Enhancement Performance of Bidirectional Optical Fiber Link UsingOptical Circulator

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Abstract

In this search, an approach has been suggested to design a bi-directional optical network to increase the data transmission through an optical cable. Ease of doubling the transmission capacity of the network can be achieved with no need to use new optical fiber cable by employing of optical circulators. Adding a new cable to a bidirectional optical fiber transmission system makes it very expensive. Optical circulators are non-reciprocating, one-directional and three port devices that are batter for bidirectional propagation of light in a single fiber. This design technique shows an interesting result in obtaining low insertion loss (around 1.6 dB), low return loss(-65 dB) and low crosstalk between two channels (around -70 dB).

Key word: optical circulator, bi-directional optical fiber, insertion loss, crosstalk.

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1. Introduction

Bidirectional optical links as up- and down-links can be operated in full-duplex or half-duplex mode. During full-duplex mode operation, the optical signals can be transmitted and received simultaneously, while in half-duplex mode, the optical signals can be transmitted or received by time-sharing. Half-duplex bidirectional transmission can be implemented through a single fiber or through two fibers .Full-duplex bidirectional transmission has been implemented through two fibers[1,2].

However, of the optical development of circulators which make it relatively expensive, designers will estimate style and the reliability imparted by less components. Consequent improving the performance often remove the need for more powerful transmitters, more sensitive receivers, and more optical amplifiers, hence making economic optical circulators is considered important suggestion. The presence of all these technologies, can expect very cheap prices optical circulator this made it wide use in optical communication [3,4,5].

Figure (1) shows the proposed of the bidirectional optical communication link established using the optical circulators. The basic component of the bidirectional optical communication link contains of two optical transmitters, two optical receivers, two optical circulators and optical fiber cable. The(port2) for each optical circulator connected to the optical fiber cable, the (Tx1) and (Tx2) connected to (port one) for each circulators and the (Rx1) and (Rx2) connected to the (port three) for each circulators. The transmitters transmit the signal having identical wavelength.

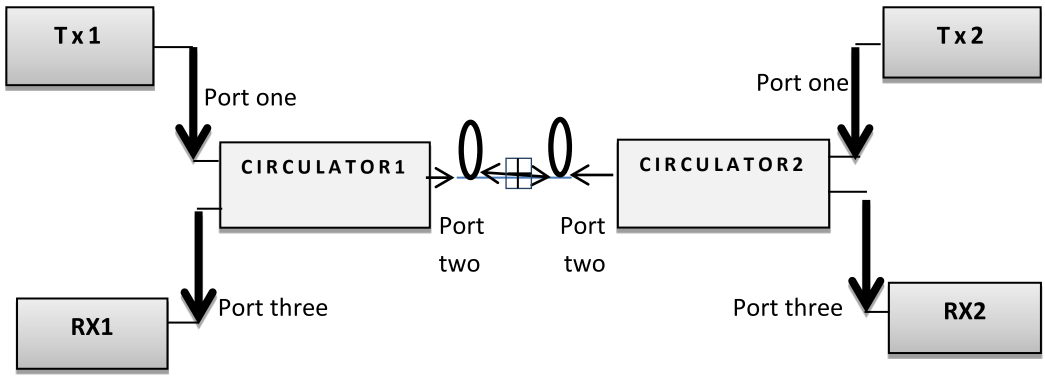
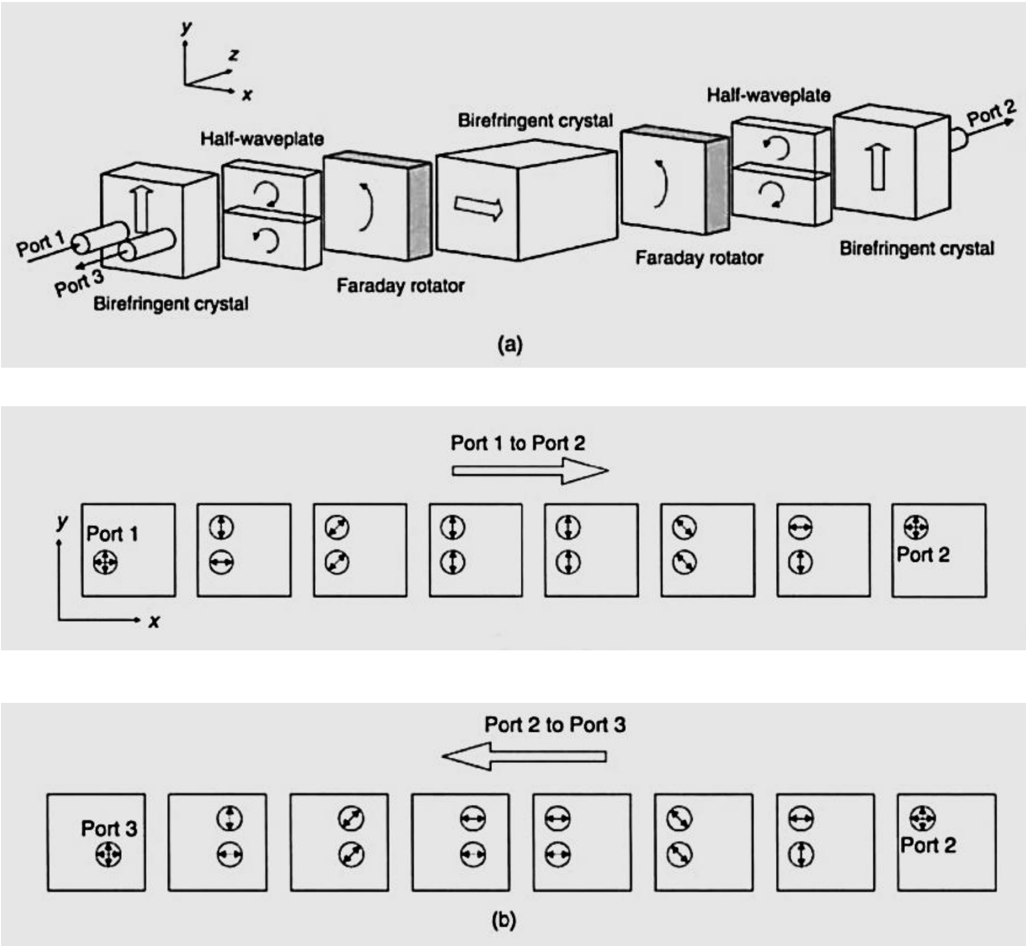


Figure (1) The suggested bidirectional optical fiber link using optical Circulator

2. Operation Principle Circulator

Optical circulator is nonreciprocal device that allow for the unidirectional propagation of light Many-port device act as a roundabout for light, with each input port routed to exactly one output port in a nonreciprocal fashion. Integrated circulators would enable bidirectional operations in optical interconnects which could double the network capacity in many data center and telecommunication applications they are also important components in many distributed fiber sensors and other inter ferometric optical sensors [6].

