An Overview of Free Space Optical Communication

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Abstract — *In recent years, Free Space Optical (FSO) communication has gained significant importance in terrestrial applications and wireless communication. Atmospheric conditions prominently affect the performance of FSO system making them highly susceptible to degrading effects of atmospheric turbulence and pointing errors. In this review paper, basics of optical wireless such as its advantages, applications and challenges along with various channel models and modulation schemes employed in free space optical communication are discussed. Comparison between different modulation schemes in different atmospheric turbulences is provided for bit error rate, signal to noise ratio, power efficiency, etc.*

Keywords — FSO, Optical wireless, Channel Modelling, Advantages, Modulation schemes, Pointing error, Atmospheric turbulence

I. Introduction

(Size 10 & Normal)Free Space Optics (FSO) is a wireless Line Of Sight (LOS) communication technology that uses light for the transmission of information through air or vacuum. In FSO, data is transmitted by propagation of light in free space allowing fiber optical connectivity. Free Space Optics is having the same capabilities as that of fiber optics, but at a lower cost and very high speed. Free Space Optics works on the principle of laser source driven technology which uses light sources at transmitter end and detector at receiver end to transmit and receive information, through the atmosphere same as Fiber Optics Communication (FOC) link, which also uses light sources and detectors but through optical fiber cable [1]. FSO links have some distinct advantages over conventional microwave, radio frequency and optical fiber communication system by virtue of their very high carrier frequencies that permit large capacity, enhanced high security, high data rate and so on respectively. FSO systems are being considered for military systems application, because of their inherent benefits as normally most of the systems are rated for greater than one kilometre in three or more lasers operating in sequence parallel to mitigate distance related issues [2].

II. Block Diagram for FSO Communication

Block diagram [Fig.1] shows the essential parts that comprise a free space optical communication system. It has a transmitter and a receiver and in between them an atmospheric channel.

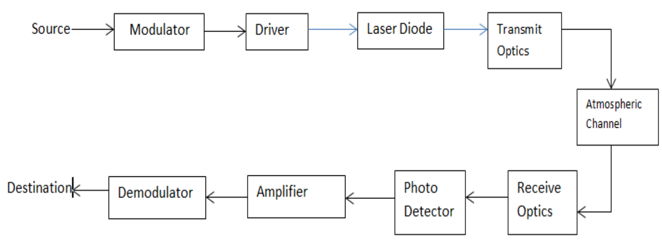

Figure 1: Block diagram of FSO system [3]

Source generates the information that has to be communicated over the optical wireless system. The modulator, using different modulation techniques, modulates the data for transmission. The optical light source can be of two types- Light Emitting Diode (LED) or Laser Diode (LD). Laser is preferred because of the high pointedness and coherence that it's beam exhibits. The transmitter and receiver are configured to deliver and receive optical signals propagating in free space. Transmitter converts incoming electrical signal from driver circuit into optical form to be transmitted over the atmospheric channel. Atmospheric channel through which the optical beam passes throws a lot of challenges for the transmitted signal. Thus the signal has to be properly modulated before transmission. Receiver side contains a photo detector which converts the received optical signal to electrical form again which can then be amplified or processed. Modulation and demodulation of the signal takes place in electrical form [3]. Received signal is demodulated and produced in the desired form to the destination.

III. ADVANTAGES OF FSO

FSO is a high speed communication system as transmission involves optical beam. Installation of FSO is an easy task to perform as installing it at normal locations takes less than an hour. Also it is easily upgradeable and supports equipment from various vendors. It has low cost and simple deployment. No burying of cables or license procurement is required; hence this makes it suitable for wireless service providers for long-range operation (in contrast with radio communication). Up gradation of security system is not needed because of LOS operation which secures the system. The high directivity and narrowness of the beam adds to the security of the optical system [4]. FSO is immune to electromagnetic- radio frequency interference. Other merits of FSO system include low power usage per transmitted bit, low bit error rates, full duplex operation and no need to connect the transmitter and receiver through a waveguide as the transmission is free space.[5]

