Enhancing Performance of Optical Transmission in Diffused Channels using All Optical Orthogonal Frequency Division Multiplexing

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***Abstract*— In this paper, an all optical orthogonal frequency division multiplexing (OFDM) is proposed for achieving better performance compared with single carrier communications and eliminating intersymbol interference in optical wireless communications. The paper shows the overall architecture along with the design considerations should be followed for parameters calculation. Analytical evaluation of the system in terms of probability of error is carried out in a non-directed (diffused) wireless optical channel. The paper confirms with simulation that the proposed system shows promising results for a high speed optical wireless channel.**

***Index Terms*— Intersymbol interference, optical orthogonal frequency division multiplexing, wireless optical communications.**

I. INTRODUCTION

In the 21th century, high speed data transmission will play an important role in our daily life. Multimedia information is envisaged to be available at any place and at any time. Wireless networks constitute a key element in achieving these goals. However, bandwidth at radio frequency ranges which allow reasonable spatial coverage is a limiting factor. For this reason, many researches are looking toward light as a way to provide the need for communications expansion. The use of modulated light as a carrier, instead of radio waves, offers the potential for such alternative. The main advantages are the unlimited bandwidth, cheap transmitters and receivers, and free light radiations of any health concerns. Another advantage is that light waves do not penetrate opaque objects and therefore they cannot be eavesdropped. As a result, it is very difficult for an intruder to (covertly) pick up the signal from outside the room.

The optical medium can be viewed as complementary to the radio medium rather than competitive. Electromagnetic waves at optical frequencies exhibit markedly different propagation behavior than those at radio or microwave frequencies. At optical frequencies, most building surfaces are opaque, which generally limits the propagation of light to the transmitter room. Furthermore, for most surfaces, the reflected light wave is diffusely reflected (as from a matte surface) rather than specularly reflected (as from a mirrored surface). Diffraction is also an important feature of radio propagation, but it is not of a significant effect at infrared frequencies as the dimensions of most building objects are typically many orders of magnitude larger than the wavelength. These differences, as well as fundamental differences in the transmitting and receiving devices, have led researchers to develop channel models and communication concepts for wireless infrared optical systems.

The characteristics of radio and infrared indoor wireless links are compared in Table 1.

Property of Medium	Radio Channel	Optical Channel
Bandwidth Regulated	Yes	No
Passes Through Walls	Yes	No
Multipath Fading	Yes	No
Multipath Distortion	Yes	Yes
Path Loss	High	High
Dominant Noise	Other Users	Background Light
Input X(t) Represents	Amplitude	Power
SNR Proportional to	$\int \lvert x(t)\rvert^2 dt$	$\int \lvert x(t)\rvert^2 dt$
Average power Proportional to	$\int \lvert x(t)\rvert^2 dt$	$\int \lvert x(t)\rvert dt$

Table 1 Comparison between radio and optical systems for indoor wireless communications [1].

Infrared links may employ various designs. It is convenient to classify infrared links into two most common configurations. The first design is a line-of-sight (LOS) link in which the transmitter (TX) and receiver (RX) must be pointed at each other to establish a link and the path between TX and RX must be clear of obstructions. The second is non-line-of-sight (non-LOS) in which the TX and RX are non-directed. The link is always maintained between the transmitter and any receivers in the same vicinity by reflecting or bouncing the transmitted information-bearing light off reflecting surfaces such as ceiling, walls and furniture. The transmitter employs a wide transmit beam and the receiver has a wide field of view as shown in Fig. 1.

Directed link design maximizes power efficiency, since it minimizes path loss and multipath distortion. On the other hand, non-directed links increase link robustness and ease of use, allowing the link to operate even when barriers, such as people or cubicle partitions, stand between the transmitter and receiver. However, these links increase multipath distortion that causes intersymbol interference (ISI) problems. The robustness and ease of use are achieved by the non-directed-non-LOS link design, which is referred to as a diffuse link.

