National Center for Radio Astrophysics,
Tata Institute of Fundamental Research,
Giant Meterwave Radio Telescope,
Khodad.(Pune)

A BIDIRECTIONAL LINK USING OPTICAL CIRCULATORS

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ABSTRACT

The report is prepared from the point of view of designing a bidirectional communication link using cirulators. The various components required for the link are discussed here. Also the performance of the link in terms of the loss penalty and the various types of noise produced is also considered. The bidirectional link using circulators and that using beamsplitter have been compared in terms of the total loss introduced while constructing the link and the loss margin available using the components. The interference caused or the degradation of the forward signal due to the superposition of the other returning signal is taken into consideration.

1.Introduction

The standard fiber cables in use today, shows variations in the attenuation characteristics. The minimum attenuation occurs at wavelengths around 1310 nm and 1550 nm. Any one of the above wavelengths is used for transmitting the signal using the laser diodes through the optical fiber. While constructing the bidirectional link, any one of the above wavelengths is considered and used for the bidirectional communication. The key component of bidirectional link is the circulator which is a 3-port, non reciprocal, passive device. The bidirectional link using circulators introduces the noise of approximately 2.0 dB, while that using the 3 dB beam-splitters imposes more than 6 dB of signal noise. Thus, the probable solution for constructing the bi-directional link is by the use of the circulators. The experimenta l observations along with the total link performance or the total link loss budget is estimated . The link is also tested for the leakage loss, back reflection, the isolation introduced due to the simultaneous transmission of the two signals.

2.Important definitions and terminologies used

2.1 Intrinsic gain

The analog fiber optic link has a conversion loss given by equation1. Due to the parallel combination of R_{load} and the output impedance only half of the detected photodiode current is available and hence the factor ½ is used in equation 1,2 and 4. The link has a conversion loss of –33.45 dB and with an optical loss of 1 dB in the link the total RF loss will be 35.45 dB. The conversion loss is also referred as intrinsic gain of a link. With better slope efficiency and reactive impedance matching at the laser and photodiode the loss can be reduced. VCSEL laser has higher slope efficiency compared to FP and DFB lasers and help in improving the conversion loss of the link. The intrinsic gain increases with an increase in optical power of an externally modulated link. A directly modulated link does not shown any improvement in gain with increase in optical power.

$$G_i = 10.Log10(\eta_l . R / 2)^2 \qquad \text{--- (1)}$$

Where η_l *= Slope efficiency of the laser diode in W/A*

R = Responsivity of the photodiode in A / W

2.2 Noise performance of the link

The total noise performance of an analog fiber optic link depends on the individual noise contribution of various components in the link. Three major noise sources in an analog link are Laser noise (RIN noise) generated at the laser, shot noise at the photodiode detection and thermal noise at the receiver circuit.

a. Laser noise

The laser noise arises from the random fluctuations in the intensity of the optical signal generated at the laser diode. The laser noise is measured directly at the transmitter and is referred to as relative intensity noise (RIN) in the laser diode specification. The RIN is the ratio of mean square amplitude of the noise fluctuations per unit bandwidth ($<P^2>$) to the square of the DC optical power (Po^2). The laser noise power P_{laser} in an analog fiber optic link for direct detection is given by equation 2.

$P_{laser} = RIN_{laser}.(I_{ph} /2)^2.R_l$ --- (2)

Where

Photodiode current $I_{ph} = (I_{bias}-I_{th}).\eta_l.R.\alpha$

---(3)

η_l = Slope efficiency of the laser in W/A

α = Optical loss in ratio [$10^{(- \text{optical loss in dB} / 10)}$]

R = Responsivity of the photodiode A/W

R_l = Load resistance at the photodiode receiver

$(I_{bias}-I_{th})$ = Bias current above threshold current mA

b. Shot noise

The average photocurrent generated at the photodiode is associated with a shot noise current generated due to the random process by which the current is generated at the photo detector. The shot noise power P_{shot} is given by equation 4.

$P_{shot} = 2.e.[(I_{ph} + I_d)/2].R_l$ --- (4)

Where e = Charge of the current carrier (1.6×10^{-19} C)

I_d = dark current of the photodiode in A

c. Thermal noise

Thermal noise is associated with the receiver circuit and the thermal noise power $P_{Thermal\_noise}$ is given by equation 5.

$P_{Thermal\_noise} = k . T_o$ --- (5)

Where k = Boltzman constant (1.38×10^{-23} J / K)

T_o = Temperature in Kelvin (290 K)

d. Total noise

The total noise is the summation of the above three major noise sources in a fiber optic link. The total noise power of the link $P_{total\ noise}$ is given by equation 6.

$P_{total\ noise} = P_{nLaser} + P_{shot} + P_{Thermal\_noise}$ --- (6)

2.3 Equivalent input noise (EIN in dBm/Hz) of the link

The EIN_{link} is the total noise referred to the link input by the following equation 7.

$EIN_{link} = P_{totalnoise} / G_{link}$ --- (7)

Where the link gain $G_{link} = (\eta_l.\alpha.R / 2)^2$

2.4 Noise figure of the link

The noise figure (NF in dB) of the link is given by the equation 8.

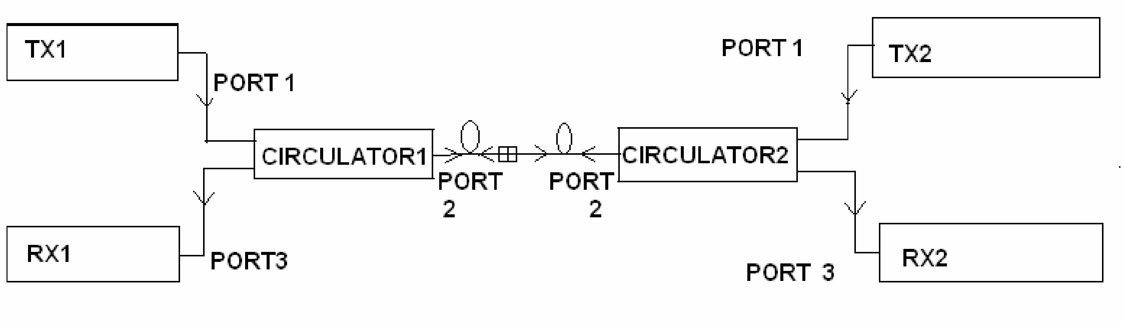
$$NF_{link} = (EIN_{link}\ dBm/Hz) + (174\ dBm/Hz) \qquad \text{--- (8)}$$

2.5 Noise equivalent bandwidth EIN_{bw}

The equivalent input noise for a given noise bandwidth is given by equation 9

$$EIN_{bw} = EIN_{link} + 10.\log_{10}(BW) \qquad \_\ \_\ \_(9)$$

3. Bidirectional optical fiber link



A BIDIRECTIONAL FIBER OPTIC LINK USING CIRCULATORS

The figure shows the bidirectional communication link established using the optical circulators as the main component. The link consists of two optical transmitters, two optical receivers, two circulators, optical fiber and connectors. The port 1 of each of the circulators serves as the input terminal while the port 2 acts as both input and output terminal, also the port 3 acts as the output terminal. Both the port 2 of the circulators are attached to each other through the optical fiber spool and the connectors. The transmitters transmits the signal having same wavelength, in this case 1550 nm, simultaneously, through the port 1 of the corresponding circulator. The receiver receives the transmitted signal from the port 3 of the corresponding circulator.