In process, a light beam launched into (port one) is divided into two beams by the polarization beam splitter, transmits the light with horizontal polarization and reflects the light with vertical polarization. The dual beams are then passed through a half-waveplate and a Faraday rotator. The optic axis of the half-waveplate is set at (22.5°) to the x-axis so that the vertically polarized light is rotated by (+45°). The width of the Faraday rotator is a selection of (45°)-polarization rotation and the rotation direction are designated to be counter-clockwise when light spreads along the z-axis direction. The polarization of the two beams is unaffected after passing through the half-waveplate and Faraday rotator for the polarization rotation introduced by the half-waveplate (+45°) is cancelled by that of the Faraday rotator (- 45°). The two beams are recombined by the second polarization splitter and coupled into (port two). Similarly, when a light beam is launched into (port two), it is splitting into two beams with orthogonal polarization by the second polarization beam splitter. Due to the non-reciprocal rotation of the Faraday rotator, in this direction the polarization rotations introduced by both the half-waveplate and Faraday rotator are in the identical direction, resulting in a total rotation of (90°). Therefore, the two beams are combined by the first polarization splitter in a direction orthogonal to (port one) and together into (port three).This optical circulator was relatively low due to limited extinction ratio (around 20 dB) of the polarization beam splitters. To raise the isolation and high extinction ratio for the optical circulator is used birefringent crystals in design it, figure(2) (a) & (b) shows the birefringent beams in crystal-based circulator.[7,8,9]



Figure(2) (a) & (b) Schematic diagram of birefringent crystal-based circulator [6].

3. Analysis of Optical Circulators

Important performance parameters of optical circulators include isolation, insertion loss, polarization dependent loss, directivity; return lossand polarization mode dispersion. Optical performance of polarization beam splitting-based optical circulators can be theoretically calculated using a Jones matrix. When launch the beam of light to(port one), the output from (port two) is the sum of the ordinary and extraordinary beams from the third birefringent crystal and can be expressed as:

$$E_{out} = E_{2o} + E_{2e} \qquad (1)$$

The optical field transfer matrix for optical circulator when the light transfer from (port one) to (port two) can be expressed as [7,8]:

$$E_{2e} = \begin{pmatrix} \alpha & zero \\ zero & 1 \end{pmatrix} \begin{pmatrix} \cos(-2\rho) & \sin(-2\rho) \\ \sin(-2\rho) & -\cos(-2\rho) \end{pmatrix} \begin{pmatrix} \cos(-\beta) & -\sin(-\beta) \\ \sin(-\beta) & \cos(-\beta) \end{pmatrix} \begin{pmatrix} \alpha & zero \\ zero & 1 \end{pmatrix} . \begin{pmatrix} \cos(-\beta) & -\sin(-\beta) \\ \sin(-\beta) & \cos(-\beta) \end{pmatrix} \begin{pmatrix} \cos(-2\rho) & \sin(-2\rho) \\ \sin(-2\rho) & -\cos(-2\rho) \end{pmatrix} \begin{pmatrix} 1 & zero \\ zero & \alpha \end{pmatrix} E_{in} \qquad (2)$$

$$E_{2o} = \begin{pmatrix} 1 & zero \\ zero & \alpha \end{pmatrix} \begin{pmatrix} \cos(2\rho) & \sin(2\rho) \\ \sin(2\rho) & -\cos(2\rho) \end{pmatrix} \begin{pmatrix} \cos(-\beta) & -\sin(-\beta) \\ \sin(-\beta) & \cos(-\beta) \end{pmatrix} \begin{pmatrix} \alpha & zero \\ zero & 1 \end{pmatrix} . \begin{pmatrix} \cos(-\beta) & -\sin(-\beta) \\ \sin(-\beta) & \cos(-\beta) \end{pmatrix} \begin{pmatrix} \cos(2\rho) & \sin(2\rho) \\ \sin(2\rho) & -\cos(2\rho) \end{pmatrix} \begin{pmatrix} \alpha & zero \\ zero & 1 \end{pmatrix} E_{in} \qquad (3)$$

Where (α)is represents the extinction ratio of the birefringent crystals, (ρ) and (β)are represent azimuth angle of the optic axis for half waveplates and rotation angle of the Faraday rotators, respectively. Signs of (ρ) and (β) represent the rotation direction and a minus sign indicates the counter-clockwise rotation.(E_{in}) is the input light beam Jones vector, and for a randomly polarized light, (E_{in}) can be extracted as [10,11,12,13]

$$E_{in} = \begin{pmatrix} aE_0 \\ bE_0 \end{pmatrix} \qquad (4)$$

Where(E_0)is the amplitude of the input electrical field also ($a^2 + b^2=1$).
Thus, can be calculated (port one) to (port two) insertion loss for circulator as follow:

$$\text{Insertion loss} = -10 \log \frac{E_{out} \, . \, E_{out}^*}{E_{in} \, . \, E_{in}^*} \qquad (5)$$

Where (E_{in}^*) and (E_{out}^*) represents the conjugate matrices to the(E_{in}) and (E_{out}), respectively.
In the same way, the isolation of the circulator from (port two) to (port one) can be written as:

$$\text{Isolation} = -10 \log \frac{E'_{out} \, . \, E'^*_{out}}{E'_{in} \; E'^*_{in}} \qquad (6)$$

Where(E'_{out}) represents(port one) output when inputs launched the beam of light (E'_{in}) is into (port two). The (E'_{out}) can be expressed as

$E'_{out} = E'_{1o} + E'_{1e}$ and (E'_{1o}) and (E'_{1e}) can be written as [14,15]:

$$E'_{1e} = \begin{pmatrix} \alpha & zero \\ zero & 1 \end{pmatrix} \begin{pmatrix} \cos(2\rho) & \sin(2\rho) \\ \sin(2\rho) & -\cos(2\rho) \end{pmatrix} \begin{pmatrix} \cos(-\beta) & -\sin(-\beta) \\ \sin(-\beta) & \cos(-\beta) \end{pmatrix} \begin{pmatrix} \alpha & zero \\ zero & 1 \end{pmatrix} . \begin{pmatrix} \cos(-\beta) & -\sin(-\beta) \\ \sin(-\beta) & \cos(-\beta) \end{pmatrix} \begin{pmatrix} \cos(2\rho) & \sin(2\rho) \\ \sin(2\rho) & -\cos(2\rho) \end{pmatrix} \begin{pmatrix} 1 & zero \\ zero & e_c \end{pmatrix} \mathrm{E}'_{\mathrm{in}} \quad \ldots\ldots(7)$$

$$E'_{1o} = \begin{pmatrix} 1 & zero \\ zero & \alpha \end{pmatrix} \begin{pmatrix} \cos(-2\rho) & \sin(-2\rho) \\ \sin(-2\rho) & -\cos(-2\rho) \end{pmatrix} \begin{pmatrix} \cos(-\beta) & -\sin(-\beta) \\ \sin(-\beta) & \cos(-\beta) \end{pmatrix} \begin{pmatrix} \alpha & zero \\ zero & 1 \end{pmatrix} . \begin{pmatrix} \cos(-\beta) & -\sin(-\beta) \\ \sin(-\beta) & \cos(-\beta) \end{pmatrix} \begin{pmatrix} \cos(-2\rho) & \sin(-2\rho) \\ \sin(-2\rho) & -\cos(-2\rho) \end{pmatrix} \begin{pmatrix} \alpha & zero \\ zero & 1 \end{pmatrix} E'_{in} \ldots\ldots\ldots\ldots(8)$$