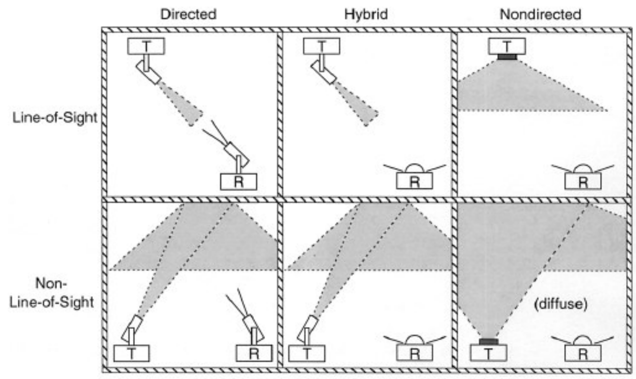

Fig. 1 Classification of simple infrared LOS and non-LOS links [1].

This paper is organized as follows. In Section II, the concept of optical OFDM is introduced as well as the current research carried out in this optical OFDM. The proposed all optical OFDM system is described in Section III. Section IV presents the design considerations that should be followed to calculate the system parameters. Analysis of the proposed system is presented in Section V. Simulation results and conclusions are given in Section VI.

II. OPTICAL OFDM SYSTEM

The ISI due to the multipath propagation is a major concern in indoor wireless optical transmission. This interference greatly degrades the quality of transmission, and its effects become more severe in case of diffuse links. This is a serious problem, especially in the case of ultra high speed optical wireless LAN such as 1 Gbit/s or more. To combat the ISI effect, a parallel transmission technique is one of the possible solutions [2]. This parallel transmission lowers the data rate per channel, which consequently diminishes the ISI effects. Optical orthogonal frequency division multiplexing (OFDM) is proposed to reduce the effects of ISI. This strategy can improve the quality of transmission to a great extent [3].

In an OFDM system, a high data rate serial data stream is split up into a set of low data rate substreams. The parallel data transmission offers possibility for alleviating many of the problems encountered with serial transmission systems such as ISI. The total channel bandwidth is divided into a number of orthogonal frequency sub channels. Each low data rate substream is modulated on a separate sub channel. The orthogonality is achieved by selecting a special equidistant set of discrete carrier frequencies. It can be shown that, this operation is conveniently performed by the Inverse Fast Fourier Transforms (IFFT). At the receiver, the Fast Fourier Transform (FFT) is used to demultiplex the parallel data streams [2].

In current research, optical orthogonal frequency division multiplexing is proposed to combat dispersion in optical fiber media [4]. The authors in [4, 5] presented the theoretical basis for coherent optical OFDM systems in direct up/down conversion architecture. In [6], the authors showed that Optical Orthogonal Frequency Division Multiplexing (OOFDM) outperformed RZ-OOK transmission in high-speed optical communication systems in terms of transmission distance and spectral efficiency. In the above mentioned research, the optical OFDM was accomplished by first performing the OFDM electronically then converting to optical signals. Here, we propose an all optical OFDM system in direct and indirect (diffused) wireless optical channels. The proposed system will be explained with design considerations and analytical evaluations in the coming sections.

III. ALL OPTICAL OFDM SYSTEM

Figure 2 shows the complete system architecture of an all optical OFDM. The system starts with the serial high data rate input which then passes to a serial to parallel (S/P) block similar to that of the conventional OFDM system. However, the all optical OFDM system differs from the conventional OFDM system in performing the discrete fierier transform (DFT) techniques optically rather than electrically at the receiver side.

Recent progress of digital signal processing circuit has made it possible to implement the DFT in wireless communication systems. However, this scheme cannot be applied to the optical communications as the data bit rate is beyond the digital signal processing speed capabilities.