4.Components used in the link

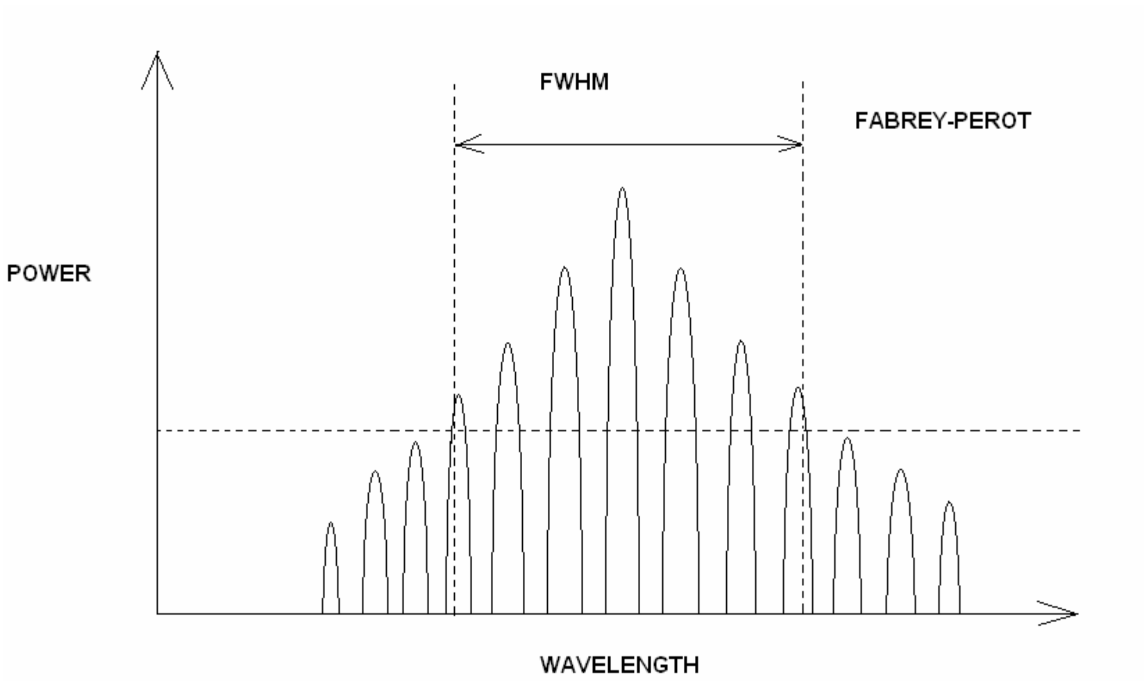
4.1-Transmitter

The transmitters used in the link comprises of the laser diode. It is observed that the laser diodes are particularly sensitive to light energy reflected back from the rest of the system. The reflected light increases the noise in the emitted beam, degrading system performance. The returning photons arrive back inside the laser cavity where they are amplified and generally take part in laser action. They compete with the photons already in the laser cavity for the exited atomic states. Because the returning photons are unlikely to be in phase with the wave existing in the laser cavity, they tend to force the diode to restart its oscillations. The new oscillation is in phase with the returned beam of the light. The result is that the laser diode occasionally randomly shifts the phase of its output radiation, adding to the system noise.

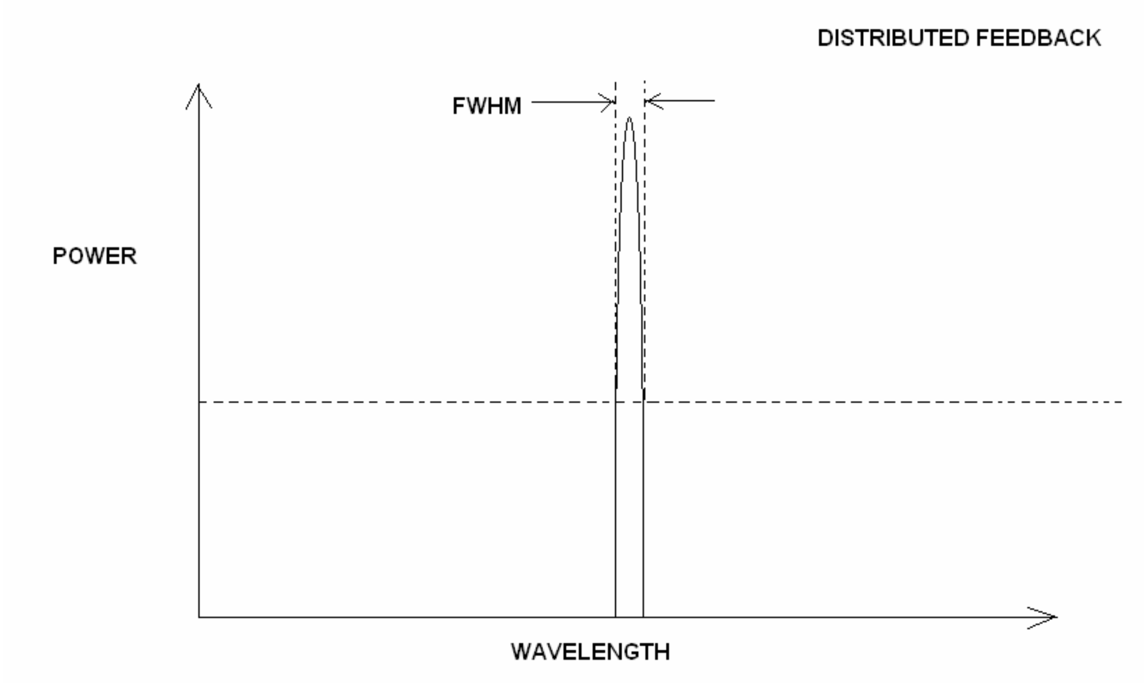
Laser types:

There are two basic types of lasers;Fabrey-Perot (FP) and Distributed Feedback laser (DFB) and both types are available for 1310 nm and 1550 nm. We need to choose which best type suits our needs.

Fabrey-Perot lasers are the simplest and least expensive, but the wavelengths of the light they emit contain too many side bands for the most critical applications. The spread in wavelength is measured as Full Width Half Max (FWHM),as shown below. An FP laser might typically have an FWHM of around 4 nm. Hence, FP lasers are used for lower data rates and for shorter distances, as they are the most economical.



DFB lasers were developed to satisfy the need of narrow, precise wavelengths as illustrated. Typically a DFB laser might have an FWHM of 0.2 nm. These lasers employ a filtering system, which reflects (feeds back) light of only one specific wavelength into the cavity where the light gets amplified. The light is evenly distributed throughout the cavity; hence the name Distributed Feedback Laser. DFB lasers are used for the more demanding applications and always for CWDM applications.



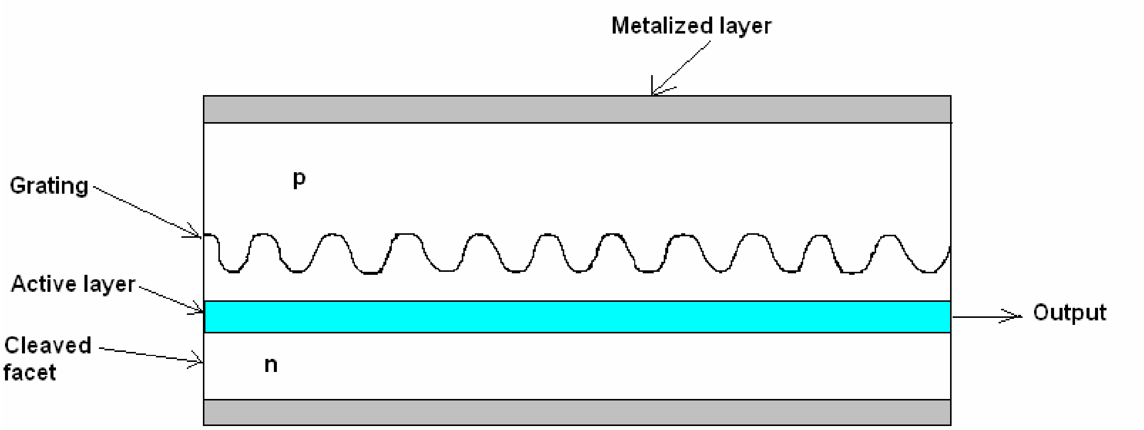


Fig: DFB laser

The DFB laser has a corrugated layer itched internally just above the active region. The corrugation forms an optical grating that selectively reflects light according to its wavelength. This grating acts as a selective filter, allowing only one of the cavity's longitudinal modes to operate back and forth. We might think of the grating and the mirrored cavity each having a set of resonant wavelengths that they will support, but having only one resonant wavelength in common. This will be the single longitudinal mode of the combined resonators. The grating is not placed in the active region itself, because etching in this region could introduce defects that would lower the efficiency of the laser, resulting in a higher threshold current.

