Design and Simulation of WDM-UWB Based OWC System

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Abstract

The streaming of wireless applications and growth in bandwidth demand led to huge interest in Ultra Wide Band (UWB) technology. In this paper a Wavelength Division Multiplexing (WDM)-UWB system based Optical Wireless Communication (OWC) is designed and simulated with two modulation formats OOk and QAM at three bit rates values(1Gbps, 2.5Gbps and 5Gbps). In the designed system, two methods to generate UWB pulses are proposed and demonstrated, optical method based cross-gain modulation (XGM) in a Semiconductor Optical Amplifier (SOA) and the electrical method depends on the differentiation of the Gaussian pulse. The full width half maximum (FWHM) of the generated pulses (monocycle and doublet) are 32 ps, 19ps for optical method and2.2 ns, 1.9ns for electrical method. All the generated pulses are compatible with the Federal Communications Commission (FCC) rules .

In order to understand the linear and nonlinear effects, and the maximum achievable reach at each modulation scheme, the performance of the system is tested under four cases of weather conditions: clear, rainy, fog and snow weather with single channel and 8-WDM channels at 100GHz, 75GHz and 50GHz channel spacing.

Key words: UWB, WDM technique, Quadrature Amplitude Modulation (QAM), OOk modulation.

الخلاصة

انتشار التطبيقات اللاسلكية و تزايد الطلب على عرض الحزمة ادى الى اهتمام كبير في تقنية الحزمة فائقة العرض. في هذه الورقة تم تصميم ومحاكاة منظومة مازج تقسيم الطول الموجي مع حزمة فائقة العرض المعتمدة على نظام الاتصال اللاسلكي الضوئي باستخدام صيغتين للتضمين: OOk و QAM لثلاث قيم لمعدل نقل البيانات (1Gbps, 2.5Gbps و 5Gbps). في المنظومة المصممة تم اقتراح واثبات طريقتين لتوليد نبضات الحزمة فائقة العرض، الطريقة البصرية تعتمد على XGM في المضخم البصري شبه الموصل والطريقة الكهربائية المعتمدة على اشتقاق نبضة جاوس. العرض الكامل لمنتصف النبضات المتولدة (الاحادية والثنائية) هو 32ps و 19ps في الطريقة البصرية و 2.2ns و 1.9ns في الطريقة الكهربائية. جميع النبضات المتولدة متوافقة مع قوانين لجنة الاتصالات الفيدرالية.

لفهم المؤثرات الخطية واللاخطية واقصى وصول ممكن تحقيقه للإشارة لكل صيغة من صيغ التضمين، تم اختبار اداء المنظومة لأربع حالات للظروف الجوية: صافي، ممطر، ضباب و ثلج. اختبرت المنظومة لقناة واحدة ثم لثمان قنوات باستخدام تقنية مازج تقسيم الطول الموجي ثلاث قيم للمسافة بين القنوات 100GHz, 75GHz و 50GHz.

الكلمات المفتاحية: حزمة فائقة العرض، مازج تقسيم الطول الموجي، تضمين تربيع السعة، تضمين الإطفاء والتشغيل.

1. Introduction

UWB can be defined as any signal that occupies more than 500 MHz bandwidth or possesses a fractional bandwidth greater than 0.2 at all the time of transmission [FCC,2002]. Fractional bandwidth is a factor used to classify signals as narrowband, wideband, or ultra-wideband and is defined by the ratio of bandwidth at –10 dB to center frequency. Equation (1.1) shows this relationship.

$$B_f = 2\frac{f_h - f_l}{f_h + f_l} \qquad (1.1)$$

Where B_f fractional bandwidth, f_h and f_l are the highest and lowest -10 dB cutoff frequencies. UWB signal can be any one of wideband signals, such as

Gaussian, chirp, wavelet [Nekoogar, 2005]. One of the major advantages of the large bandwidth for UWB pulses is improved channel capacity according to Hartley-Shannon's capacity formula as shown in equation (1.2).

$$C = B\log_2(1 + SNR) \qquad (1.2)$$

Where C is the maximum channel capacity, B is the bandwidth, and SNR is the signal to noise power ratio.

Today, wireless communications is the fastest growing segment of the communication industry. Cellular phones and the internet have rapidly become an essential part of our everyday life [Mirshafiei,2013], the popularity of streaming videos over the internet and the high definition television (HDTV)has caused a growth in bandwidth demand.(UWB)communications is a research field that promises very high data rate wireless communications so,UWB wireless systems have recently attracted considerable interest for wireless communication and sensor networks thanks to their intrinsic properties, such as the immunity to multipath fading, extremely short time duration, carrier free, and low power spectral density [Zeng and Yao, 2006;Porcino and Hirt, 2003; Ran, Lembrikov and Ben Ezra, 2010].

UWB communications field remained almost limited until February 2002 where the Federal Communications Commission (FCC) approved the use of the 3.1-10.6GHz band for UWB communication [FCC, 2003].

Due to interference concerns from UWB radiators to other existing wireless services and narrow band (NB) communication systems include Worldwide Interoperability for Microwave Access (WiMAX) operating in the 3.3–3.7-GHz band, Wireless Fidelity (Wi-Fi) operating in the 5.15–5.825-GHz band [Lee, Su, and shen, 2007], the FCC placed "conservative" requirements on UWB emissions. These frequency limits and the equivalent isotropically radiated power (EIRP) are tabulated in Table (1-1) and shown in Fig. (1.1)

Table (1-1) FCC Mask Limits

Frequency Range [MHz]	Indoor Limit [dB/MHz]	Outdoor Limit [dBm/MHz]
Below 960	FCC 15.209	
960-1610	-75.3	-75.3
1610-1990	-53.3	-63.3
1990-31000	-51.3	-61.3
31000-10600	-41.3	-41.3
Above 10600	-51.3	-61.3

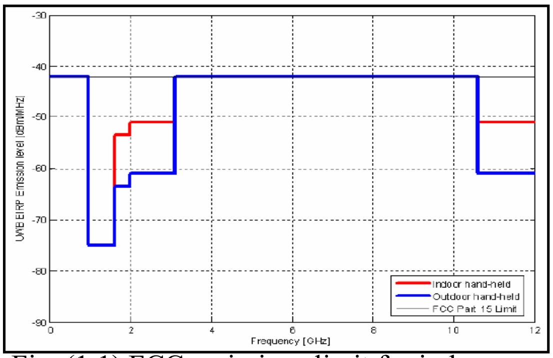

Fig. (1.1) FCC emissions limit for indoor and outdoor UWB communication

In this paper an outdoor wireless optical communication system is designed, this system uses the UWB pulse as a carrier of the data, the generation of the UWB pulse is the essential part of the work which was done by two methods, electrical method depends on the first and second derivative of Gaussian pulse[Ghavami, Michael and Kohno,2007] and the optical method based the XGM of the SOA [Wang, Zeng, Blais, and Yao, 2006]. To increase the capacity of the channel,WDM technique was integrated with optical wireless communication (OWC) systems in this work which can significantly increase the bitrate in OWC systems[Nejad, Mohammadi and Anwar, 2013].