The low rate parallel substream is converted to an optical signal using electrical to optical conversion. This is followed by modulating each optical substream using any type of optical modulation as discussed in Ref. [7] having the different optical orthogonal wavelength and by using different distributed feedback lasers as light sources. The optical conversion and modulation is called baseband optical modulator. The output is added together by using a wavelength division multiplexer at the transmitter side. By this way, we generate an optical orthogonal wavelength division multiplexing (WDM) signal. Optical transmitter is used to propagate light to the wireless optical channel. At the receiver side, optical OFDM signal is detected by an optical receiver. The multiplexed data sequence can be separated by using optical discrete fierier transform (DFT).

$$d_n = \sum_{k=0}^{N-1} s(k\Delta t) e^{-j2\pi(f_o + n\Delta f)k\Delta t}, \quad (1)$$

where n and $d_n(t)$ denote the channel number and the data sequence of the n^{th} channel, respectively. S(kΔt) represents the multiplexed signals passing through an optical Delay line with delay time kΔt , the term of the exponential function represents shifting of the phase of the signals and the summation means an optical coupler putting the delay and the phase shifted signal together.

IV. Design consideration

OFDM system design, as in any other system design, involves a lot of trade off's and conflicting requirements. The most important design parameters of the OFDM system is the bit rate required for the system, band width available and rms delay spread of the channel to calculate guard time, T_g, OFDM symbol duration, T_{OFDM}, and number of subcarriers, N. The guard time of an OFDM system usually results in a signal to noise ratio (SNR) loss since it carries no information. The choice of the guard time is straight forward once the multipath