Impact of various key parameters on the insertion loss and isolation can be evaluated using equations (1) – (8).where the insertion loss and isolation are effected directly with the rotation angle error of the Faraday rotators. For ideal optical circulator lets ($\alpha = zero$) and (ρ = 22.5°), the equations. (5) & (6), can be written as:

Insertion loss = -10 log[(cos(45 + Δβ) + sin(45 + Δβ))^4/4]....……………(9)

Isolation = -10 log [(cos(45 + Δβ) - sin(45 + Δβ))^4/4]..………………....(10)

(Δβ) represented the rotation angle error of the Faraday rotator. To calculate the retardence error can be replaced the Jones matrix for the half-waveplate with the general waveplate and the effect of wavelength and temperature in the optical circulator can be guess by combining the temperature and wavelength dependencies of the Faraday rotator and waveplates into the Jones matrices [14,15].

4. Power Budget and Rise Time Budget

The power budget in optical transmission system is equal the sum of all the power losses plus with the power margin. The power budget is the difference between the power output of transmitter and the sensitivity of the optical receiver in dBm, it can be expiration as [16,17]:

$\mathrm{P_s} - \mathrm{R_S} = \alpha\, \mathrm{L_f} + \mathrm{L_c} + \mathrm{L_A} + \mathrm{P_M}$……………………………...........……….....(11)

Where:

P_s = transmitter output power (dBm)

R_S = receiver sensitivity (dBm)

α = fiber attenuation (dB/km)

L_f= fiber length (km)

L_c = coupling loss (dB)

L_A = additional known losses (dB)

P_M= power margin (dB)

The rise time budget of a linear system is defined as the time during which the response increases from (10 %to 90%) of its final output value when the input is changed abruptly .Where the total rise time for any optical fiber link is equal to [2,6]

$T_{system}^2 = T_{transmitter}^2 + T_{fiber}^2 + T_{\text{receiver}}^2$ ……………………...………………(12)

Where:

T_{system}: Rise time of optical system.

$T_{transmitter}$: Rise time of transmitter.

$T_{receiver}$: Rise time of receiver.

T_{fiber}: Rise time of single mode fiber.

$T_{receiver} = \frac{0.35}{B_{recever}}$……………………………………………..........................…..(13)

Where$B_{recever}$: is the electrical band width of optical receiver in GHz

T_{fiber}= D . Δλ . L……………..………………...........……………………………..(14)

Where Δλ is the spectral width of the optical source in nm ,Dis the dispersion parameter of the single mode fiber and L is the length fiber optical in Km [4].

5. The Simulation and Results

5.1 The Optical Transmitter Structure

In the simulation the transmitter with frequency 193.414489 THz (1550 nm), optical power is assumed to be 1mw (0 dBm). Figure (3) shows the schematic representation of modulator type NRZ-OOK in transmitter.

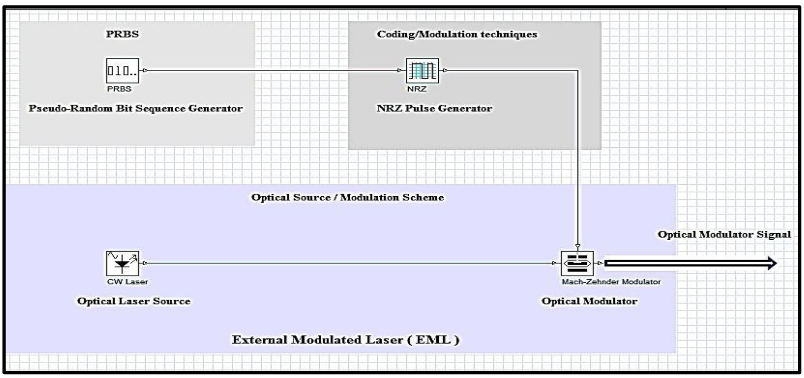


Figure (3) The schematic representation of modulator type NRZ-OOK for transmitter

The first stage is the PRBS which uses the same engine as the Pseudo-Random Bit Sequence Generator. The bit rate, Order, number of leading and trailing zeros can be managed by the internal Pseudo-Random Bit Sequence Generator.

The second stage includes the Coding/Modulation techniques, where the coding type (NRZ) is used. The third stage is related to the optical source and the modulation scheme. An external modulated laser schemes (EML) is used because it uses high transmission bit rate (10 GBits/s). Table (1) represents the main setting of the transmitter.

Table (1) The main setting of transmitter

Parameters	Setting
Type of optical source	Continuous wave (CW) optical signal
The input power of each channel	1 mW (0 dBm)
wavelength	1550 nm
Line width	10MHz
Extinction ratio	10 dB
Bite rate	10 GBits/s
Coding type	NRZ
Transmitter type	EML(external modulated)
Laser Relative intensity Noise(RIN)	-155dB/Hz
Rise time	0.005 ns

5.2 Optical Circulator

In the optical circulator the light never goes to other ports because of its non-reciprocal device this property made optical circulators have wide applications in optical communication system. One of this application used to convert an existing unidirectional fiber optic communication link to a full duplex communication link by connected an optical circulator at both end of the link. Table (2) display the main factors to the optical circulator.

Table (2) the main factors of optical circulators

Parameters	Values
Center Wavelength	1550 nm
Insertion Loss	0.8dB
Return Loss	60dB

5.3 The Transmission Optical Channel

The transmission optical channel contains of single mode fiber (SMF-28). Table (3) shows the main specific of the transmission channel is used in design.

Table (3) Specifics of the transmission channel

SSMF-28 main parameters	
Parameters	**Setting**
Length	50 km
Reference wavelength	1550 nm
Attenuation	0.2 dB/km @1550 nm
Dispersion	16.5 ps/nm/km @1550 nm
Dispersion slope	0.05 $ps/nm^2/km$
Nonlinear index of refraction	$2.6x10^{-20}$ m^2/w
Effective area (A_{eff})	$80μm^2$ @ 1550
Rise time	0.000067 ns
Core diameter	8.2 μm
Brillouim scattering threshold power	1.52dBm
Raman scattering threshold power	30.7 dBm

5.4 The Receiver of Optical Fiber

After the optical signal is receivedtoport3 of optical circulator, the signal is applied to the receiver, which detects and converts an optical signal. The optical receiver subsystem is built using a PIN photo detector, a low pass Bessel filter and a 3R regenerator. The photo detector converts the optical signal to electrical signal. It generates the original bit sequence, and a modulated electrical signal to be used for BER analysis. It is a subsystem based on the data recovery component and a NRZ pulse generator. Figure (4) shows the receiver of optical fiber subsystem and main parameters are show in Table (4).

