SNR is 38.42 dB. The SMSR parameter also high at 48.6 dB because the second peak is attenuated. The result also shows that there is no high oscillation along the width of the signal spectral at 1 nm. It means that the signal spectral does not exhibit noise modulation in the signal spectral as a consequence of optical propagation in a non-turbulent media. Thus, a random occurence of optical phenomena does not exist along the propagation path. Hence, the result for the signal spectral is quite the same as the original signal from the EDFA.

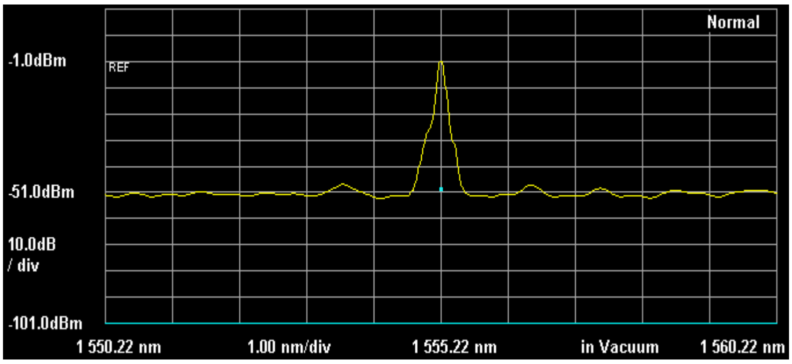


Figure 4 Transmission of the signal spectral in a non-turbulent condition into the BTS.

4.3. Direct-Detection Method

The DD method is used to measure the signal spectral at a strong turbulence level in the BTS. Noise modulation in the signal spectral is present for a width of 1 nm or in the region of a Full-Width at Half Maximum (FWHM) as shown in Figure 5. The received signal power decreases extremely at -32.67 dBm and the SNR falls to 32.6 dB. The signal spectral is highly deteriorated, caused by the turbulence effects, where signal power falls below P_{Th}. Moreover, the center frequency of the signal spectral at the FWHM modulates noise to its maximally possible level. The signal power is almost flat with the high order of temporal noise. It means the photodiode received noise is maximal. Those degradations are caused by random optical phenomena that occur along the propagation path in the turbulent media of the BTS. The signal spectral under the turbulence effects modulates noise maximally and degrades the performance of the SNR value which also falls into a condition of maximal fading. By all means, the deteriorated signal spectral leads to degradation maximally in FSO performance.

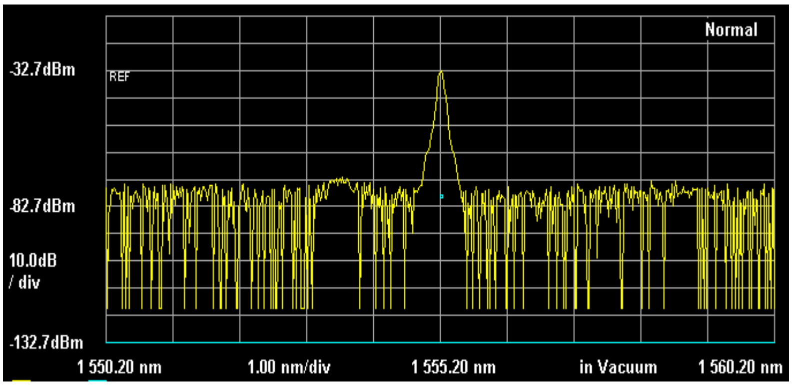


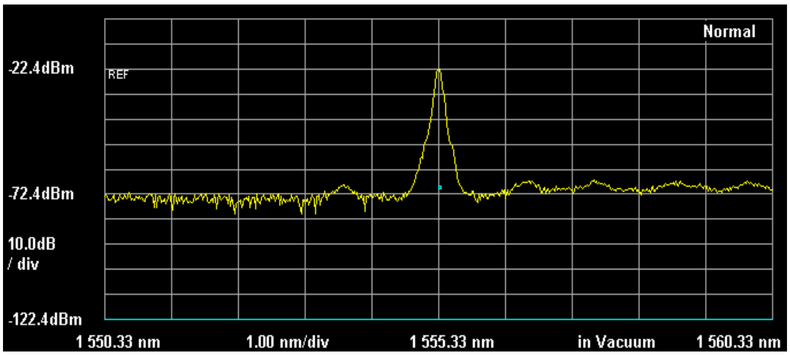
Figure 5 The signal spectral received by the DD method at a strong turbulence level.

4.4. The OSF Method

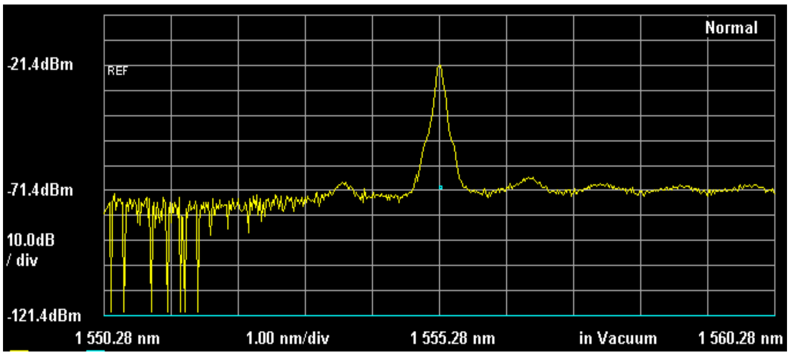
In order to suppress noise modulation in the signal spectral that exists in DD method, the OSF is installed at the focus spot before the PD, where the front diameter for the cone reflector is 1.5 mm and the width is 2 mm. The parameters for the cone reflector are designed as a constant for all pinhole diameters. The cone reflector is made of silver that is capable of reflecting optimally in long-wavelength conditions. The trend as shown in Figures 6(a) to 6(d) indicates significant improvement in recovering the signal spectral which has deteriorated maximally by the turbulence effects in the BTS. We also used a smaller pinhole whose diameter is 20 µm. The results of signal power for pinhole diameters (D_P) of 50 µm, 40 µm, 30 µm, and 20 µm are -22.4 dBm, -21.42 dBm, -20.3 dBm, and -15.31 dBm, respectively. The SNR values are 37.5 dB, 38.5 dB, 38.7 dB, and 39.2 dB for pinhole diameters of 50 µm, 40 µm, 30 µm, and 20 µm respectively also. The trend shows that the signal spectral modulates noise at a minimum level and is fully recovered as the original signal spectral from the EDFA as shown in Figure 3.