IV. APPLICATIONS OF FSO

FSO communication link is currently in use for many services at many places to enable communication. It ensures last mile access [5]. It cut down on the costs required to install and repair cables but still offers high speed link. It, in fact is used to bypass local-loop systems of other kinds of networks. Also, these systems are easily installable. This feature enables them to connect two or more Local Area Network (LAN) in a building. It can also serve as a backup link in case of failure of transmission via optical fibers due to some reasons. It can be used in extending the fiber rings of an existing metropolitan area. These systems can be deployed in less time and connection of the new networks and core infrastructure can be done easily. It can also be used to complete Synchronous Optical Network (SONET) rings [6]. It is useful in transporting the traffic originating through cellular telephone from antenna towers back to the Public Switched Telephone Network (PSTN) with higher speed and higher data rate since the speed of transmission would increase. It can also be used to provide instant service to customers when the corresponding fiber infrastructure is being deployed in the meantime. FSO is beneficial in Wide Area Netwrok (WAN) where it supports high speed data services for mobile users and small satellite terminals acts as a backbone for high speed network. It can be used to communicate between point-to-point links, for example, two buildings, two ships, and point-to-multipoint links, for example, from aircraft to ground or satellite to ground, for short and long reach communication. LOS propagation makes it secure and undetectable, thus it can connect very large areas safely with minimal planning and deployment time. All such features make it suitable for military applications.

V. CHALLENGES FACED IN FSO

As the medium for transmission in FSO is free space, there are many challenges faced in implementing the free space optical system. They include atmospheric challenges due to change in various weather conditions as well as many others. Atmospheric turbulence refers to a random phenomenon that causes redistribution of the signal energy which results from the inconsistency in the refractive indices of the atmosphere. It results in intensity fluctuations and degradation of the optical beam [7]. The size of the turbulence effect can cause different effects. If the size of the turbulence cell is of larger diameter than optical beam then beam wander would be the dominant effect. Beam wander is the displacement of the optical beam spot rapidly. If size of turbulence cell is of smaller diameter than optical beam then the intensity fluctuation or scintillation of the optical beam is dominant.

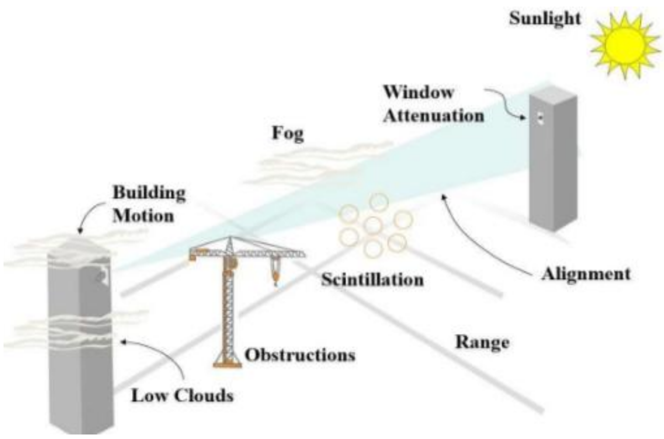

Figure 2: Challenges in Atmospheric channel [8]

Other losses are also there that impede the communication such as scintillation, geometric, absorption and scattering losses [9]. Scintillation refers to heat emissions from the earth's surface cause temperature variations in air packets of the atmosphere. These temperature variations cause fluctuations in intensity of the transmitted signal. [10] Since it is LOS communication, anything that comes in the way of optical beam that is being transmitted is treated as physical obstruction. It can be a flying bird, a kite or a plane which may lead to error. Scattering takes place when the optical beam collides with a scattering particle. It is a wavelength dependent phenomenon. Geometric losses involve signal attenuation caused by the spreading of the optical beam. They result in power reduction at the receiver end of the system. Atmosphere has suspended water molecules present in the form of water vapour and also other gases like Carbon-dioxide which cause absorption. Absorption directly effects the optical transmission and decreases the optical power. Atmospheric attenuation is the result of different weather conditions in the atmosphere which are the main cause of attenuation. These can be rain, fog or snow. As the radius of raindrops (150–2000μm) is significantly larger than the transmitting wavelength of typical Free Space Optics light sources, it has a moderate attenuation in the range 4-17 dB/km [11]. On the other hand snow results in attenuation between 20-30 dB/km because the size of snowflakes is larger when compared to the operating wavelength of transmitting information. [12] The highest attenuation in the transmitted signal is caused due to fog as it is mainly composed of small water droplets. The particles of fog are comparable to the wavelength of the optical beam. Its attenuation is from 40 to 70 dB/km for light fog and from 80 to 200 dB/km in heavy fog that is much higher when compared to the attenuation in clear weather which is in the range 0-2 dB/km. [13]