Table (4) The main factors to optical receiver

The factor	**Setting**
Photo detector type	PIN photo detector
The responsively	0.8 A/W
Dark current	10 nA
Insertion loss	0 Db
Reference bit rate	10GBits/s
Sensitivity	-31dBm
Rise time	0.023 ns
Filter	
Type	Low Pass Bessel Filter
Insertion loss	0 dB
Order	4
Cutoff frequency	7.5 GHz

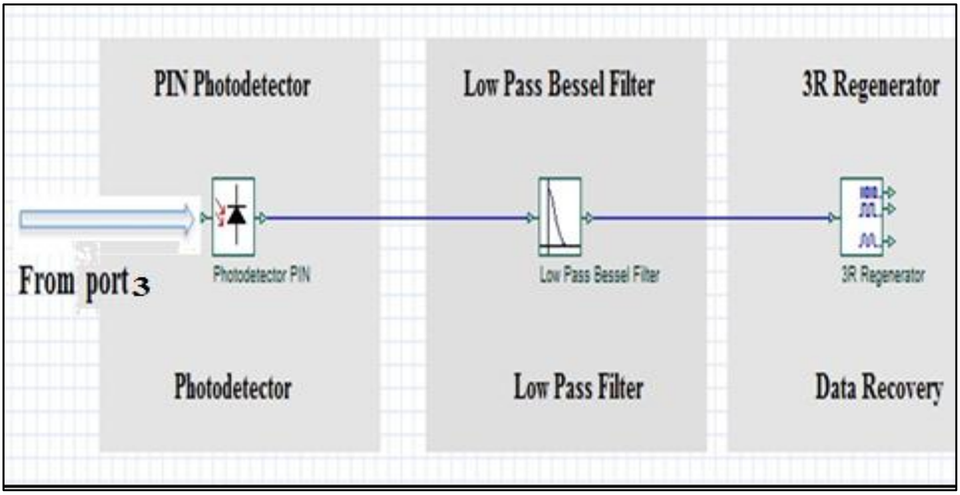


Figure (4) The subsystem of optical receiver

Table (5) The main optical fiber link performance

System performance	
Connecter loss	0 dB
Insertion loss	1.6 dB
Number of connectors	6
Optical fiber loss	10 dB
Margin loss	10 dB
Total system loss	21.6 dB
Min power of optical transmitter	- 9.4dBm
Max power of optical transmitter	1.52dBm
The total rise time of system	0.0259 nm
The max bitrate for NRZ code in the system	27 GBits/s

The simulation of the proposed bi-direction optical link can be shown in figure (5)

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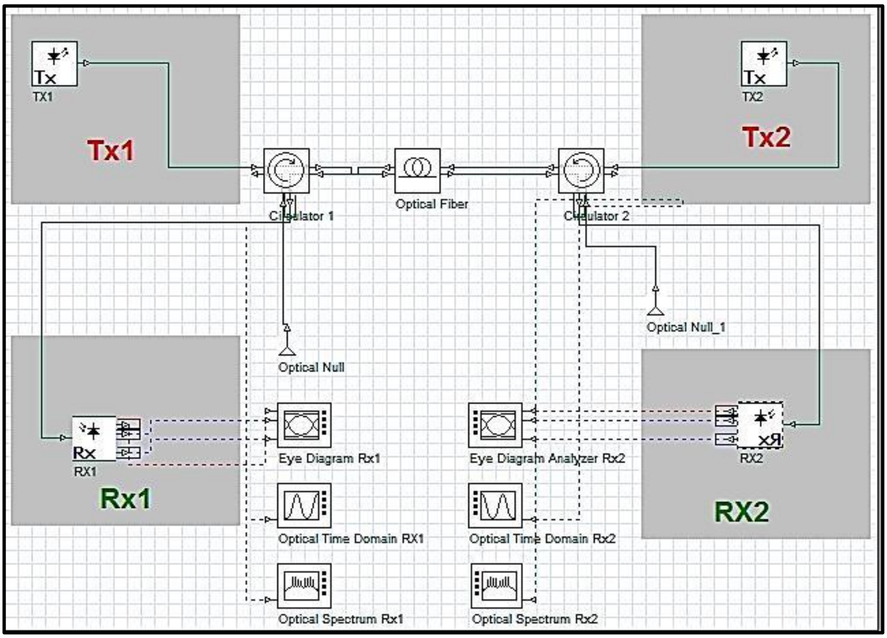
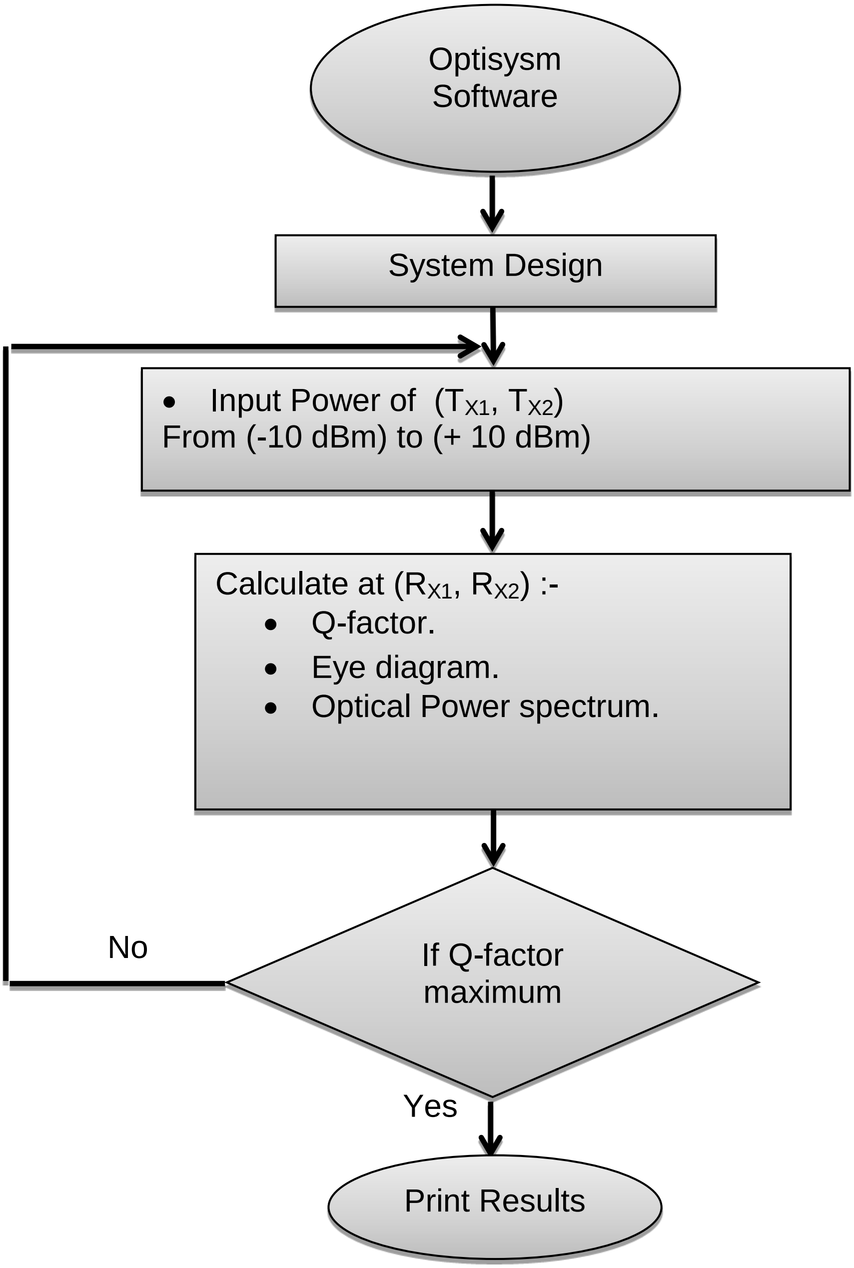