2. Wavelength Division Multiplexing (WDM)

An important technique which significantly enhanced the performance of the UWB communication system is the WDM.WDM represents the scheme in which several optical carriers with different wavelengths are modulated using independent bit streams and then simultaneously transmitted over specified channel. The received optical signal is demultiplexed into different channels to be demodulated as shown in Fig.(2.1). If N channels at bit rates $B1$, $B2$, . . ., and BN are simultaneously transmitted through an optical channel, the total bit rate , becomes:

$$B_T = B_1 + B_2 + \cdots B_N \qquad (2.1)$$

interchannel crosstalk issue is limited the minimum channel spacing Δv_{ch}, which typically exceed $2B$. The spectral efficiency of the WDM system can be measured by equation (2.2)

$$\eta s = B/\Delta vch \qquad (2.2)$$

Where ηs is the spectral efficiency [Agrawal, 2002].

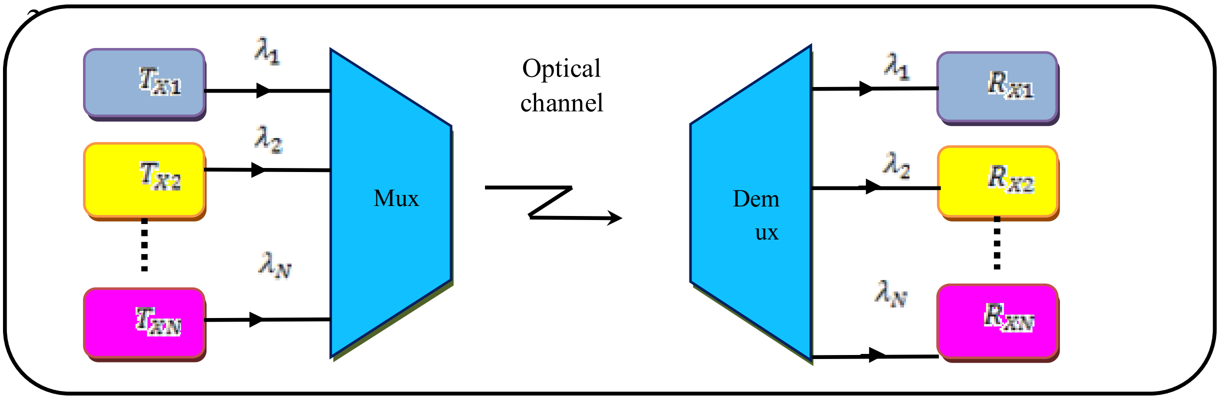

Fig. (2.1) Multichannel WDM transmission

3. Pulse generation in the electrical domain

Gaussian pulses always used because of the simplicity, achievability and uniformly distributed over their frequency spectrum. the zero-mean Gauss function is described by Equation (3.1), where σ is the standard deviation.

$$G(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp(-\frac{x^2}{2\sigma^2}) \qquad (3.1)$$

The basis of these Gaussian waveforms is a Gaussian pulse represented by equation (3.2) [Ibrahim A. Murdas, 2009].

$$y_{g_1}(t) = K_1 \exp(-(\frac{t}{\tau})^2 \qquad (3.2)$$

where $-\infty < t < \infty$, τ is the time-scaling factor, and $K1$ is a constant. More waveforms can be created by a sort of high-pass filtering of this Gaussian pulse.

Filtering acts in a manner similar to taking the derivative of equation (3.2). Gaussian monocycle can be obtained from the first derivative of the Gaussian pulse, as in equation (3.3).

$$y_{g2}(t) = K_2 \frac{-2t}{\tau^2} \exp(-(\frac{t}{\tau})^2 \qquad (3.3)$$

A Gaussian monocycle has a single zero crossing. Higher derivatives give additional zero crossings, one additional zero. If the value of τ is fixed, by taking an additional derivative, the fractional bandwidth decreases, while the center frequency increases. A Gaussian doublet is the second derivative of the Gaussian pulse and is defined by the equation (3.4).

$$y_{g3}(t) = K_3 \frac{-2}{\tau^2}(1-\frac{2t^2}{\tau^2})\exp(-(\frac{t}{\tau})^2) \qquad (3.4)$$

4. Pulse generation in the optical domain

There are many optical methods to generate UWB monocycle and doublet pulses, as known above, Gaussian monocycle and doublet are represent the first and second order derivative of the Gaussian pulse. The first and second order derivatives can be approximated mathematically by the first and the second order differences, which can be performed using a photonic microwave delay line filters, having two or three taps, these filters with one negative tap[Wang and Yao, 2007].