Another major challenge in FSO communication is pointing error. It is very important to maintain alignment and acquisition throughout the process of communication. Thermal expansions, dynamic wind loads and weak earthquakes result in the building sway that causes mechanical vibration of the transmitter beam leading to a misalignment between transmitter and receiver. The effect of pointing error consists of three essential parameters: beam width, jitter and boresight displacement. The beam width represents the beam waist, the jitter represents the random offset of the beam center at receive aperture plane and the boresight represents the fixed displacement between beam center and the alignment point. It should, however, be noted that there are two kinds of boresight displacements: the inherent boresight displacement and the additional boresight error. The first of them is related to the spacing among receive apertures at the receiver. This inherent boresight displacement represents a fixed distance, i.e., the distance between each receive aperture and the corresponding alignment point. The second one is related to the boresight error that is due to the thermal expansion of the building [14]. Pointing error can lead to link failure or can significantly reduce the amount of received power at the receiver resulting in high probability of error. To achieve pointing accuracy, proper care has to be taken to maintain sufficient bandwidth control and dynamic range in order to compensate for residual jitter. Also, pointing error loss is more significant at visible wavelength and decreases at higher wavelength due to inherent broadening of beam. Pointing error has significant impact on BER performance of FSO system. Fig. 2 shows the BER performance in the presence of random jitter.

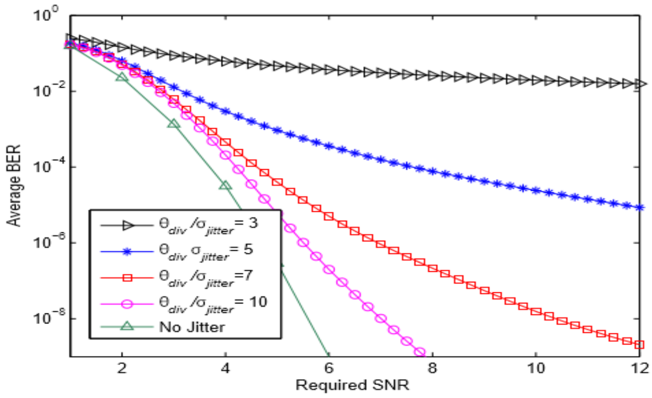

Figure 3: BER performance with random jitter [9]

VI. CHANNEL MODELLING

For modelling of FSO link we need to account for atmospheric turbulences. The temperature and pressure fluctuation leads to variations in the refractive index which results in atmospheric turbulence. This atmospheric turbulence leads to an increase in the system's bit error rate, therefore degrading the performance of FSO system [15]. A number of statistical channel models have been proposed to describe atmospheric turbulence conditions. The statistical channel model is given by:-

$$y = sx + n \qquad [1]$$

where y is signal at the receiver , s is instantaneous intensity gain, x is the modulated signal and n is AWGN [15].

Various channel models are:-

1) Log normal
2) Gamma-Gamma
3) Negative Exponential

- Log Normal
  The log normal channel model is used for weak turbulence condition. It is widely used model due to its simplicity in terms of mathematical calculation. It is applicable for propagation distances less than 100 m. For weak turbulence, scintillation index SI falls in the range of [0, 0.75]. Therefore for $\sigma_1^2<1$, log normal distribution is used.

The PDF of the received optical field I is given as f (I) [20]:

$$f(I)=(1/2\pi I\sigma^2)\exp[-(\ln(I)-m_i)^2/2\sigma_i^2] \qquad [2]$$

Where m_i is the mean and σ_i the standard deviation of ln(I). When the strength of turbulence increases, multiple scattering effects are considered [16]. In this case, Log normal channel exhibit large deviations compared to experimental data [17].