Figure (5) The layout of the proposed bi-direction optical link



Figure(6) The results calculation algorithm

5.5 Channel 1(Forward Link)

The forward link consists of the transmitter one, receiver two and the two circulators as shown in Figure (7).

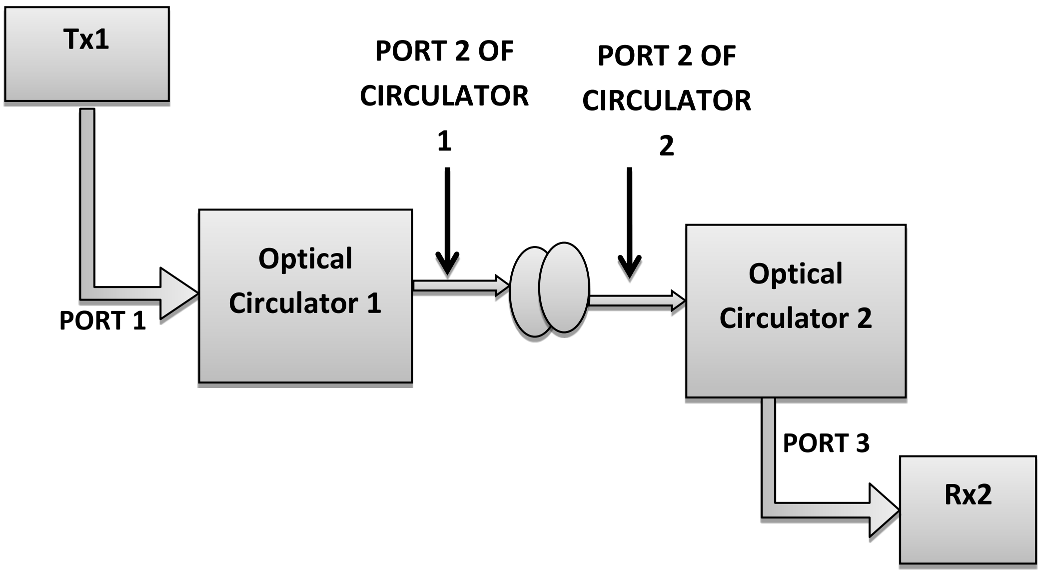


Figure (7) Channel 1 (forward link)

Figure (8) shows the variation in the Q-factor for the receiver two (Rx2) with the input power, where the relationship between them is linear until (2dBm) after that the Q-factor begins to decrease with the increasing of the input power, this is because of the nonlinear effect of the refractive index and also appearance of brillouim scattering (BS) in optical fiber cable because of the power more than threshold power. The nonlinear effects that start to increase with increasing input power; rather the input power per channel must be more than (-9.4dBm) and lower than (1.52dBm) in order to get the greatest result of Q-factor.

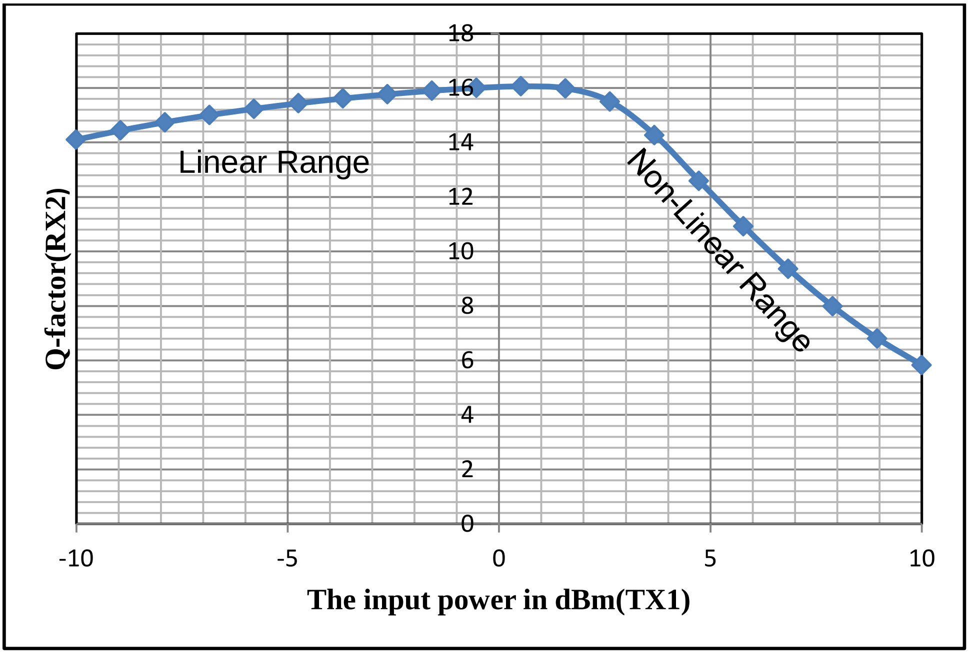


Figure (8) The variation in the Q-factor with the input power

Figure (9) shows a clean opening - eye diagram pattern of the receiver signal at receiver two(Rx2) . Because an eye pattern is an excellent tool for viewing some cycles of the long pattern signal, it is considered by the "quality" of the signal and what the range of particular signal spaces from "ideal" digital signal. Where the rectangle eye diagram is represented to an ideal digital signal Thus, the eye diagram isn't only an instrument from which is measured parameters of the signal is also provides a fast snapshot of the quality of a signal too. The parameters of signal which are obtained from an eye diagram can be distributed into two groups. The amplitude related parameters and time related parameters. The vertical eye opening (Eye Height) is directly related to the eye amplitude and it is a measure of signal to noise ratio with the account effects of the inter symbol interference [13, 14]. From the eye pattern shown in figure (9) it is observed that a clean opening - eye diagram pattern. This means noise and inter symbol interference is very low where SNR is equal to (47.23 dB).From figure (10-a)shows the optical power spectrum of the receiver signal at receiver two (Rx2) and figure (10-b) shows the optical power spectrum of the receiver signal at receiver two

(Rx2) when the transmitter one (Tx1) is off. From figure (10-a) & figure (10-b) it shows that the isolation between the transmitter two (Tx2) and the receiver two (Rx2) is more than 65 dB and optical signal to noise ratio is equal to (37,412)dB.