The improvement of the signal spectral is successfully achieved by using the OSF before signal reception into the PD. The intensity of the signal spectral rises up to a level beyond P_{Th}. It is also optimized by the operation of the pinhole diameter to sweep-out the spatial noise. By implementing the OSF, noise modulation in the signal spectral can be suppressed optimally while the signal power is still received at a higher value than the DD method. It brings benefit for the PD to minimize fading effects when strong turbulence induces optical propagation of the FSO. Hence, the performance of the SNR can be increased also under influences of strong turbulence.

The ultimate contribution made by installing the OSF for suppressing the beam wander effect in strong turbulence is noise suppression in the signal spectral, which can be achieved optimally where random spatial and temporal noise exist in the signal spectral and under turbulence effects that can be minimized through spatial localization in the near field, such as occurs in the size of the pinhole diameter. Beam wander fluctuates randomly, hence the focus spot experiences random displacement around the optical axis of pinhole. Meanwhile, spatial noise that is caused by random scattering leads as well to random signal spectral decay. Thus, the signal spectral modulates maximum noise in the presence of beam wander and spatial noise. Henceforth, by designing the optimum angle to reflect the displacement of the focus spot, the cone reflector can guide optimally a larger angle of beam wander into the pinhole diameter. Thus, the signal spectral is at a minimum for noise modulation. It means that a minimum noise bandwidth in the signal spectral contributes to a higher SNR value.



(a)



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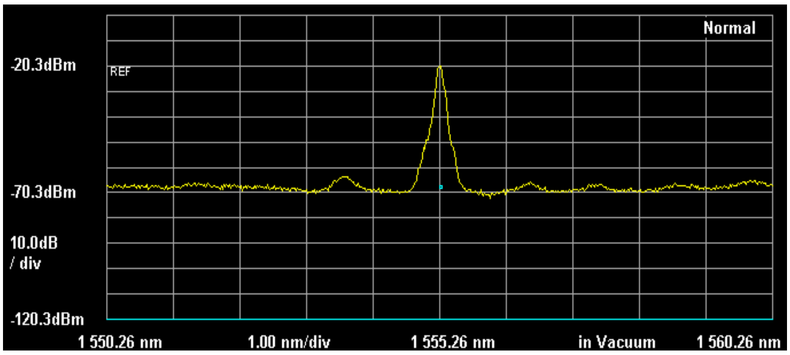

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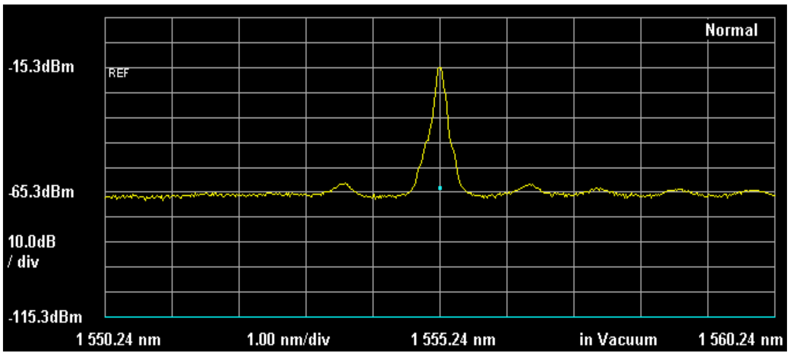

(d)

Figure 6 Signal spectral measurement by the OSF: (a) $D_{P1} = 50\ \mu m$; (b) $D_{P2} = 40\ \mu m$; (c) $D_{P3} = 30\ \mu m$; (d) $D_{P4} = 20\ \mu m$

The OSF which is composed of a cone reflector and a pinhole works optimally to suppress noise modulation in the signal spectral that is modulated by beam wander and spatial noise. The signal spectral which has deteriorated maximally by strong turbulence, as shown in Figure 5, can be fully recovered with the benefit of enhancement in signal intensity and minimum noise modulation as shown in Figure 6. In comparison to the DD method, the signal spectral by the OSF is fully recovered where the characteristics are nearly to the original signal spectral as it was produced by the EDFA, as shown in Figure 3.

5. CONCLUSION

The cone reflector and pinhole as the components of the OSF have successfully suppressed beam wander and spatial noise effects in order to recover the signal spectral that has deteriorated due to noise modulation with the benefit of higher signal power and lower noise bandwidth in comparison to the DD method. Moreover, signal power is successfully enhanced beyond the threshold level of the PD, where -22.4 dBm, -21.42 dBm, -20.3 dBm, and -15.31 dBm are for pinhole diameters 50 µm, 40 µm, 30 µm, and 20 µm, respectively. The values of the SNR increase and are shown as 37.5 dB, 38.5 dB, 38.7 dB, and 39.2 dB for pinhole diameters 50 µm, 40 µm, 30 µm, and 20 µm, respectively.

6. ACKNOWLEDGEMENTS

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