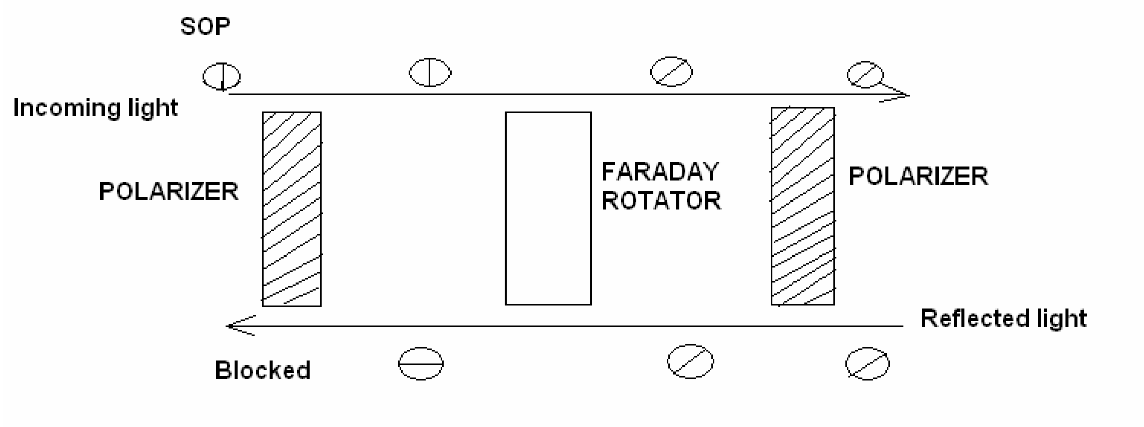
Specifications for DFB Laser:

Parameter	Symbol	Test Conditions	Value
Optical Output Power	P_F	CW, nominal	2 mW
Threshold current	I_{TH}	T=full range	26 mA
Slope effeciency	SE	P_F=2 mW, T=25'C	0.095 mW/mA
Laser Relative Intensity Noise (RIN)	RIN	P_F=2 mW, T=25'C	-155dB/Hz
Biasing Current	I_{bias}	------	61.12 mA

4.2 Optical circulator

4.2.1-Isolators

The principle of operation of an isolator is as shown in the figure. Assume that the light signal has the v ertical SOP as shown. It is passed through a polarizer, which passes only light energy in the vertical SOP and blocks light energy in the horizontal SOP. The Faraday rotator is used to rotate the SOP, say, clockwise by 45 degrees, regardless of the direction of propagation. This is again followed by polarizer that passes only SOPs with 45 degrees orientation. Thus the light signal from left to right is passed through the device without any loss. On the other hand, light entering the device from the right due to the reflections, with the same 45 degree orientation, is rotated another 45 degrees by the Faraday rotator, and thus blocked by the first polarizer.



The isolator constructed using Spacial Walk-off Polarizer (SWP) and Half-Waveplate is shown in the figure below. This forms the basic principle of circulators. The SWP is used to split the light into two components i.e. horizontal and vertical. The Half Wave plate is similar to the Faraday rotator except that it rotates 45 degree clockwise the light coming from left to right and 45 degrees counterclockwise, the light coming from right to left.

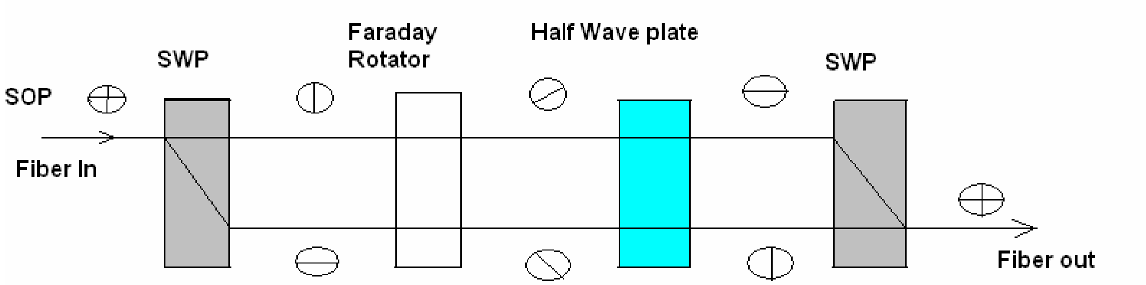


fig : Light travelling from left to right

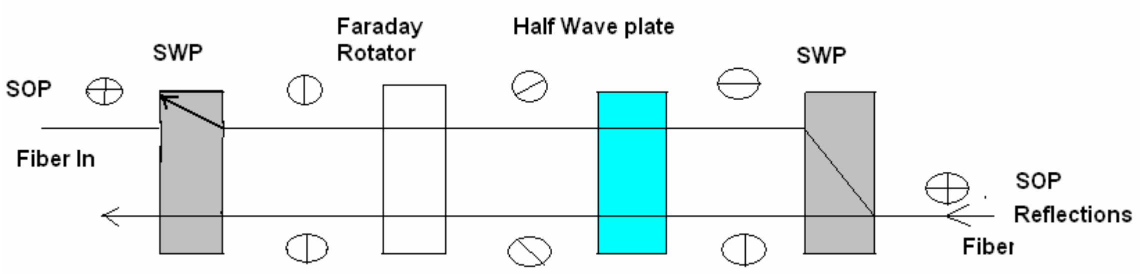


fig: Light travelling from right to left

4.2.2-Optical Circulators

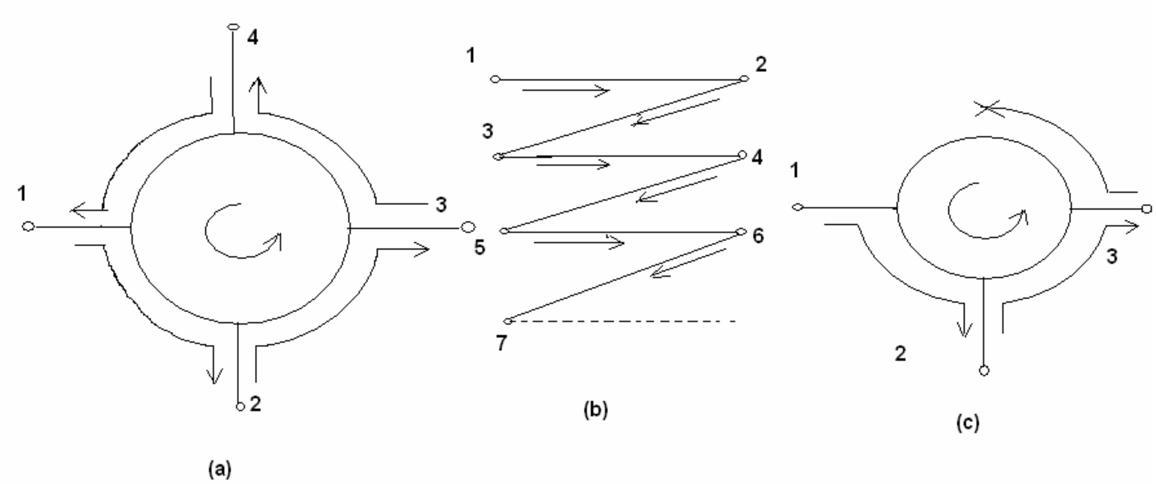


Fig. Three types of circulator connections. (a) Strict-sense circulator with four ports. (b) Non-strict-sense circulator in ladder topology. Light input to the last port is lost. (c)Non-strict-sense three- port circulator.

An optical circulator is a generalized isolator having three or more ports. While an isolator causes loss in the isolation direction, a circulator collects the light and directs it to a non-reciprocal output port. The figure drawn above shows the severa l possible circulator configurations. Figure (a) illustrates the port mapping for a four-port circulator. The ports cyclically map 1 → 2 → 3 → 4 → 1. This is called a strict-sense circulator because every input port has a specific non-reciprocal output port. Construction of a strict-sense circulator with more ports becomes inelegant but ones with three ports becomes simple. Figure (b) illustrates a non-strict-sense circulator having any number of ports greater than two. In this case each input port has a specific non-reciprocal output port except for the last port; the light input to the last port is lost. The ladder diagram reflects the optical path within the component and indicates the disconnect between the first and the last ports. Figure (c) illustrates the three-port non-strict-sense circulator. This circulator has significance in telecommunication applications because return of light from port 3 to port 1 is not often required. For instance, the reflected light from a fiber Bragg grating need only be separated from the input light without loss, but as optical links are not typically operated in reverse there is no need for strict-sense behaviour.