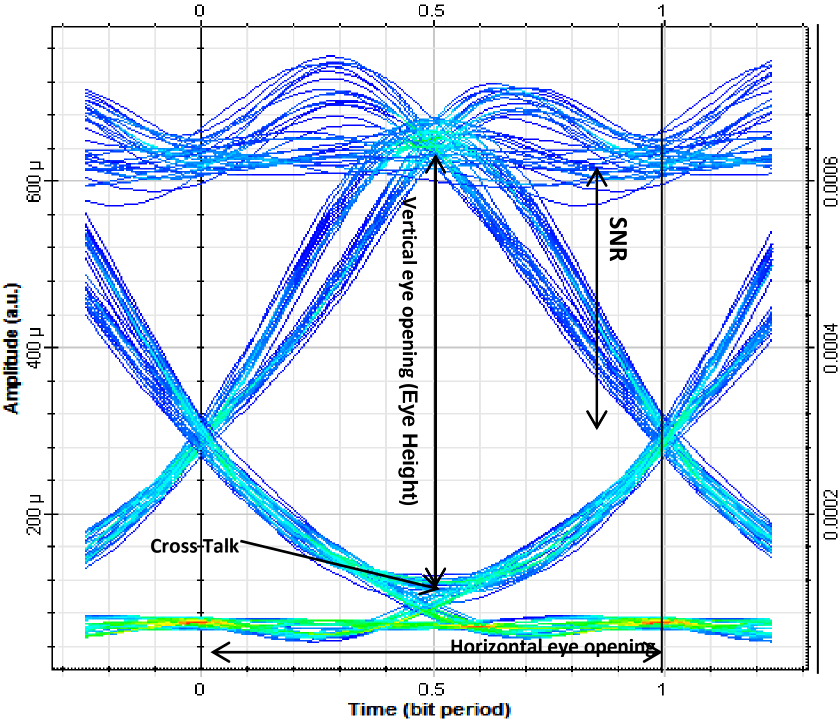


Figure (9) the eye diagram of digital signal of the receiver2 (Rx2)

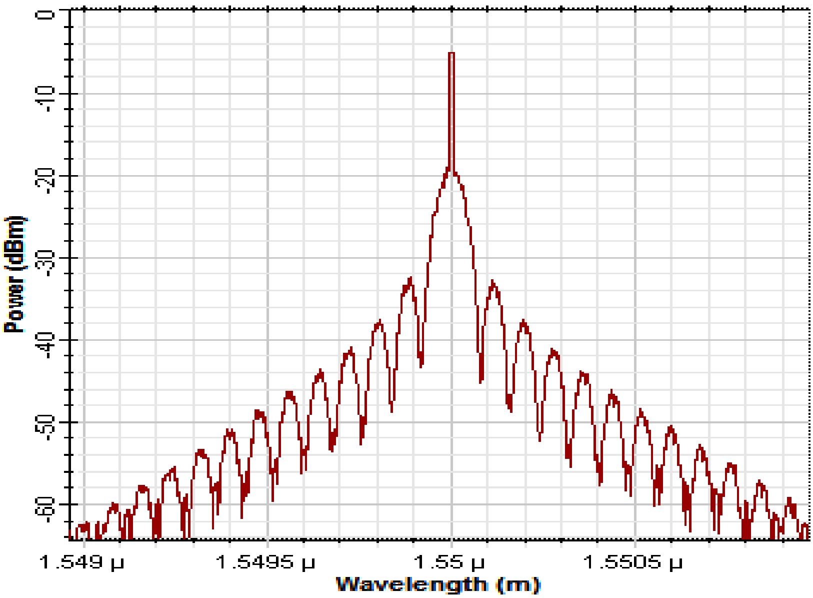


Figure (10. a) The optical power spectrum of Rx2

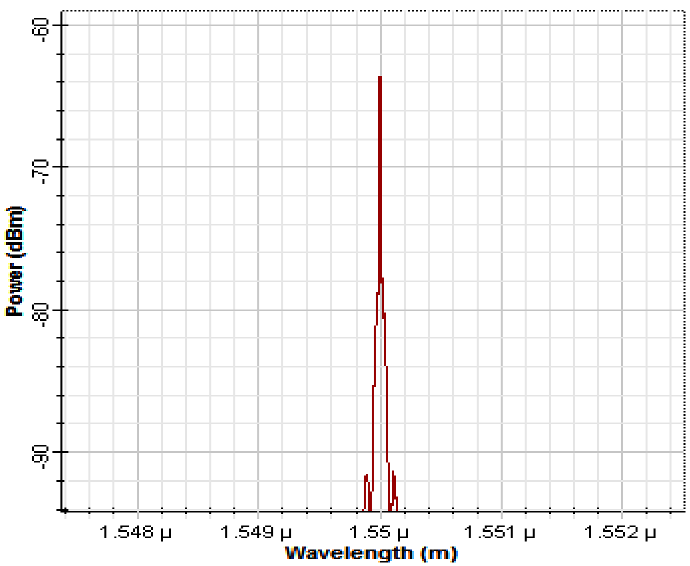


Figure (10. b) Optical power spectrum of the receiver signal at receiver two (Rx2) when the transmitter one (Tx1) is off.

5.6 Channel 2 (Return Link):-

The return Link consists of the transmitter 2, receiver 1 and the two circulators as shown below:-

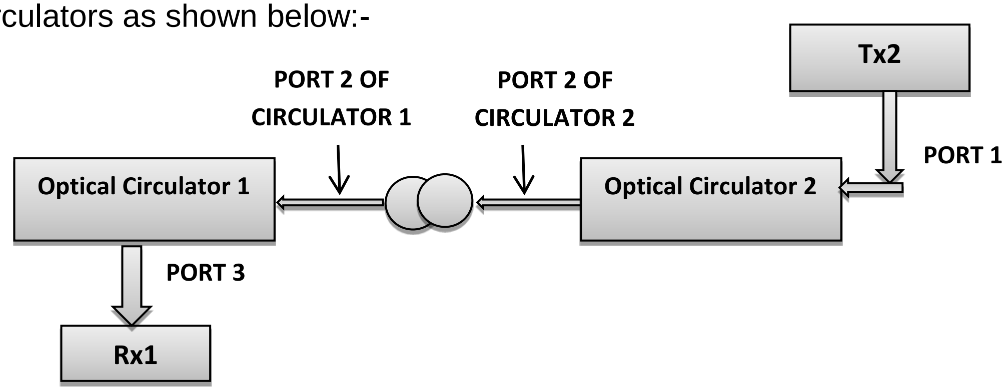


Figure (11) Channel 2 (forward link)

Figure (12) shows the variation in the Q-factor of (Rx1)with the input power(Tx2), where the relationship between them is linear until (2dBm) after that the Q-factor begins to decrease with the increasing of the input power, this is because of the nonlinear effect of the refractive index and the appearance of brillouim scattering (BS) in optical fiber cable because of the power more than threshold power.