- Gamma-Gamma

Gamma-gamma scintillation model is based on Doubly Stochastic theory. It shows its properties for weak to strong turbulences [18]. The Probability Density Function (PDF) of its intensity I can be obtained by the product of two gamma random variables. Here the two described gamma random variable represents fluctuations from small and large turbulence which are given by PDF of X and Y and the received intensity I is:

$$I=XY \quad [3]$$

The Gamma-gamma PDF is given by the equation :-

$$f(I)=(2\alpha\beta^{(\alpha+\beta)/2}I^{(\alpha+\beta)/2-1}K_{\alpha-\beta}\sqrt{(2\alpha\beta I)})/(\Gamma(\alpha)\Gamma(\beta)) \quad [4]$$

Where $K_a(.)$ is the modified Bessel function of second order, α and β are the effective number of small scale and large scale eddies of the scattering environment, I is irradiance and Γ is gamma function.[18]

Here α and β are given by equation [5] and [6] respectively:-

$$\alpha = 1/\exp[0.49\sigma^2/(1+1.1\sigma^{12/5})^{7/6}]^{-1} \quad [5]$$

$$\beta = 1/\exp[0.51\sigma^2/(1+0.69^{12/5})^{5/6}]^{-1} \quad [6]$$

where σ^2 represents variance. SI for this channel model is given by the equation:-

$$\sigma^2 = (1/\alpha) + (1/\beta) + (1/\alpha\beta) \quad [7]$$

- Negative Exponential

When strong irradiance fluctuations take place, independent scatter become large in number [16]. So signal amplitude follows Rayleigh distribution which in turn leads to a negative exponential statistics .

The PDF for Negative Exponential is given by:-

$$P(I)=(1/I_o)\exp(-I/I_o), I>0 \quad [8]$$

where I_o is the mean radiance. For strong turbulences, $\sigma_{SI}^2 \geq 1$.

FSO has many advantages to offer so it is one of the most important medium of information exchange. In this type of wireless communication atmospheric conditions play an important role. Turbulence model must be used wisely while designing the FSO system . As already discussed for weak turbulence, log normal distribution is used, for strong turbulence negative exponential is used while Gamma-Gamma distribution is used for both weak and strong turbulences.

VII. TABLE I. CHANNEL MODELS WITH TURBULENCE [18]

Channel model	Turbulence
Log normal	Weak
Gamma Gamma	Weak to Strong
Negative Exponential	Strong

VIII. BASIC MODULATION SCHEMES

The information to be conveyed cannot be directly sent without error at the receiver. Hence, several modulation techniques are used in FSO so that message is less affected by noise and is sent to the receiver at high speed, without or acceptable distortion. The various techniques that can be used in FSO are:

On Off Keying (OOK), the modulation technique is the simplest form of modulation scheme. In this technique, transmission of 1 is detected by presence of signal and 0 is detected by absence of signal. It is widely used in FSO communication system. If no turbulence is accounted The BER for OOK is defined by the formula:

$$Pe,OOK = \mathrm{erfc}(0.5\sqrt{SNR})/2 \quad [9]$$

where erfc() indicates error function and SNR indicates Signal to Noise Ratio. This technique is primarily used because of its simplicity and ability to recover from failure quickly. It can use Non Return to Zero (NRZ) or Return to Zero (RZ) formats. In RZ-OOK, the bit duration is more than pulse duration, giving an improvement in power efficiency over NRZ-OOK at the expense of an increased bandwidth requirement [19]. Binary Phase Shift Keying (BPSK) is the simple two stage phase shift keying. In this, the phase of the carrier is set to 0 or in accordance with the information signal. If phase is set to 0 for '0' bit then is set for '1' bit. It is the simplest form of Phase Shift Keying (PSK) and is rather more robust than OOK to resist noise. [20-22]. The BER for BPSK is defined by the formula:

$$Pe,BPSK = \mathrm{erfc}(\sqrt{SNR})/2 \quad [10]$$

where erfc() indicates error function and SNR indicates Signal to Noise Ratio. To obtain a specific BER, the NRZ-OOK requires $2\sqrt{2}$ times the power required by BPSK. Also, BER for BPSK is lower than that of OOK for a specific SNR. Differential Phase Shift Keying (DPSK) is relative phase modulation model. The information that is transmitted is the result of phase difference between the current and previous symbol. Hence, the value 0 indicates no change in symbol. It is advantageous over BPSK because it does not need complex circuitry for synchronization. The BER for BPSK is defined by the formula:

$$P_{e,DPSK}=\mathrm{erfc}(\sqrt{SNR}/\sqrt{2})/2 \quad [11]$$

where erfc() indicates error function and SNR indicates Signal to Noise Ratio. The required bandwidth for DPSK is equal to the bit rate,B of DPSK $=R_b$. For a specific BER, the average power of NRZ-OOK is twice than that of DPSK. It is, in fact better than OOK for its ability to resist noise. [23] Quadrature Phase Shift Keying (QPSK) uses two bits that are grouped together to form a signal. There are four particular phases when signals are transmitted. Since QPSK can be regarded as composition of two orthogonal signals of BPSK hence, bandwidth required by QPSK is double than that of BPSK. The BER for QPSK is defined by the formula:

$$P_{e,QPSK}=\mathrm{erfc}(\sqrt{SNR}) \quad [12]$$

where erfc() indicates error function and SNR indicates Signal to Noise Ratio. The BER is lower for QPSK than OOK. Also, the data rate is maximized in this technique. Pulse Position Modulation (PPM) is used to encode the message bits by transmitting a signal M in any of the 2^M time shifts [24]. However, it poses a serious drawback of synchronization. Multiple PPM (MPPM) is an enhanced technique over PPM [25]. It offers advantages like decreases bit error rate, decreased average power. It uses the concept of Hamming weight. Differential PPM (DPPM) further reduces the average power constraint. Overlapping PPM (OPPM) is a technique in which at non orthogonal positions, symbols contain the transmitted pulse. As the name suggests, it allows overlapping amongst pulses of various symbols. Sub-carrier Index Modulation (SIM) introduces sub carrier index as an extra parameter to convey useful information to the receiver. Digital Pulse Interval Modulation (DPIM) is a pulse time technique of modulation. In this, discrete time intervals contain data. Also, the length is variable depending on the amount of content.

In the following table, comparison of different modulation schemes is presented:

IX. *TABLE II. COMPARISON OF DIFFERENT MODULATION TECHNIQUES*

Modulation Techniques	Applications	Features
OOK-NRZ	It is greatly affected by fog and is used for communication in clear weather.	Moderate SNR, Low Cost, requires adaptive threshold
OOK-RZ	It is less affected by fog and can be used is normal weather conditons.	High sensitivity
PPM	It offers best performance for scintillation index less than 0.5 and weak turbulence effects.	Superior power efficiency than any other baseband modulation
MPPM	BER is affected by rise in temperature in PPM. MPPM however is suitable in such conditions. Also, provides high peak power.	High bandwidth efficiency, spectral efficiency than PPM
DPPM	It is superior to PPM but inferior to MPPM.	Improved power efficiency, bandwidth efficiency, throughput than MPPM
DPIM	It does not require synchronization at the receiver. But both bandwidth and capacity efficient.	High bandwidth efficiency, spectral efficiency than PPM
OPPM	It offers risk of error propagation in detecting a received frame of symbol.	High bandwidth efficiency than PPM

SIM	For random varying turbulence, this technique is the best estimate.	Low cost, poor power efficiency, high capacity, improved throughput

X. CONCLUSIONS

In this paper, we have presented a concise and comprehensive study of communication through FSO. We have taken into account applications, advantages and limitations of various channel models used for different turbulence conditions. Hence, with different modulation techniques, the parameters are varied and optimised. We thus conclude that with relatively low or no turbulence, BPSK projects minimum bit error rate and is the best of all techniques considered as per the application.

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REFERENCES

[1] H.A. Willebrandand, B.S. Ghuman, "Fiber optics without fiber," IEEE Spectrum, vol.38,no.8, pp.40–45, 2001.

[2] H Henniger and O. Wilfert, "An Introduction to Free Space Optical Communications", Radio Engineering, vol. 19, no. 2, June 2010.

[3] Md Mehedi Farhad, Md. Rubaiyat Islam, Nazmun Nahar Islam, Maruf Mohammad Ali, "Performance Analysis Of Turbo Coded Free Space Optical Communication System Over AWGN Channel", International Journal of Science and Advanced Technology (ISSN 2221-8386). Volume 3, No 7, July 2013.

[4] M. A. Khaligi and M. Uysal, "Survey on free space optical communication: A communication theory perspective," IEEE Commun. Surveys and Tutorials, vol. 16, no. 4, pp. 2231-2258, June (2014).