An optical circulator allows the routing of light from one fiber to another based upon the direction of the light propagation. Nonreciprocal optical devices, such as optical isolators and optical circulators, are essential components of optical communication systems. Optical isolators pass light propagating in a forward direction while inhibiting the propagation of light in a backward direction. Since the optical circulator is an inherently non-reciprocal device, the light never goes to other ports. Optical circulators have wide applications. They are used to convert an existing unidirectional fiber optic communication link to a full duplex communication link by installing an optical circulator at each end of the link. Optical circulators are also used in fiber amplification systems, wavelength division multiplex (WDM) networks, optical time-domain reflectometers (OTDRs) and for test instruments.

Specifications for the circulators

Parameter	Value	
Port Number	3 Ports	
Central Wavelength (nm)	1310 or 1550	
Grade	P	A
Typ. Insertion Loss *±20nm, 0~70°C, all SOP* (dB)	0.6	0.8
Isolation *±20nm, 23°C, 2 to 1 or 3 to 2* (dB)	Typ. 50 (Min. 40)	
Max. WDL (dB)	0.20	
Directivity (dB)	60	
Max. PDL (dB)	0.10	
Max. PMD (ps)	0.10	
Return Loss (dB)	60	
Fibre Length (m)	1.0	
Min. Tensile Load (N)	5	
Power Handling (mW)	300	
Operating Temperature (°C)	0 ~ 70	
Storage Temperature (°C)	-40 ~ 85	
Dimension (mm)	ϕ5.5 × L60.0	

Advantages

Although the optical sophistication of circulators makes them comparatively expensive, designers will appreciate the reliability and elegance imparted by fewer components. The resultant performance improvement may eliminate the need for more powerful transmitters, more sensitive receivers, and intermediate amplifiers , thus making optical circulators an economically interesting proposition. And, as with all technology, we can anticipate sharply lower prices as the optical circulator gains wider acceptance.

As one examines optical circulator applications, the notion of integrating the circulator, transmitter, and receiver into a single housing becomes very attractive. All elements would be aligned on a common platform, thus avoiding a multitude of external connectors and splices.

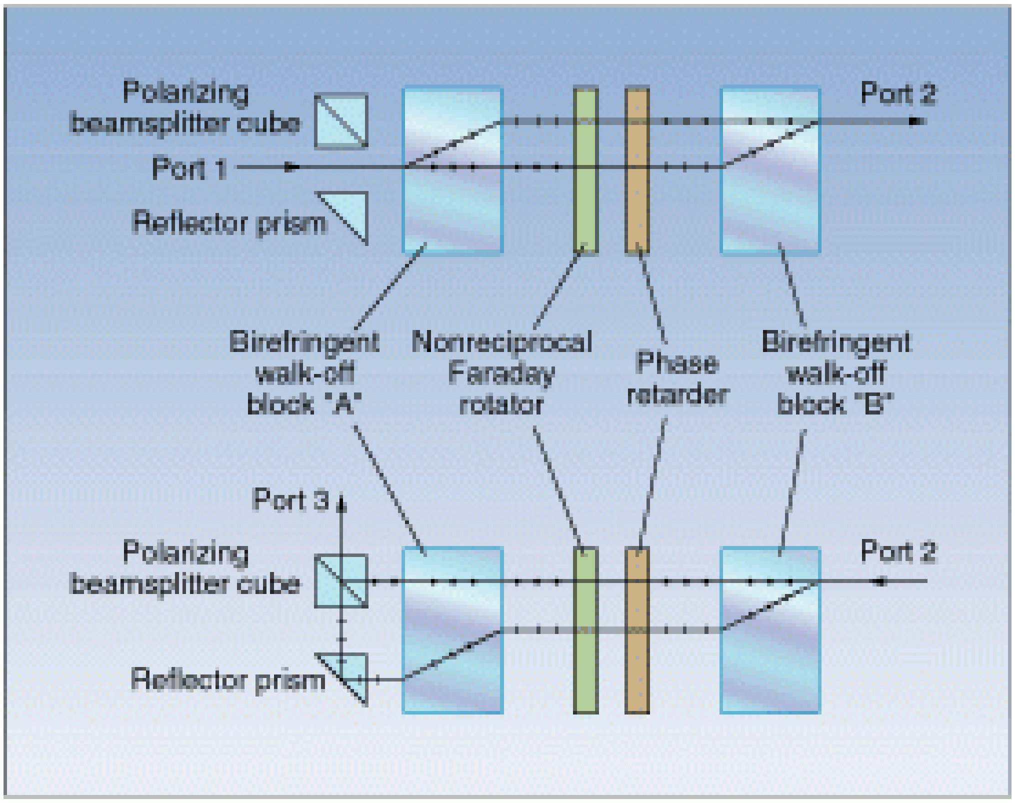
How circulators work………..

All circulator s have this common: a signal entering at Port 1 exits only at Port 2; a signal entering at Port 2 exits only at Port 3. In a so-called "perfect" circulator a signal entering at Port 3 would exit only at Port 1. In many applications, however, this last condition is unnecessary. Most commercial circulators therefore are designed to be "imperfect" so as to absorb any signal directed into Port 3.

The design used by Optics for Research shows how forward and return signals are separated and directed to the desired ports (see figure). The simplified diagram omits input/ output alignment provisions and connectors. In practice, connection usually is via fiber pigtails that are aligned during final assembly.

In the forward direction (Ports 1 to 2), birefringent walk-off block "A" splits the entering beam into orthogonally polarized ordinary and extraordinary rays. The ordinary ray continues along its original path; the extraordinary ray is displaced upward. Next, the combined effect of the nonreciprocal Faraday rotator and phase retarder reverses the polarization azimuth of both rays. Because of the reversed polarization, walk-off block "B" reverses the action of the first walk-off block and recombines the rays to exit at Port 2.

In the reverse direction (Ports 2 to 3), the entering beam again is divided by the walk-off block into two orthogonally polarized rays. Because the Faraday rotator is nonreciprocal, ray polarization does not change in this direction. Walk-off block "A" now increases the separation between rays (instead of combining them) so that they are off-axis with respect to Port 1. Finally, the two rays are recombined and reflected upward by the polarizing beamsplitter cube and reflector prism to emerge as required at Port 3.