To know the principle of Photonic Microwave Delay-Line Filters to generate UWB pulse,assume that the input Gaussian pulse $x(t)$ is applied to a microwave delay-line filter with two taps, as shown in Fig. (4.1) the filter has one positive and one negative coefficient of [1 -1]. The output of the filter $y(t)$ is given by

$$y(t) = x(t) - x(t-\tau) \qquad (4.1)$$

where τ is the time-delay difference. Applying Fourier transform to (4.1), we obtain

$$Y(\omega) = X(\omega) - e^{-j\omega}X(\omega) = X(\omega)(1-e^{-j\omega\tau}) \qquad (4.2)$$

where $X(\omega)$and $Y(\omega)$ are the Fourier transforms of $x(t)$ and $y(t)$, respectively. The magnitude for the filter frequency response is given by

$$|H(\omega)| = \left|\frac{Y(\omega)}{X(\omega)}\right| = \sqrt{2-2\cos(\omega\tau)} \qquad (4.3)$$

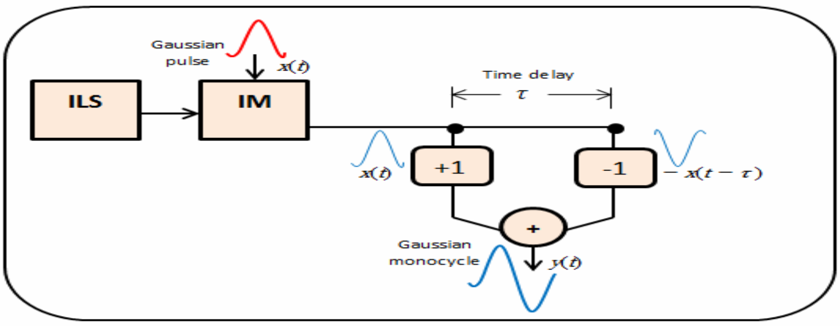

Fig. (4.1) UWB monocycle generation based on a two-tap microwave delay-line filter with one negative coefficient, ILS: Incoherent Light Source, IM: Intensity Modulator.

An UWB doublet signal can be generated by performing the second-order derivative for a Gaussian pulse, which can be approximated by second-order difference.

$$\begin{aligned} y(t) &= [x(t) - x(t-\tau)] - [x(t-\tau) - x(t-2\tau)] \\ &= x(t) - 2x(t-\tau) + x(t-2\tau). \end{aligned} \qquad (4.4)$$

UWB doublet signal can be generated by using a microwave delay-line filter which has three taps with coefficients of [1−2 1], as shown in Fig.(4.2). The frequency response of three-tap microwave delay-line is given by

$$H(\omega) = \frac{Y(\omega)}{X(\omega)} = 1 - 2e^{-j\omega\tau} + e^{-2j\omega\tau} \qquad (4.5)$$

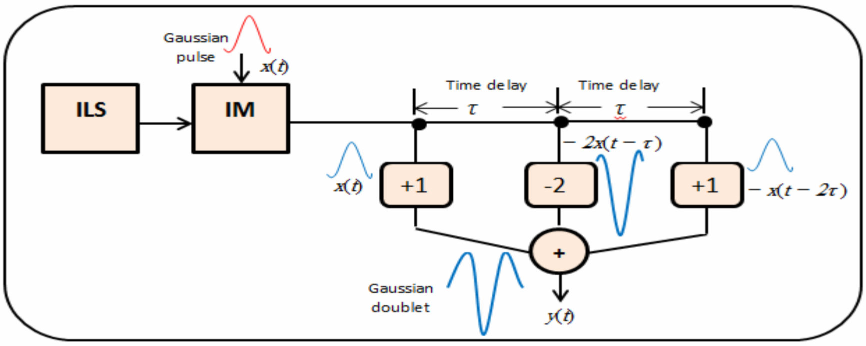

Fig. (4.2) UWB doublet generation based on a three-tap microwave delay-line filter [1 -2 1] with one negative coefficient, ILS: Incoherent Light.

The negative coefficient can be generated based on the cross gain modulation (XGM) in a semiconductor optical amplifier (SOA). In this method both the signal light and the probe light are coupled in to the SOA in opposite directions. The light from the optical source with constant power is divided into two parts by a power splitter (ps). The upper part is modulated to signal light through MZM by a bit pattern generator (BPG),while the lower one is used as a probe light. The probe light and the signal light are coupled into a wideband traveling-wave SOA through opposite directions. The probe light is amplified during the propagation process from right to left, and reach the maximum at the right of SOA, while the signal light is amplified from right to left and become maximum at the left side of SOA. So the probe light is obtains a polarity-reversed Gaussian shape at the left side of SOA due to XGM. The monocycle pulse is formed because of the overshoot at the pulse leading edge of probe light. Because the gain of the Gaussian pulse at the leading edge is larger than at the trailing edge. The pulse peak is moving to the leading edge, which cannot lead to fully cancellation of signal light and polarity reversed probe light. As a result, UWB doublet pulse is generated.

The data from Bit pattern generator (BPG) is reshaped using non return to zero (NRZ) code and externally modulated using MZM. The modulated data are transmitted using suitable antenna, for high data-rate indoor applications the antennas are required to be Omni-directional and small like Sky-Cross Antenna, circular monopole antenna.

5. Atmospheric effects on optical signal

To study the performance of WDM UWB OWC system under various weather conditions, there are three cases which are taken as below:

5.1 .Fog effect

The specific attenuation (A_{Fog}) caused by fog that is depending on the visibility as given by Eq. (5.1) [Khan, and Naqvi, 2013].

$$A_{Fog}\left(\frac{dB}{km}\right) = \frac{10\log(V\%)}{Vkm}\left(\lambda/\lambda_{\circ}\right)^{-q} \approx \frac{13dB}{Vkm}\left(\frac{\lambda nm}{550nm}\right)^{-q} \qquad (5.1)$$

Where: V=Visibility, q=particle size distribution coefficient, λ=wavelength.

The value of q can be calculated as in the relation (5.2)

$$q = \begin{cases} 1.6 & if\ V > 50km \\ 1.3 & if\ 6km < V < 50km \\ 0.585V^{1/3} & if\ V < 6km \end{cases} \qquad (5.2)$$

5.2 .Rain effect

The specific attenuation (A_{rain}) caused by rain is depending on the rain rate as given by Eq. (5.3) [Saleem, 2010]

$$A_{rain} = 1.07R^{\frac{2}{3}} \quad \left[\frac{dB}{km}\right] \qquad (5.3)$$

Where:
R: is the rain rate in mm/hr

5.3 .Snow effect

The specific attenuation (A_{snow}) caused by light snow is depending on the snowfall intensity S (mm/h) as given by Eq. (5.4) [16]

$$A_{snow} = aS^{b} \quad \left[\frac{dB}{km}\right] \qquad (5.4)$$

Where the parameters a and b categorize snowfall type and have values as:
For dry snow : $a = 5.42 * 10^{-5}\lambda + 5.4958776$, $b = 1.38$

6. Proposed System Design and Simulation Results

In order to increase the bit rate of the transmitted data and the transmission reach of the optical signal and improve the system performance by minimize the bit error rate (BER) of the received data, the system was designed properly by the accurate selection of the various components in the system..