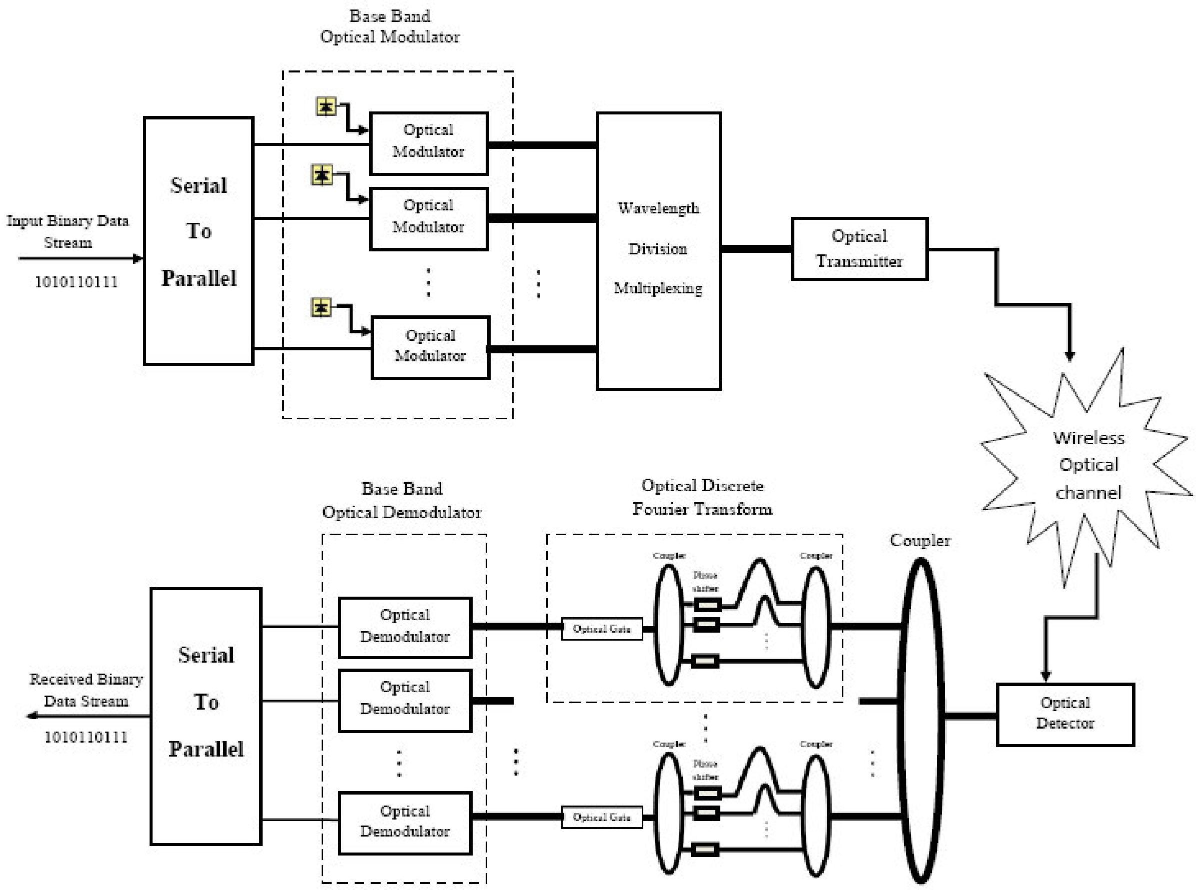

Fig. 2 Complete system architecture of all optical OFDM.

The optical DFT is implemented optically. The multiplexed signals are fed into the optical coupler and divided into the N delay lines, which have the relative delay time of kΔt. After shifting the phase of the delayed signals by 2πnk\N, the signals are added by the coupler and correlated with each other. Operation in time domain is also needed because the orthognality holds within one bit; that is the optical DFT is effective for the duration of unchanged $d_n(t)$. Therefore, one needs to synchronize the incoming bit streams at the input, and to place an optical gate that extracts the duration of T/N, where the same bits are overlapped at the output. The optical demodulator is performed to get the corresponding transmitted bit streams.

delay spread, τ, is known. Based on [9], the value of τ of non-directed indoor infrared channels ranges from 5 to 20 ns.

Since $T_g \geq \tau$, as a rule of thumb, to avoid ISI the guard time must be at least 2-4 times the delay spread of the multipath channel, one can choose $T_g = 4\ \tau$. The symbol duration T_s, must be set mush larger than the guard time. A practical design choice for the symbol time is to be at least five the guard time [10].

The OFDM symbol duration consists of symbol time add to guard time and its duration is to be at least six times of the guard time. To calculate the numbers of subcarriers, N, one has two methods; the first is [8]

Bandwidth (BW) = N×Δf , (2)

where Δf is the frequency spacing. The frequency spacing is equal to the OFDM symbol rate R_s, which is the inverse of T_{OFDM}. Using the previous discussion, the number of subcarriers can be calculated as

$$N = 2^{\lceil \log_2 24 \times BW \times \tau \rceil}. \quad (3)$$

The second method through the data rate, R_b, and the type of modulation gives the number of subcarriers as follows

$$\text{Number of bits per symbol} = \frac{R_b}{R_s}, \quad (4)$$

$$N = \frac{\text{Number of bits per symbol}}{\text{Number of bits per subcarrier}}, \quad (5)$$

where the number of bits per subcarrier is equal to the number of bits per symbol in binary modulation, but in QPSK modulation, the number of bits per subcarrier is equal to half number of bits per symbol.

The number of subcarriers is equal to the number of low rate parallel data substream. The baseband optical modulator follows the parallel substream, which transfers the low rate substream information to light using the same optical source as light carrier. The two baseband types of optical modulators are intensity or phase modulation [7]. The on–off keying (OOK) intensity modulation is excluded because all carriers should be imposed in our system.

In the DFT using the optical elements, the optical parallel substreams are passing into N optical delay lines which have the relative delay time (K Δt). One can calculate the relative fiber delay lines length, L, as follows

L = Relative delay time × Velocity inside the fiber (v), (6)

where v=c/n, c is the velocity of light in air and n is refractive index of the fiber.

The exponential function in (1) represents the phase shift of the signal. This is implemented by an optical phase shifter, with a phase shift of 2πnK/N. The optical coupler implements the optical multiplexer. An optical gate follows the optical multiplexer. The reason for this gate is to maintain orthogonality between subcarriers in an OFDM symbol and the electroabsorption modulator can be used as the optical gate.

V. Analytical Evaluation of Optical OFDM

Before going through the analytical evaluation of the proposed system in optical wireless channels, a round figure for the number of subcarriers needed in the system is calculated.