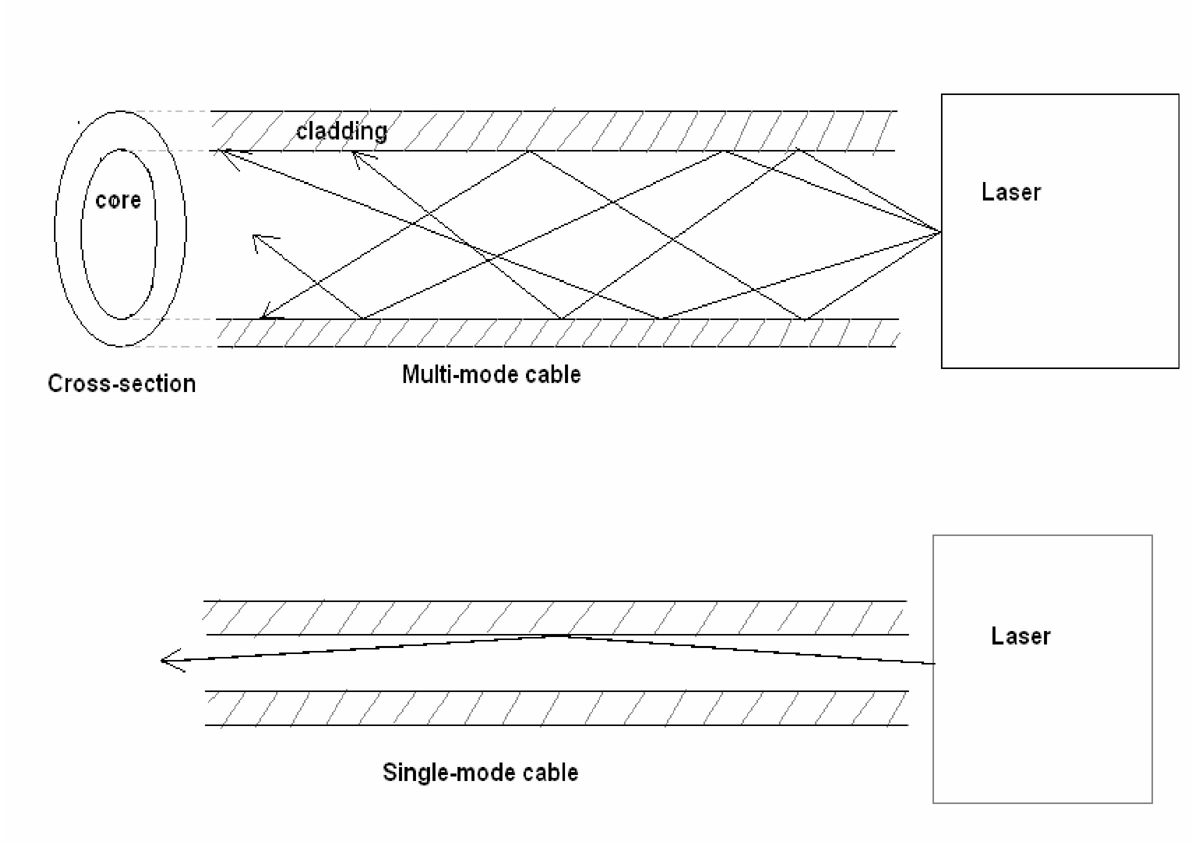


11-FEA-6 Sidebar Figure

4.3- Optical Fiber

Single mode Fiber and Multi mode Fiber

Fiber optic cable is available in single-mode and multi-mode types. Multi-mode cable has a larger core diameter (50 um or 62.5 um) than single mode fiber (9 um core diameter). When light travels down multi-mode fiber it is reflected at different angles as it propagates down the transmission path. These multiple reflections cause the light to spread out in time as it propagates down the fiber, making it more difficult for the receiver to recover the data. Single-mode fiber being more narrower, confines the optical signal to a straighter path with fewer reflections. As a result, optical signal dispersion is significantly reduced, which translates into a cleaner signal. Longer transmission lengths can therefore be achieved with single-mode cable.



4.4-Connectors

Optical Return Loss

A small amount of light is reflected back at any fiber optic cable interface and this is known as Optical Return Loss (ORL). The more connectors we have in a system, the more loss we will encounter due to optical return loss. (If a connector is left disconnected, much of the light will be reflected back to the transmitter and a 14.7 dB return loss can be expected). ORL is important in bidirectional systems using a single fiber because of the need to keep the sending signal out of the local receiver. To help keep reflections below the minimum sensitivity of the receiver, Evertz limits the transmission power of lasers in single fiber bi-directional systems.

In many systems fiber patch cords are needed in a system, it is sometimes expedient to employ Angle Polished Connectors (APC) to minimize the ORL. The optical ends to these connectors are angled at 8 degrees, such that any reflected light is deflected into the cladding and not back to the source. (i.e. 8 degrees from a line perpendicular to the direction of the fiber). Angle polished connectors with SC fittings, are generally coloured green instead of the more usual blue.

4.5-Receiver

The optical receiver consists of a photodetector called InGaAs PIN photodiode along with inbuilt Transimpedance amplifier. Transimpedance receiver provides good matching to the photodiode and it benefits a thermal noise limited system. The receiver provides a very low noise and a very low group delay. The InGaAs PIN + TIA exhibits linear RF output voltage up to 1.8 Vpp and RF output power up to +10 dBm. Wide spectral response enables use for 850 nm as well as 1310 nm, S, C and L telecommunications wavelength bands. InGaAs/InP photodiode and a transimpedance amplifier with low electrical return loss, improves link performance.

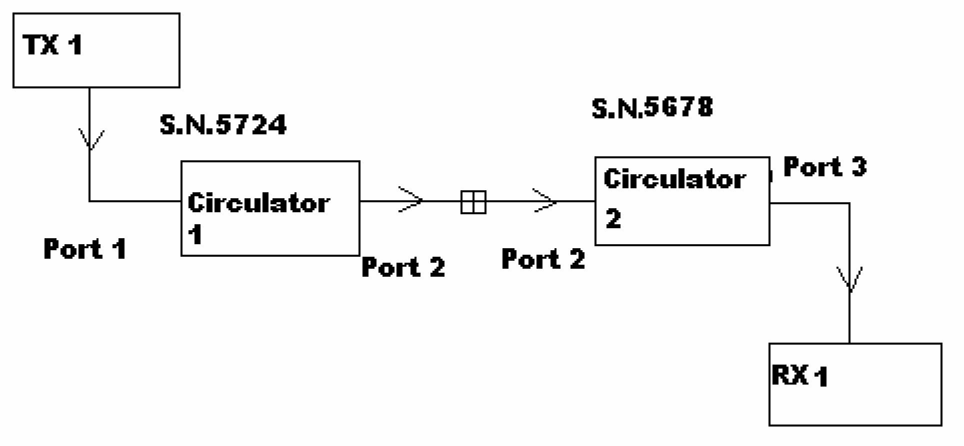
Specifications for optical receiver:

PARAMETER	**SPECIFICATION**
Responsivity	0.8 mA/mW
Operating wavelength	1100nm to 1600nm
Return loss	> 45 dB
Transimpedance	500 ohms
Electrical return loss @ 1550dB	-15 dB

5. Link performance

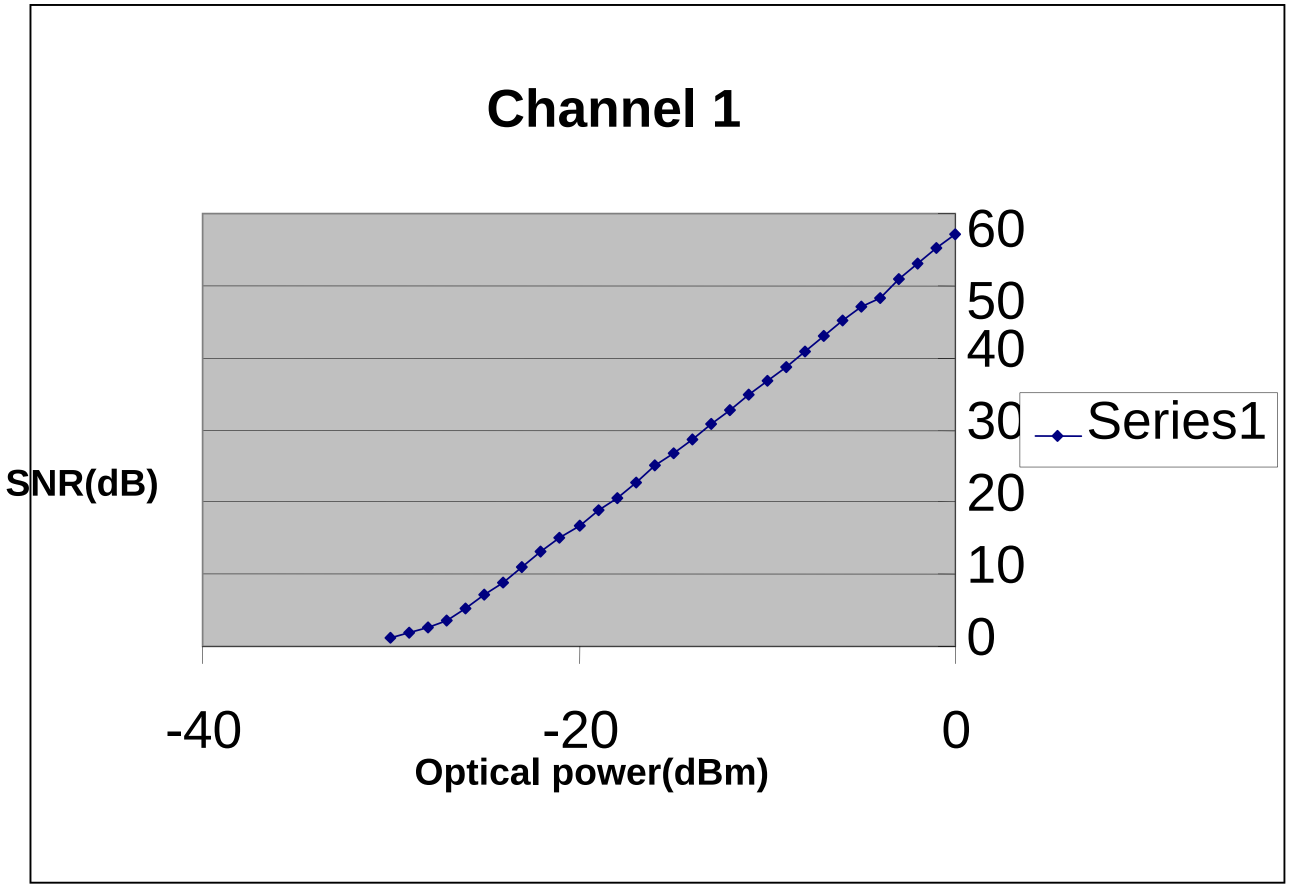
a. Considering channel 1(Forward link)