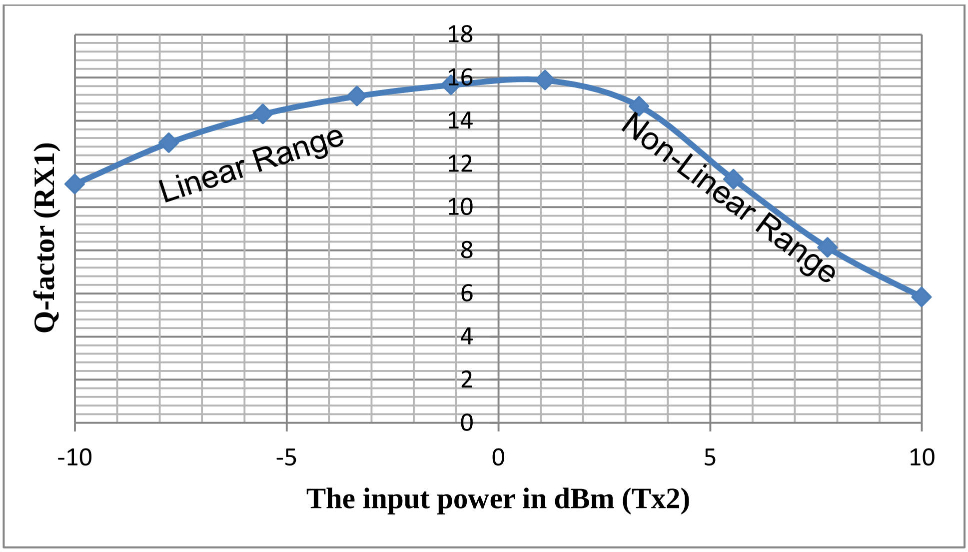


Figure (12) The input power of (Tx2) variation with Q-factor (Rx1)

The figure (13) shown the eye pattern of (Rx1) it is observed that a clean opening - eye diagram pattern. This means inter symbol interference and noise is very low where SNR is equal to (46.42 dB).From figure (14.a) shows the power spectrum of (Rx1), it shows that the isolation between the (port one) of optical circulator 1 (Tx1) and the port three of opticalcirculator1 (Rx1) is more than 66.5 dB and optical signal to noise ratio equal to (37, 35) dB.

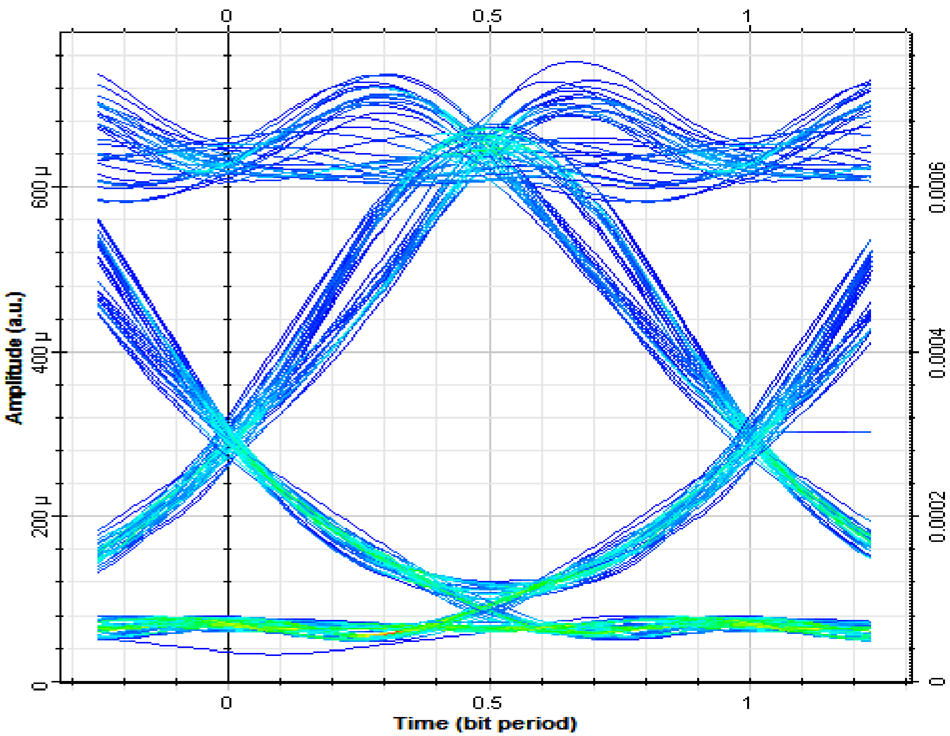


Figure (13) The eye diagram of digital signal at output of the receiver (Rx1)