The most common UWB pulses are Gaussian monocycle and doublet, these short pulses have typical duration in picosecond range and thus bandwidths of over 1 GHz. There are two fields to generate UWB pulse electrical and optical method, This work reviews both areas. The generated pulses in two methods are compatible with the Federal Communications Commission (FCC) rules.

6.1 .Pulse generation in the electrical domain

The electrical method for generation of UWB monocycle and doublet is shown in Fig. (6.1)

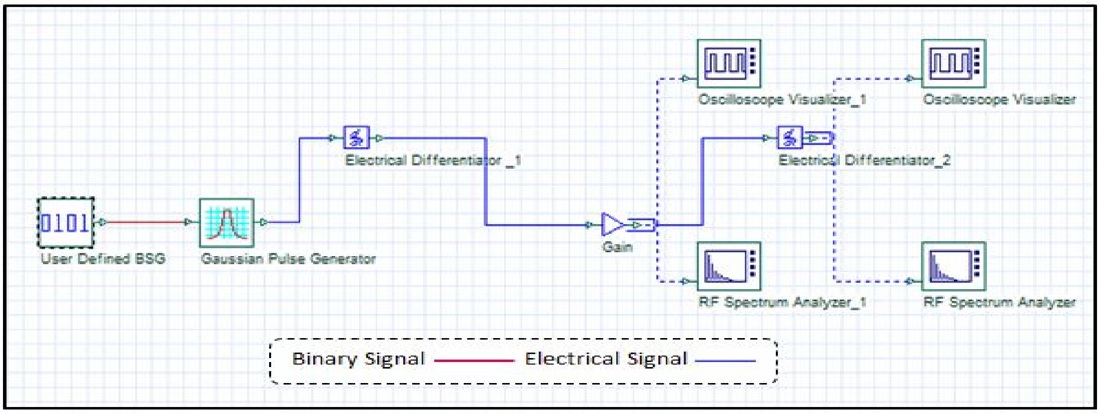

Fig. (6.1) UWB pulse generation in electrical domain

The specification of the generated pulses including Full width Half Maximum (FWHM),10-dB bandwidth, center frequency, and fractional band width are listed in table (6-1). From the RF spectrum it can be seen that the generated pulses are compatible with FCC regulations.

Table (6-1) specifications of the Electrically generated UWB pulses

Pulse Type	Monocycle	Doublet
FWHM	1.15 ns	0.75 ns
10-dB Bandwidth	656 MHz	666 MHz
Center Frequency	400 MHz	483 MHz
Fractional Bandwidth	164%	137%

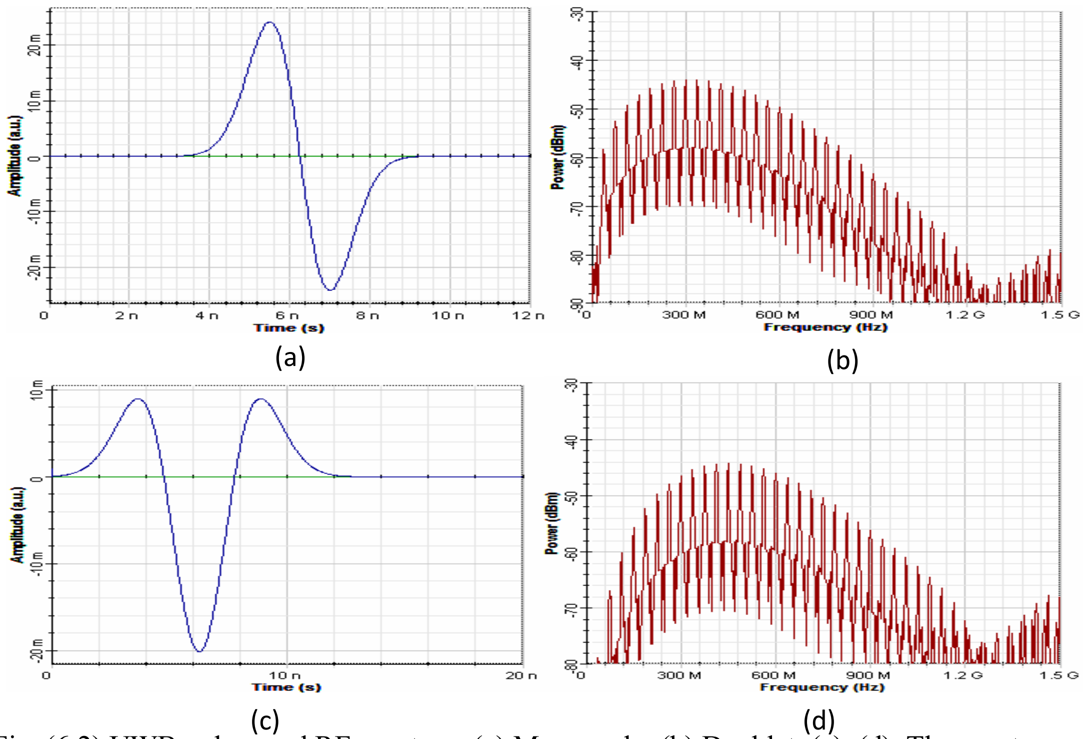

Fig. (6.2) UWB pulses and RF spectrum (a) Monocycle, (b) Doublet, (c), (d), The spectrum of Monocycle and Doublet respectively.

6.2. Pulse generation in the optical domain

UWB monocycle and doublet pulses are generated optically based on XGM in a semiconductor optical amplifier SOA. Fig. (6.3) shows the schematic diagram of the experimental setup for the pulse generation.