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



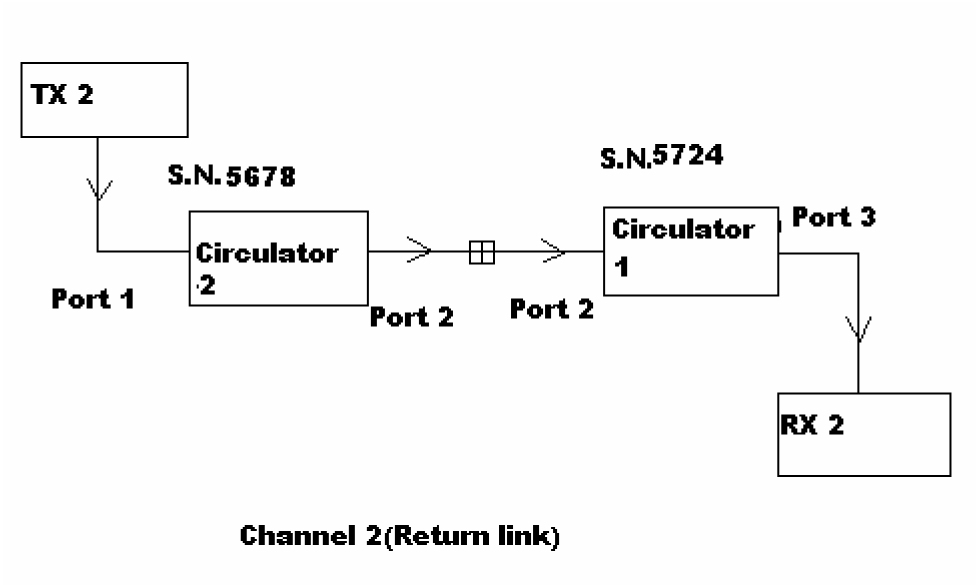
Channel 1(Forward link)

The optical power of the transmitter was reduced gradually and corresponding change in the signal power at output i.e. at receiver was observed. It was observed that the SNR of the link decreases with decrease in power.

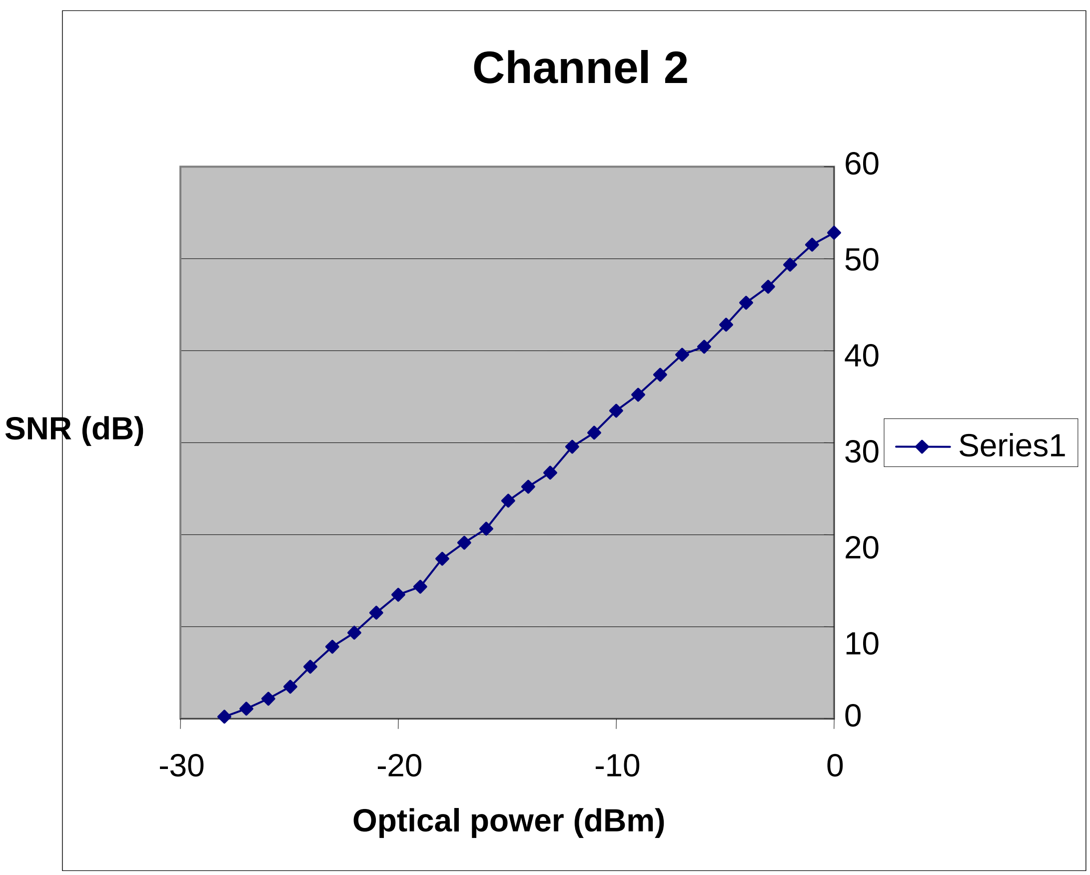


b. Channel 2 (Return link)

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



The optical power of the transmitter was again reduced gradually as in the first case and corresponding change in the signal power at output i.e. at receiver was observed. It was observed that the SNR of the link decreases with decrease in power.



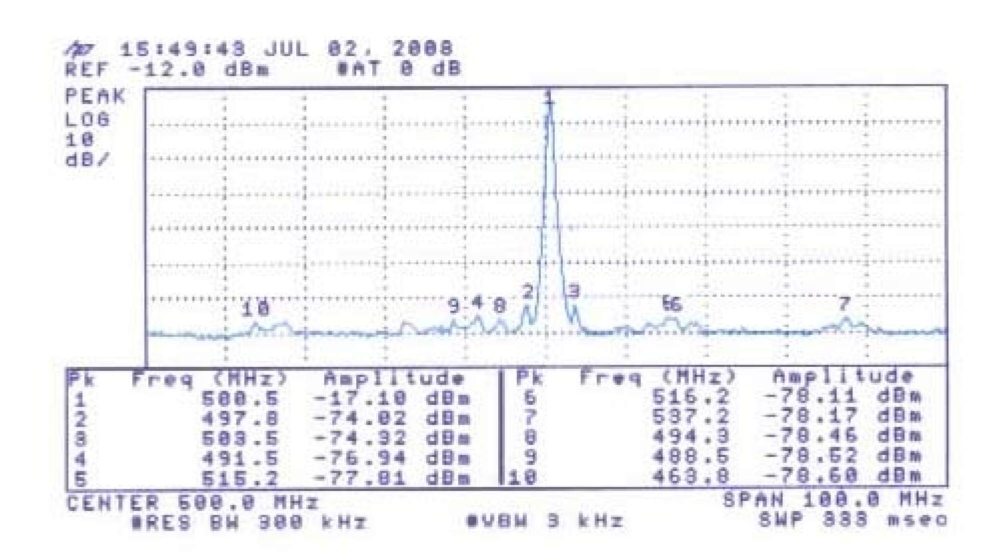
The carrier Frequency selected for the signal generator in both the cases was 500 MHz.