[5] T.H. Carbonneau, D.R. Wisley: Opportunities and Challenges for optical wireless; the competitive advantage of free space telecommunications links in today's crowded market place, in SPIE Conference on Optical Wireless Communications, Massachusetts, 1998

[6] J. Kaufmann, "Free space optical communications: an overview of applications and technologies," in Proceedings of the Boston IEEE Communications Society Meeting, 2011.

[7] L. C. Andrews, R. L. Phillips, and C. Y. Hopen, "Laser beam scintillation with applications", SPIE Press, 2001.

[8] John Schuster, Free Space Optics (FSO) Technology Overview, Chief Technology Officer, Terabeam Coporation.

[9] H.kaushal, G.kaddoum, "Optical Communication in Space: Challenges and Mitigation Techniques", IEEE pub. , Volume: PP, Issue: 99 , 1553-877X, August (2016).

[10] F. David, "Scintillation loss in free-space optic systems", LASER 2004, Vol. 5338. San Jose USA, 2004.

[11] A. K. Rahman, M. S. Anuar, S. A. Aljunid, and M. N. Junita, "Study of rain attenuation consequence in free space optic transmission," in Proceedings of the 2nd Malaysia Conference on Photonics Telecommunication Technologies (NCTT-MCP '08), pp. 64–70, IEEE, Putrajaya

[12] Akiba, M., Ogawa, K., Walkamori, K., Kodate, K., Ito, S. Measurement And Simulation Of The Effect Of Snow Fall On Free Space Optical Propagation. Applied Optics, 2008, Vol. 47, No. 31, P. 5736-5743.

[13] M. Ijaz, Z. Ghassemlooy, J. Pesek, O. Fiser, H. Le Minh, and E. Bentley, "Modeling of fog and smoke attenuation in free space optical communications link under controlled laboratory conditions," Journal of Lightwave Technology, vol. 31, no. 11, Article ID 6497447, pp. 1720–1726, 2013

[14] F. Yang, J. Cheng, T. Tsiftsis, "Free-space optical communication with nonzero boresight pointing errors," IEEE Trans. Commun. 62(2), 713–725 (2014).

[15] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, Optical Wireless Communications: System and Channel Modelling with MATLAB, New York: CRC Press, 2013.

[16] Dhaval Shah, Bhavin Nayak, Dharmendra Jethawani , "Study Of Different Atmospheric Channel Models", IJECET, Volume 5, Issue 1, January (2014), pp. 105-112

[17] Mazin Ali A. Ali, "Performance Analysis of WDM-FSO Link under Turbulence Channel", Journal (World Scientific News), P.p 160-173, 2016.

[18] Kulvir Kaur, Rajan Miglani and Jagjit Singh Malhotra, "The Gamma-Gamma Channel Model - A Survey", Indian Journal of Science and Technology, Vol 9(47), December 2016.

[19] Popoola, Wasiu Oyewole. 2009. Subcarrier intensity modulated free-space optical communication systems, Ph.d thesis (September 2009). University of Northumbria at Newcastle

[20] WO Popoola, Z Ghassemlooy. BPSK subcarrier intensity modulated free-space optical communications in

[21] atmospheric turbulence. Journal of Lightwave Technology. 2009; 27: 967-973.

[22] X Tang, S Rajbhandari, WO Popoola, Z Ghassemlooy, E Leitgeb, SS Muhammad, "Performance of BPSK subcarrier intensity modulated free-space optical communications using a log-normal atmospheric turbulence model," Symposium on Photonics and optoelectronic (SOPO). Chengdu, China. 2010: 1-4.

[23] Yan Li, Mi Li, Yin Poo, Jiachen Ding, Minghui Tang, Yuangang Lu, "Performance analysis of OOK, BPSK, QPSK modulation schemes in uplink of ground-to-satellite laser communication system under atmospheric fluctuation." Optics Communications. 2014; 3(17): 57-61.

[24] Kamran Kiasaleh, "Performance of Coherent DPSK Free-Space Optical Communication Systems in K Distributed Turbulence" IEEE Transactions on Communications. 2006; 54: 604-607.

[25] Arun K. Majumdar, "Advanced Free Space Optics (A System Approach)", New York :Springer Series in Optical Scences, Vol.186, 2015 .