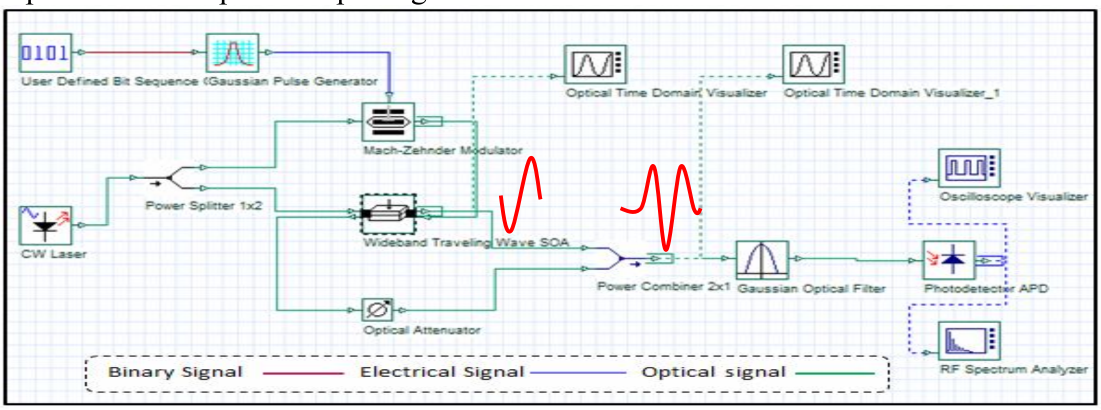

Fig. (6.3) Monocycle and doublet pulses generation based XGM of SOA

The simulation has been done by taking the symbol rate 40 Gbit/s with data pattern "1000000000000000". The Gaussian pulse width of 0.5 bit and the power of the optical signal is varied in four values (-15dBm, -5dBm, 5dBm and 15dBm) with wavelength of 1552 nm. The length of the active region of SOA is 0.6 mm and the injection current 80 mA. The bandwidth of the band pass filter o.4 nm with center frequency of 1552 nm. The attenuator is set to 24 dB. With these parameters of the circuit obtained an UWB doublet pulses with RF spectrum as shown in Fig (6.4).

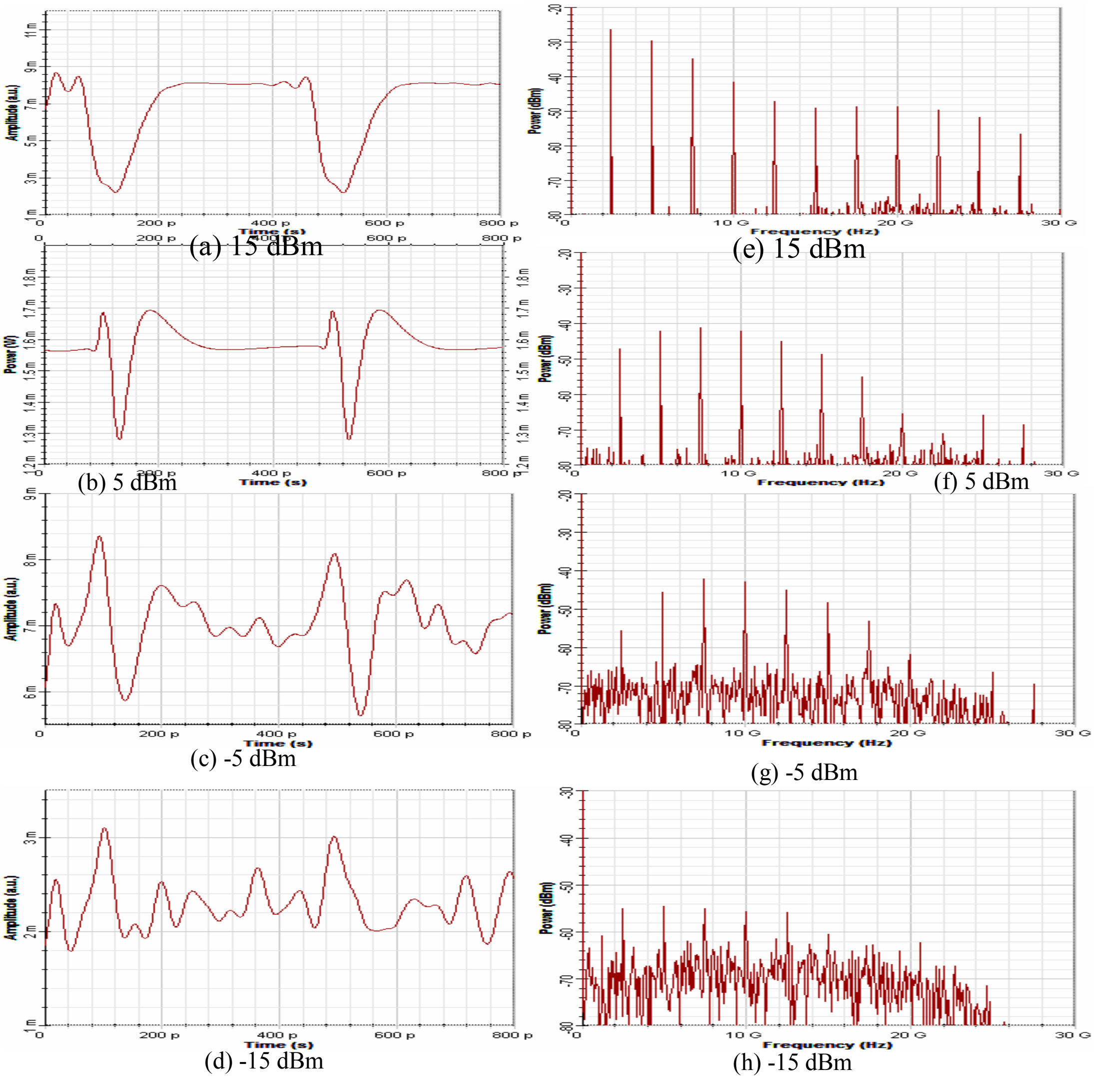

Fig. (6.4) Photonic generation of UWB doublet and its spectrum for various source power.

When the optical source power is too low (-15 dBm), as shown in Fig.(6.4)d, the output signal is reduced by noise. With the optical source power increasing, the average power of output signal increases. The right positive pulse of doublet pulse disappears when the source power continues to increase, as shown in Fig. (6.4)a.

The optimum UWB doublet pulse which compatible with FCC obtained at 5 dBm input source power, the monocycle can be also generated at this power as shown in Fig. (6.5). The specification of Monocycle and doublet that generated at 5dBm is listed in table (6-2).