From (3), the values of N are calculated as a function of the delay bandwidth product BW×τ as presented in Table 2

Range	**BW × τ (GHz.ns)**	**N**
R_1	6 - 10	128
R_2	11 - 21	512
R_3	22 – 42	1024
R_4	43 – 85	2048
R_5	86 - 170	4096

Table 2 Calculated values of subcarriers.

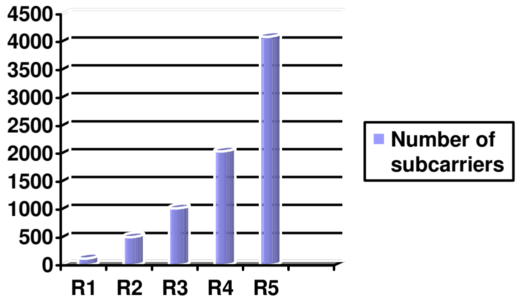

Fig. 3 Values of delay BW product and N.

Characterization for optical wireless channels has been done by a variety of methods at different levels [9]. Carruthers and Carroll described models for characterizing the properties of transmitters, receivers and reflecting surfaces within the indoor environment [11]. The distribution of channel gain in dB for LOS channels including all reflection follows a modified Rayleigh distribution and the channel gain in dB of diffuse channel follows shifted lognormal distribution.

The probability of error (P_e) of a diffuse channel can be derived using a shifted lognormal probability density function as follows [12]. Consider a link with one transmitter and one receiver apertures. X(t) is the received optical OFDM signal plus noise. After removing cyclic prefix, X(t) will be composed of s(t) plus noise as (5). Performing IFFT the output will be

$$X(k) = \sum_{n=0}^{N-1} (s(n) + N)\, e^{-j2\pi n k / N} \quad K = 0,1,\ldots, N-1 \quad (7)$$

The received signal after the optical demodulator is

r(k) = d(k)×η×I + v , (8)

where d(k) is logic 0 or 1 in each branch, η is the optical-to-electrical conversion coefficient, and v is an additive white Gaussian noise with zero mean and variance of $\sigma_v^2 = N_o/2$. The fading channel coefficient, I, which models the channel from the transmit aperture to the receive aperture is given by

$$I = I_o \exp(2X), \quad (9)$$

where I_o is the signal light intensity without turbulence and X is normal random variables with mean μ_x and variance σ_x^2. Therefore, "I" follows a shifted lognormal distribution.

$$f(I) = \frac{1}{2\mathrm{I}}\frac{1}{\sqrt{2\pi\sigma_x^2}}\exp(-\frac{(\ln(I/I_o)-2\mu_x)^2}{8\sigma_x^2}). \quad (10)$$

Assuming two level intensity modulations L_1 and L_2 and perfect channel state information (CSI) available at the receiver side, the P_e is calculated as [12].

$$P_e = P(L_1)\, P(e/L_1) + P(L_2)\, P(e/L_2)\ , \quad (11)$$

where $p(L_1)$ and $p(L_2)$ are the probabilities of transmitting "1" and "0" bits, respectively. $P(e/L_1)$ and $p(e/L_2)$ denote the conditional bit error probabilities when the transmitted bit is "1" or "0". Conditioned on the fading coefficient I^3, one has

$$P(e/L_1) = P(e/L_2) = Q = (\frac{\eta I}{\sqrt{2N_0}}). \quad (12)$$

Averaging over the fading coefficient, one obtains

$$P(e/L_1) = P(e/L_2) = \int_0^\infty f_I(I) Q(\frac{\eta I}{\sqrt{2N_0}} dI\ , \quad (13)$$

where Q(.) is the Gaussian-Q function defined as

$$Q(y) = (1/\sqrt{2\pi})\int_y^\infty \exp(-t^2/2)dt. \quad (14)$$

Consider the symmetry of the problem, i.e, $p(L_1) = p(L_2) = 1/2$ and $p(e/L_1) = p(e/L_2)$ and replacing I in terms of x, P_e can be obtained as

$$P_e = \int_0^\infty f_I(I) Q(\frac{\eta I}{\sqrt{2N_0}} dI\ , \quad (15)$$

$$= \int_{-\infty}^\infty \Omega(x, -\sigma_x^2, \sigma_x^2) Q(\frac{\eta I_0 e^{2x}}{\sqrt{2N_0}})dx\ , \quad (16)$$

where $\Omega(u,v,w)$ is defined by

$$\Omega(u,v,w) = (\frac{1}{\sqrt{2\pi w}}\exp(\frac{-(u-v)^2}{2w}). \quad (17)$$