Both The Transmitters were made ON and bidirectional link was established.

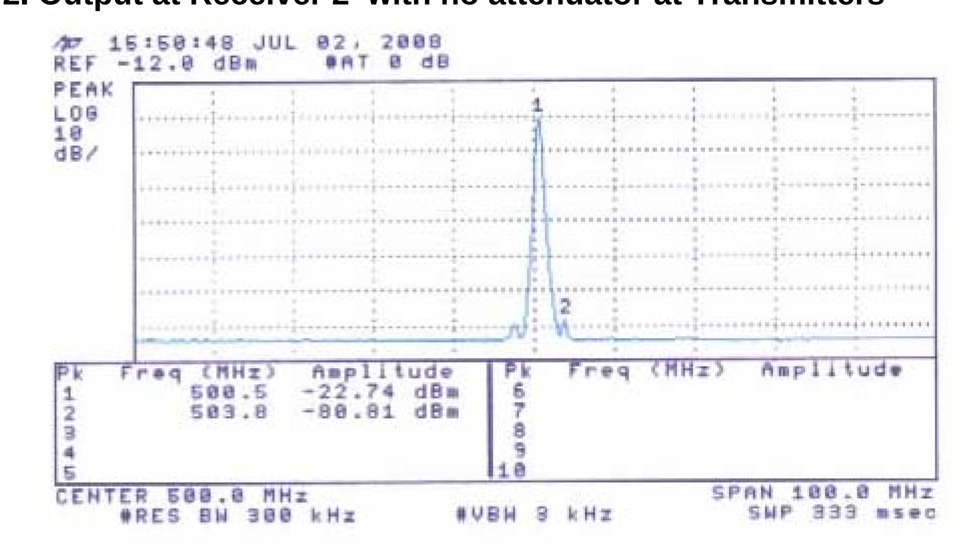
Both the transmitters were made to transmit the signal having a frequency of 500 MHz. The signals obtained at the receiver were analyzed for checking the interference, if any. Firstly there were no attenuators at the transmitter output, then 2 dB attenuators were connected and change in the output was observed. Again 4 dB attenuators were connected at the transmitter output and readings were taken. It was observed that there was no significant change in the optical performance.

Transmitt-ers with	Signal power at RX1	Noise power at RX1	Signal power at RX2	Noise power at RX2
no attenuator	- 17.10 dBm	-80.13 dBm	-22.74 dBm	-83.81 dBm
2 dB attenuator	- 21.09 dBm	-82.89 dBm	-26.92 dBm	-84.32 dBm
4 dB attenuator	-27.90 dBm	-84.12 dBm	-31.48 dBm	-85.63 dBm

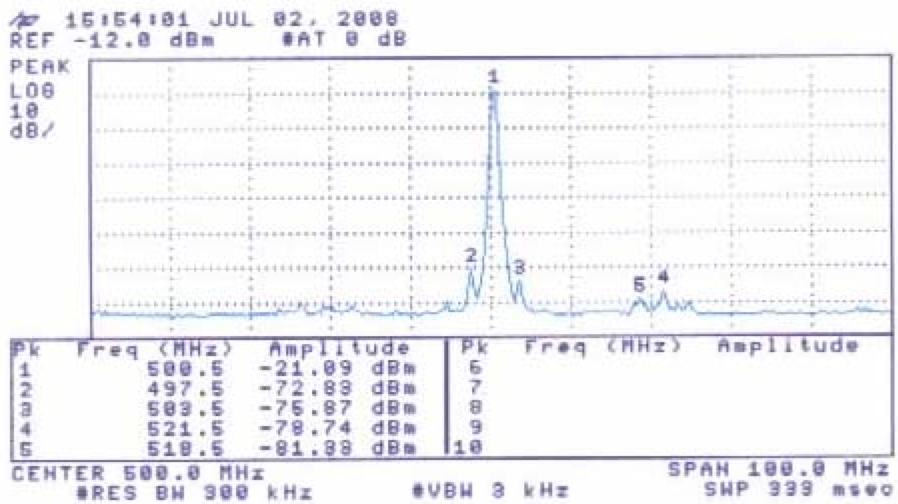
1. Output at Receiver 1 with no attenuator at Transmitters



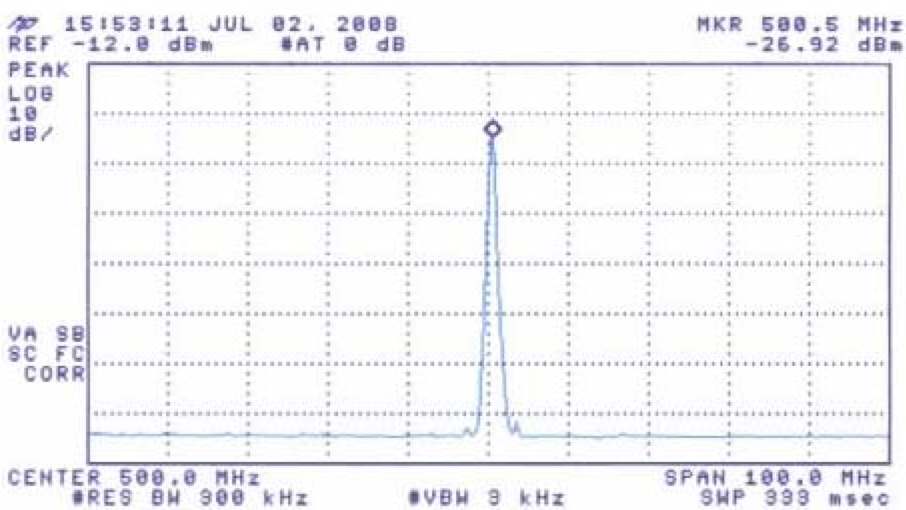
2. Output at Receiver 2 with no attenuator at Transmitters



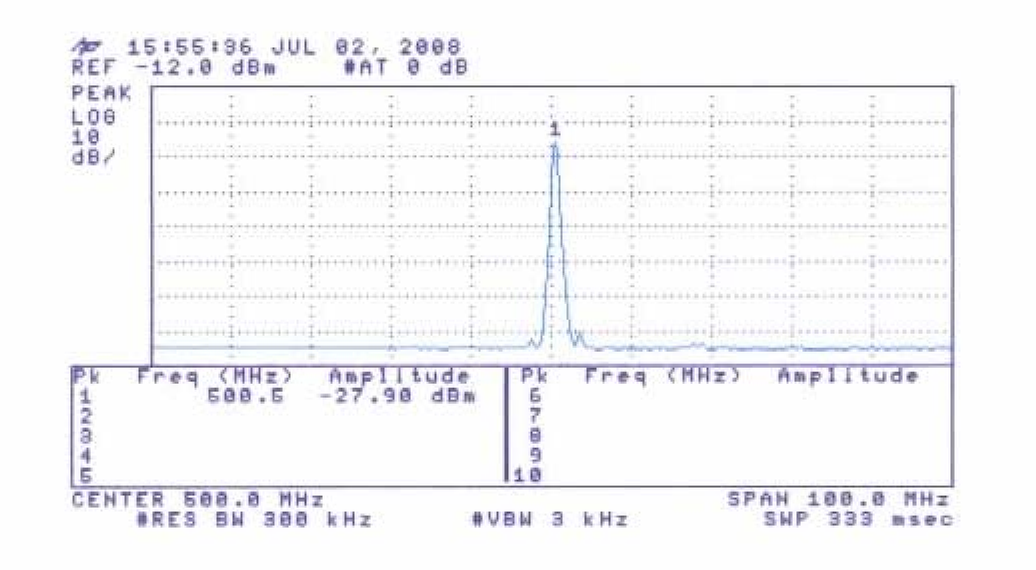
3. Output at Receiver 1 with 2 dB attenuator at Transmitters