Table (6-2) specifications of the Optically generated UWB pulses

Pulse Type	Monocycle	Doublet
FWHM	32 ps	19 ps
10-dB Bandwidth	9.5 GHz	14.2 GHz
Center Frequency	5.05 GHz	8.9 GHz
Fractional Bandwidth	188%	159%

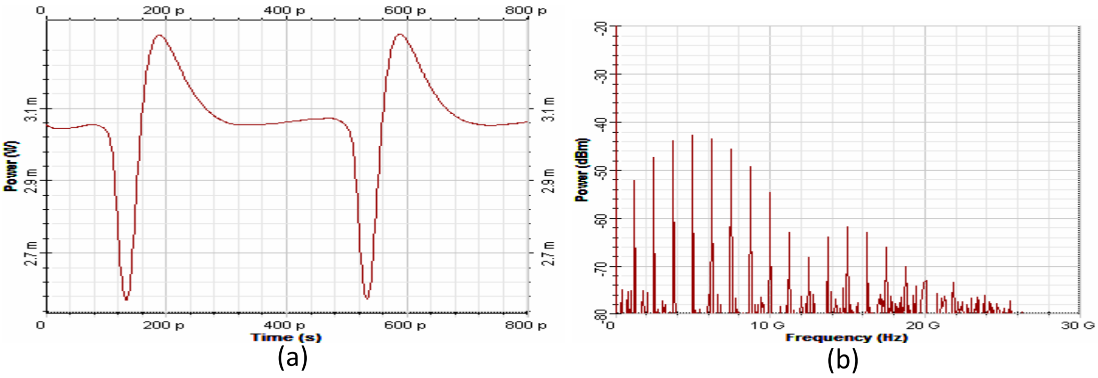

Fig. (6.5) (a) UWB monocycle, (b) RF spectrum

6.3 . The structure of the single channel UWB transmitter

In the designed system the structure of the transmitter is different according to the modulation scheme, so two transmitters are designed as following:

I. The single channel transmitter with OOk modulation is shown in Fig. (6.6)

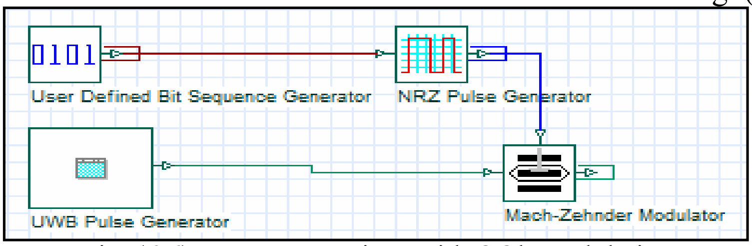

Fig. (6.6) UWB transmitter with OOk modulation

II. The single channel transmitter with 16-QAM is shown in Fig. (6.7)

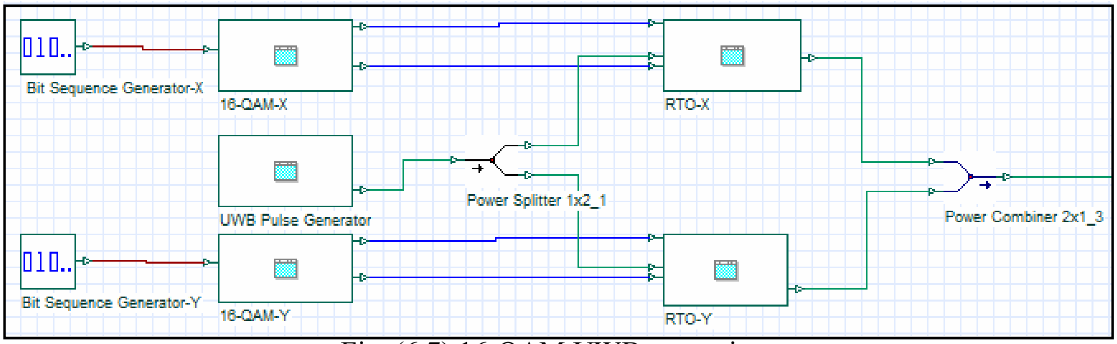

Fig. (6.7) 16-QAM UWB transmitter

6.4 The structure of the single channel UWB receiver

In the designed system the structure of the receiver is different according to the modulation scheme, so two transmitters are designed as following:

I. Fig (6.8) show the schematic diagram of single channel UWB receiver with OOK modulation

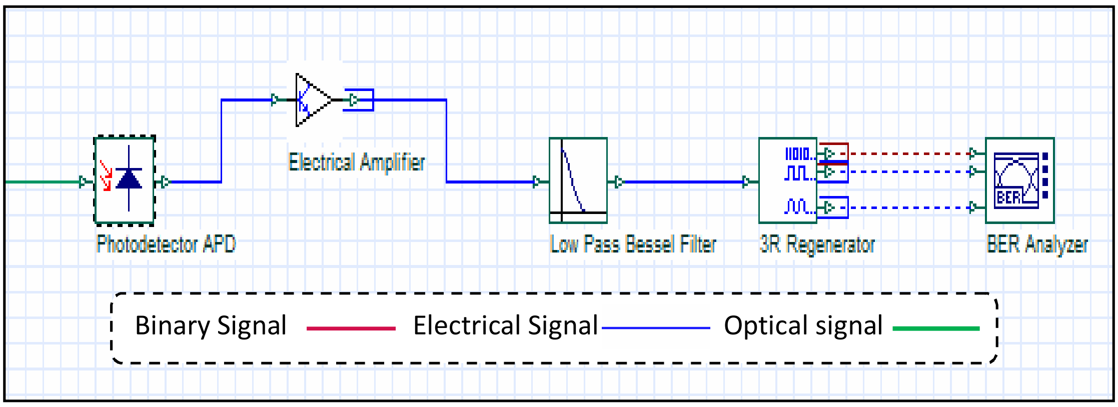

Fig. (6.8) UWB receiver with OOK

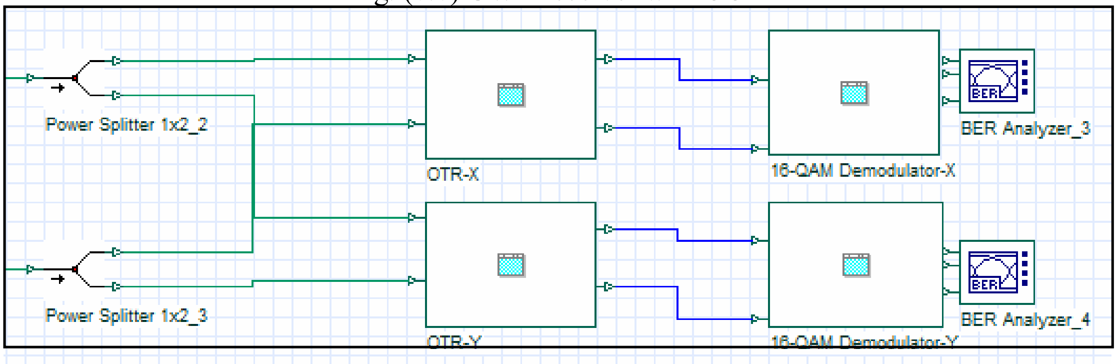

Fig. (6.8) UWB receiver with 16-QAM coherent detection

Table (6-3) Simulation parameters of OWC channel

OWC Channel		
Parameter	**Value**	**Units**
Frequency	1550	nm
Range	variable	m
Transmitter aperture diameter	15	cm
Receiver aperture diameter	15	cm
Transmitter optics efficiency	0.8	
Receiver optics efficiency	0.8	
Tx & Rx gain	0	dB
Atmospheric attenuation	variable	dB/km
Additional loss	5	dB
Pointing loss	3	dB

6.5 WDM System Description

The description of the UWB OWC system with 8-WDM channel can be simulated as in Fig. (6.9). The optical amplifier has been put to raise the low power of the UWB signal. The simulation parameters OWC channel are shown in table (6-3).

To characterize the transmission performance of 8-WDM UWB OWC system with OOK modulation at 2.5Gbps, and 16-QAM at 5Gbps, the Q factor measured as a function of transmission distance with four attenuation values: 0.338dB/km, 1.988dB/km, 7.743dB/km and 19.76dB/km corresponding to four weather conditions: clear weather, light rain with rain rate 2.5 mm/h, light fog with visibility $V < 1km$ and light snow with rate equal to 2.5 mm/h respectively. These attenuation values are computed according to equations (5.1), (5.3), (5.4). The transmission measurements were performed for a central WDM channel (channel 4), since it experiences the maximum amount of nonlinearity which make it the worst performance channel and, hence, minimum transmission distance. Transmission distance and its corresponding Q factor were computed for three values of channel spacing: 100GHz, 75GHz and 50 GHz.

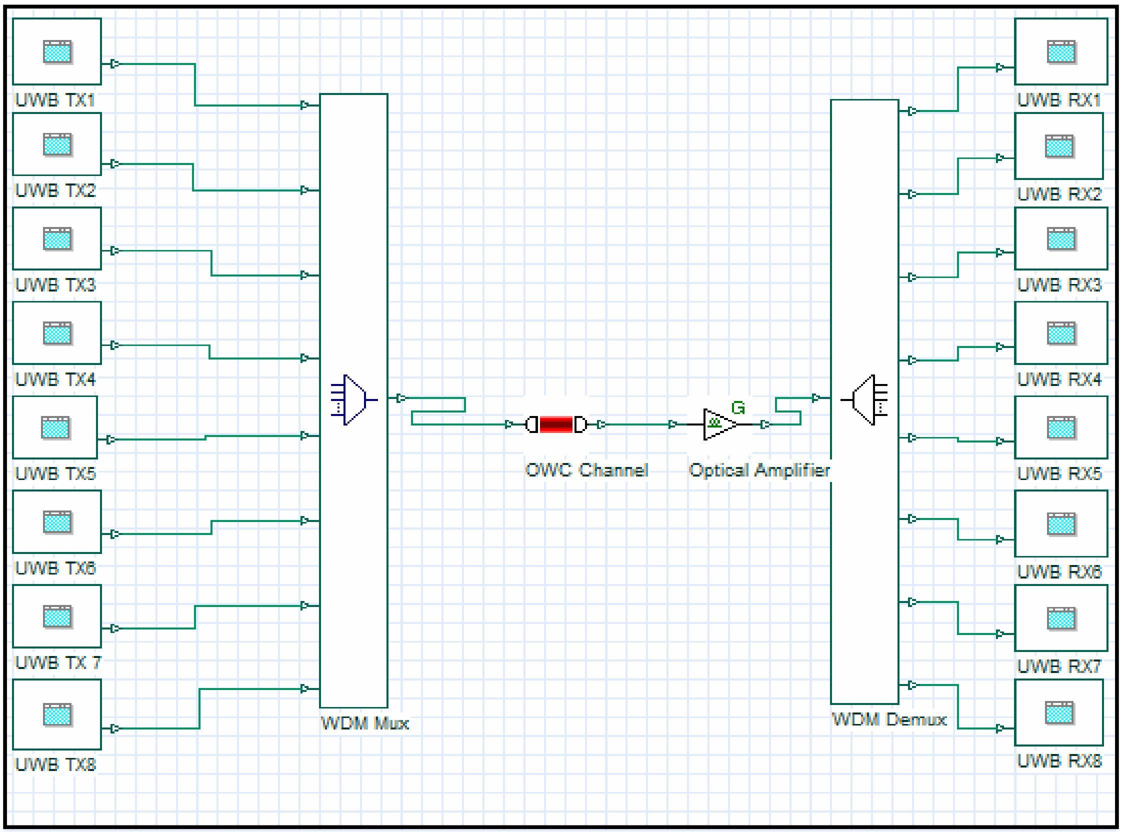

Fig. (6.9) 8-channel WDM UWB OWC system with optical amplifier

The simulation results for Q factor verses transmission distance at different weather conditions with OOK modulation format and different channel spacing (100GHz, 75GHz, 50GHZ) is shown in Fig. (6.10)