The integration in (16) can be efficiently computed by Gauss-Hermite quadrature formula [12]

$$P_e \approx \frac{1}{\sqrt{\pi}}\sum_{i=1}^{n} w_i Q(\frac{\eta I_0 e^{-2\sigma_x^2 + z_i\sqrt{8\sigma_x^2}}}{\sqrt{2N_0}})\ , \quad (18)$$

where n is the order of approximation z_i, i=1,…,n are the zeros of the n^th-order Hermite polynomial and w_i, i=1,…,n are weight factors for the n^th-order approximation.

Figure 4 shows the optical OFDM system versus the SNR. The SNR is the electrical SNR defined as I_0^2/N_0. The figure is evaluated at σ_x = 0.3 and at different order of approximation (n), as shown in Fig. 4, as n increases the P_e converges to a single curve with a negligible difference from which one can use n = 12 to have a good approximation.

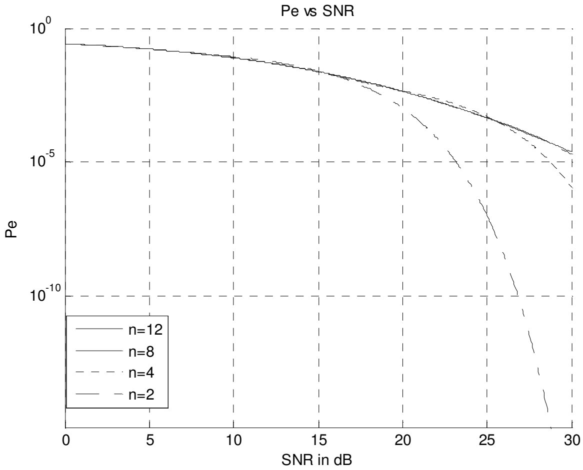

Fig. 4 Probability of error with signal to noise ratio.

V. Simulation Results

The universal software **OPTISYSTEM** is used to perform the simulation of proposed system. The model starts by constructing a single carrier system. A 100 Gbps optical communication system that uses a pseudo-random bit sequence is followed by non return to zero pulse generators as the input data and then modulated with a light source such as intensity modulation as shown in Fig. 5.

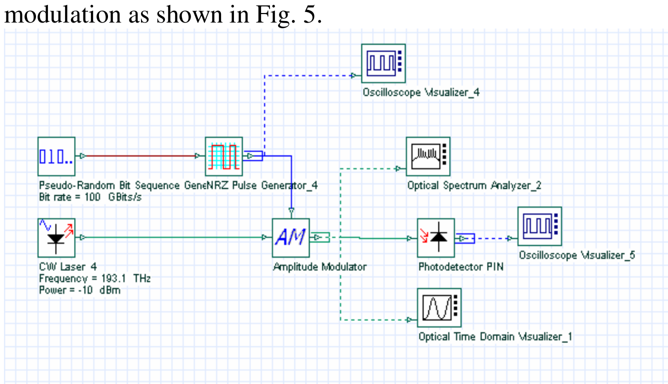

Fig. 5. 100 Gbps optical communication system.

The power spectrum of the system output (after the intensity modulator) is displayed in Fig. 6. It is clear that there is a single carrier having a wavelength 1.55 µm and a larger bandwidth that becomes a problem in diffused environments.