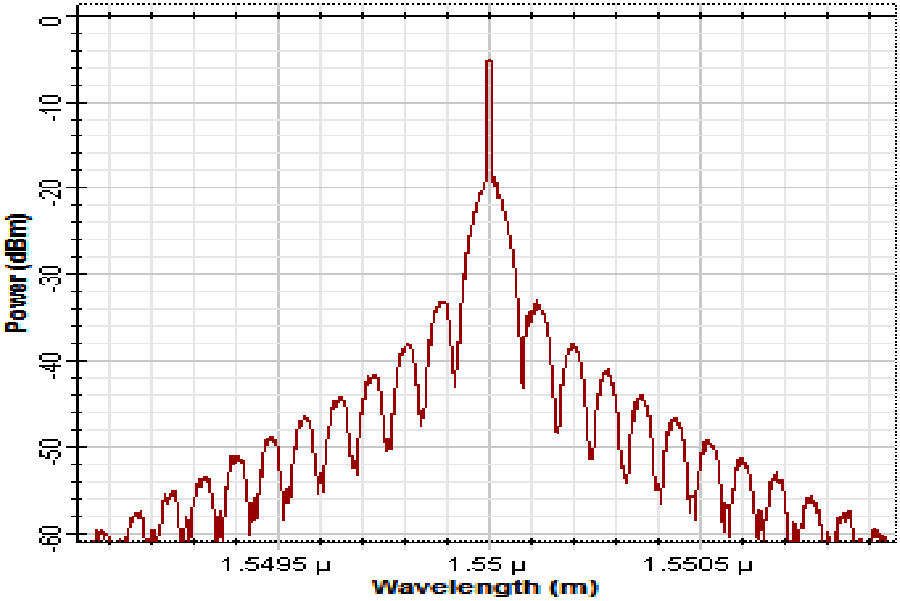


Figure (14. a) The optical power spectrum at output Rx1

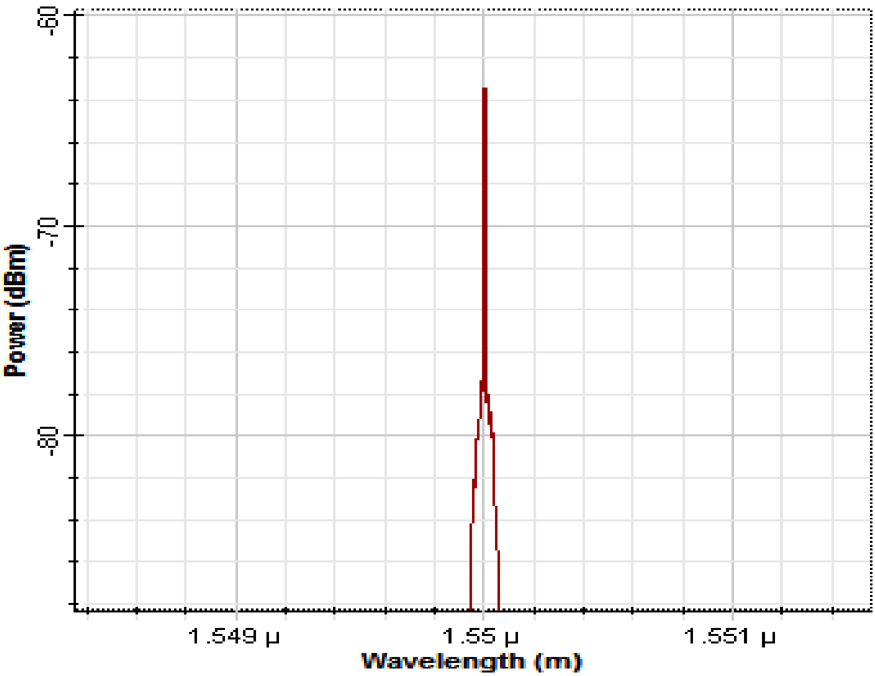


Figure (14. b) the effect of Tx1 to Rx1

Figure (15) is show the variation between the Q- factor and SMF-28 length , it indicates that the system can detect the receiver signal (1550 nm) when the SMF-28 has a max-length of 80 km without amplifier and Dispersion Compensating Fiber (DCF), this is because the system has low insertion loss of nearly 1.6 dB, in order to obtain the Q -factor equal to (10)

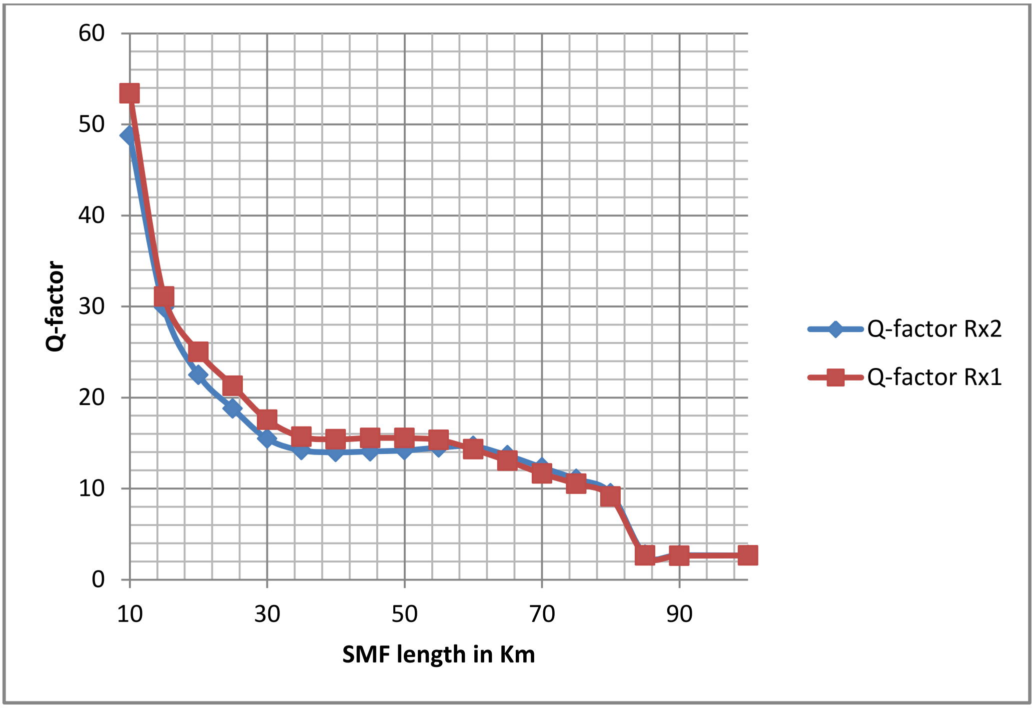


Figure (15) The variation between the Q- factor and SMF-28 length

6. Conclusions

- The bidirectional link designed using circulators introduces a very low loss and hence improves the bidirectional system.
- It is observed that by using a single mode optical fiber of length 50 Km between the ports 2 of both the circulators, the losses are minimized.
- When using the circulator in a bi-directional link given high isolator between the two channels, which reduces the crosstalk and noise transmitted from the first to the second channel.
- The transmitters are operated at the frequencies separated by some quantity. This is because, when same frequency was used the phenomenon of construction of beats was detected and the ripples were seen. But when different frequencies were used, the ripples were reduced to a great quantity.
- Because the optical circulator has wide bandwidth (more than 100 nm) can use for double data rate capacity in WDM and DWDM optical network easily by using transmitter and receiver type (WDM or DWDM) only.
- when using optical circulator to convert the optical network form half-duplex mode to full-duplex mode is very low cost comparator with addition new optical fiber because the low cost of optical circulator.

7. References

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تحسين أداء الرابط الضوئي ثنائي الاتجاه باستخدام المدور الضوئي

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المستخلص

في هذا البحث تم اقتراح تصميم شبكة ضوئية ثنائية الاتجاه وذلك لزيادة نقل البيانات خلال الشبكة الضوئية وذلك باستخدام المدور الضوئي. حيث تم مضاعفة سعة البيانات المنقولة خلال الشبكة الثنائي الاتجاه بسهولة وذلك بواسطة إضافة المدور الضوئي بدون الحاجة إلى إضافة كيبل ضوئي ثاني وذلك لان عملية إضافة الكيبل الضوئي صعبة ومكلفة جدا.

المدور الضوئي هو غير ترددي، الاتجاه واحد، وله ثلاثة أجهزة منافذ حيث يستفاد منه في نشر الضوء باتجاه ثاني في الليف الواحد.

في هذا التصميم تم الحصول على نتائج مهمة حيث كان معدل فقدان الإدراج حوالي (1.6) ديسيبل و خسائر العودة (-65) ديسيبل وقلة التداخل بين القناتين حيث كان بحدود (-70) ديسيبل.

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