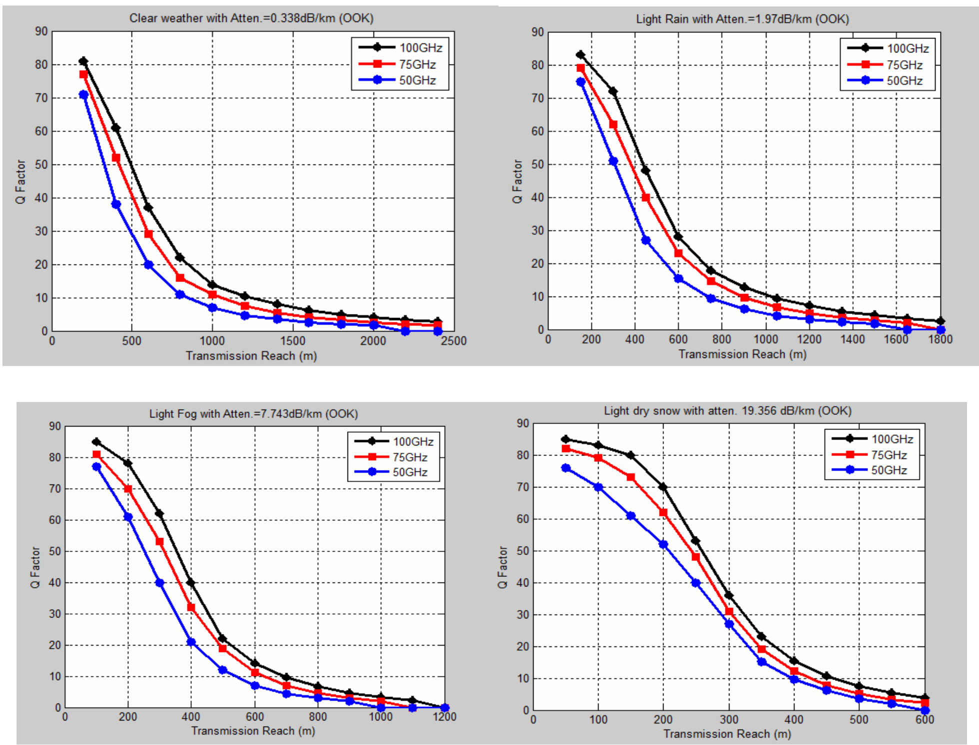

Fig. (6.10) Q factor verses transmission distance at different weather conditions with OOK modulation.

The simulation results for Q factor verses transmission distance at different weather conditions with 16-QAM format and different channel spacing (100GHz, 75GHz, 50GHZ) is shown in Fig. (6.11)

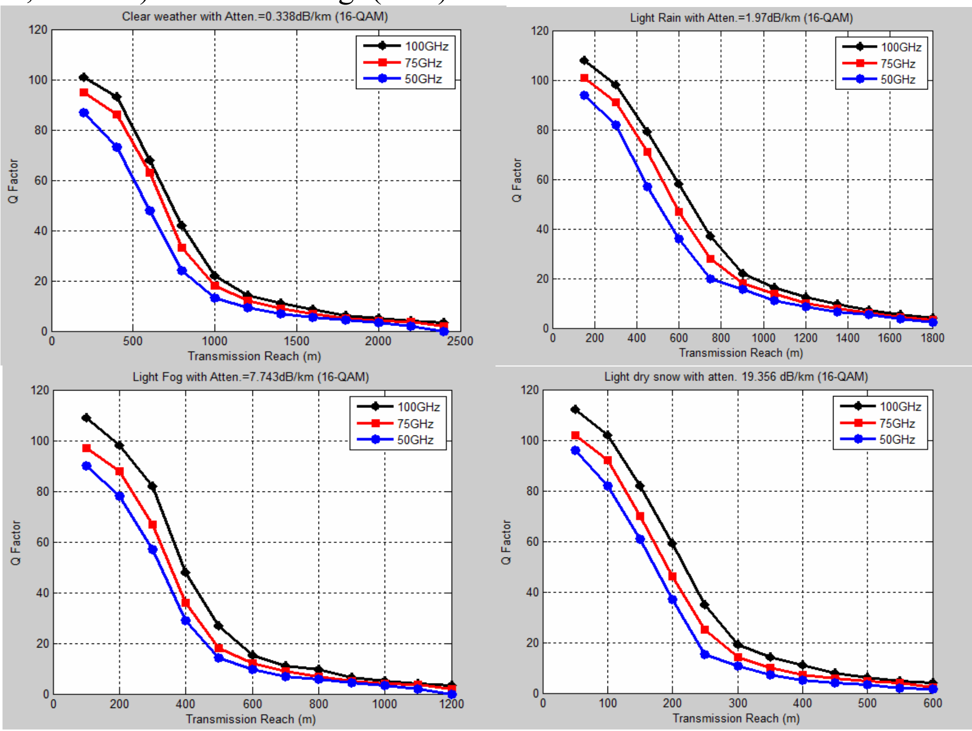

Fig. (6.11) Q factor verses transmission distance at different weather conditions with 16-QAM

From the simulation results of the designed system under four cases of weather conditions and two modulation schemes, The transmission distances with acceptable BER, (i.e. BER $\leq 10^{-9}$ or $Q \geq 6$) can be summarized in table (6-4).

Table (6-4) summary of results for the designed system under four weather conditions.

Modulation Type	**Channel Spacing (GHZ)**	**Weather Condition**	**Max. correctly Reach (m)**
OOK	100	Clear	1632
		Light Rain	1298
		Light Fog	834
		Light Snow	532
	75	Clear	1334
		Light Rain	1096
		Light Fog	732
		Light Snow	481
	50	Clear	1064
		Light Rain	905
		Light Fog	635
		Light Snow	426
16-QAM	100	Clear	1672
		Light Rain	1324
		Light Fog	858
		Light Snow	557
	75	Clear	1358
		Light Rain	1113
		Light Fog	749
		Light Snow	493
	50	Clear	1081
		Light Rain	928
		Light Fog	652
		Light Snow	439

8. Conclusion

We design and simulate an WDM-UWB OWC system using two methods for pulse generation the optical method is more efficient than the electrical one, where the UWB pulses generated in the optical method have a FWHM of 32ps and 20 ps for monocycle and doublet respectively, while in electrical method, the FWHM was 1.15 ns and 0.75 ns. This means that the optical method gives larger bandwidth, farther more this pulse is more compatible with FCC mask.

Increasing the order of derivative for Gaussian pulse gives better pulse specifications, but for higher order derivatives, the improvement in the impulse characteristics are few compared to the cost of each added derivative.

Using advanced modulation format gives higher spectral efficiency and transmission reach.

Using WDM technique is significantly enhance the channel capacity and the aperture diameter transceiver antenna must adjusted according the transmitted data.

Decreasing the channel spacing of the WDM-UWB OWC system, improved the system performance by increasing the capacity of the channel, but it effects on the correct detection of the receiving UWB signal because the crosstalk increase as the channel spacing increase

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