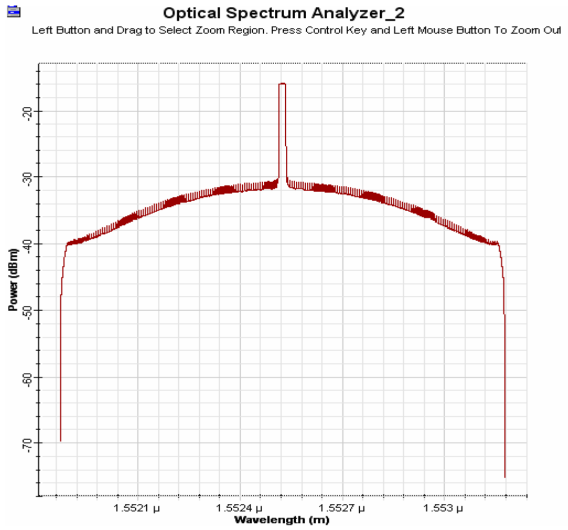

Fig. 6. The output of the 100 Gbps optical communication System

Our proposed system is shown in Fig. 7. Instead of having a single carrier with 100 Gpbs as input, we use four 25 Gpbs parallel transmission with orthogonal wavelength and multiplexing them with a WDM multiplexer (like conventional OFDM).

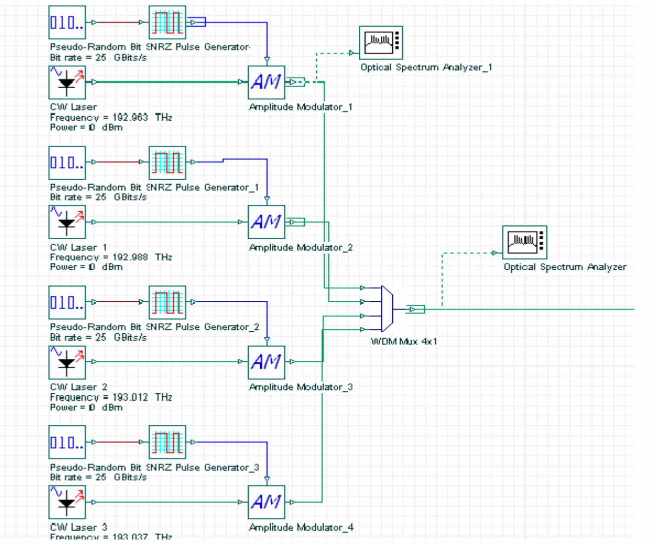

Fig. 7. 4×25 Gbps optical communication system.

Figure 8 shows the spectrum of the output of the system shown in Fig. 7 that has a bandwidth much smaller compared to that shown in Fig. 5. The figure also shows the four subcarriers of the OFDM at 1554.7, 1554.5, 1554.3 and 1554.1 nm. With this smaller bandwidth, the proposed system can overcome the problems of diffused wireless optical channels and achieves higher throughput with longer transmission distances.

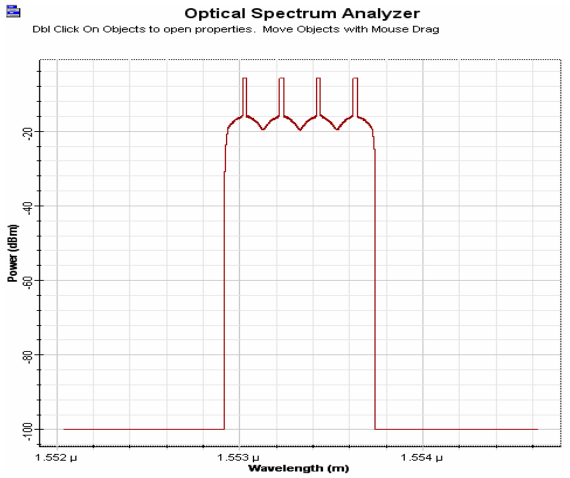

Fig. 8. The output of the proposed system with the smaller bandwidth.

VI. CONCLUSION

In this paper, a novel optical orthogonal frequency division multiplexing technique is proposed. The theory of system is explained with design consideration. The formula of probability of error is driven in diffused channel. The proposed optical OFDM system could yield promising results to overcome multipath effects and ISI for optical wireless channels.

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