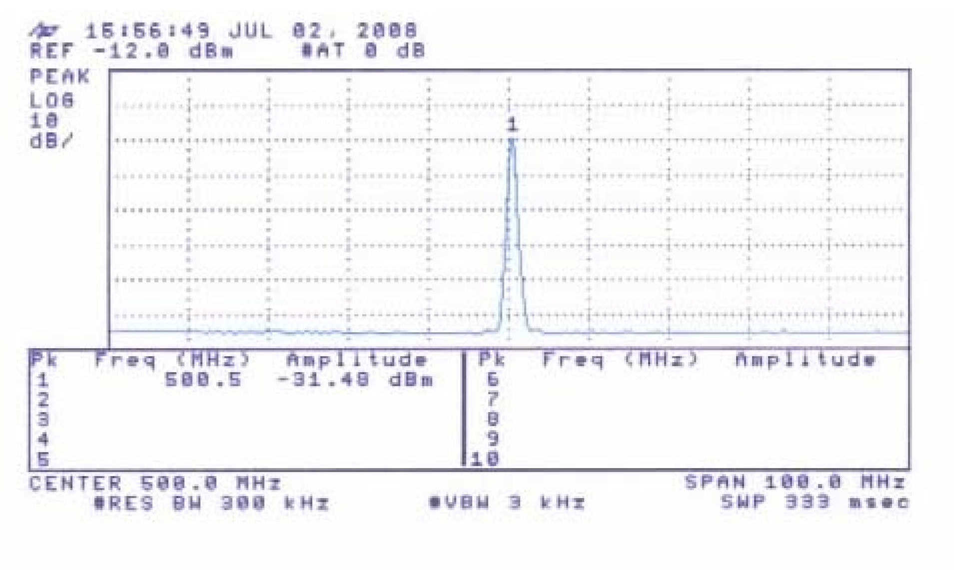
4. Output at Receiver 2 with 2 dB attenuator at Transmitters



5. Output at Receiver 1 with 4 dB attenuator at Transmitters



6. Output at Receiver 2 with 4 dB attenuator at Transmitters

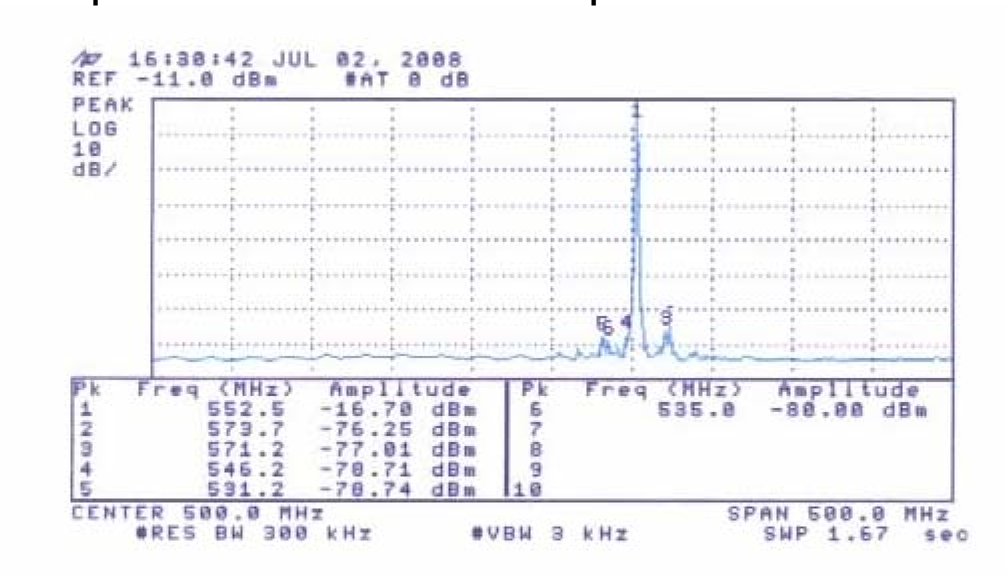


Experiment to check the Isolation between the two signals.

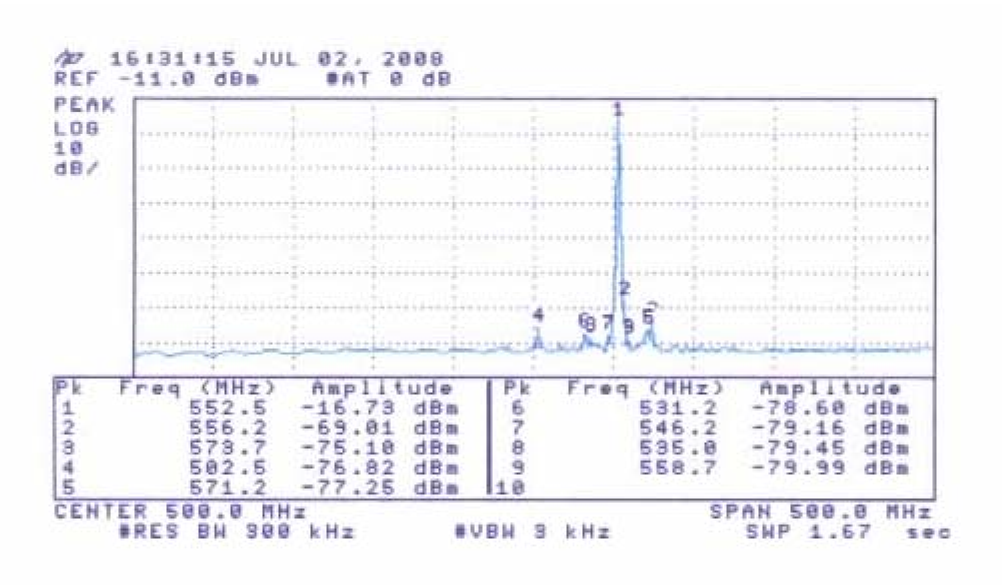
In order to check the isolation, the transmitter TX 1 was having its RF level ON, while the transmitter TX2 was having RF level OFF , initially. Then its RF level was made ON and was gradually increased in the steps of 5 dB. The corresponding change in the isolation i.e. the signal power obtained at the receiver RX2 was observed.

The transmitter TX1 was operated at a carrier frequency of 550 MHz and the transmitter TX2 was operated at 500 MHz. This arrangement was done in order to minimize the effect of beats.

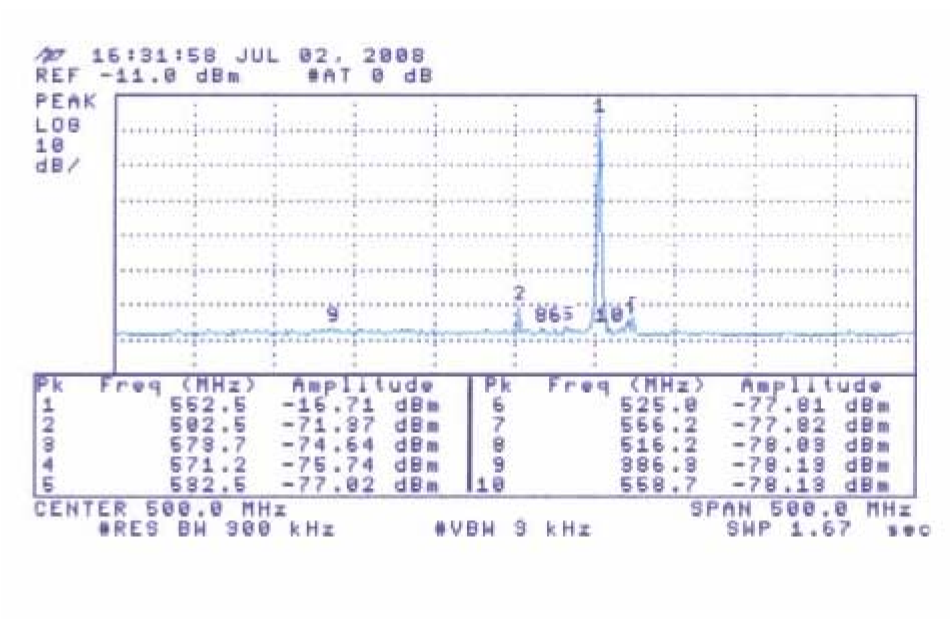
1. Output at RX1 when TX2 with no RF power



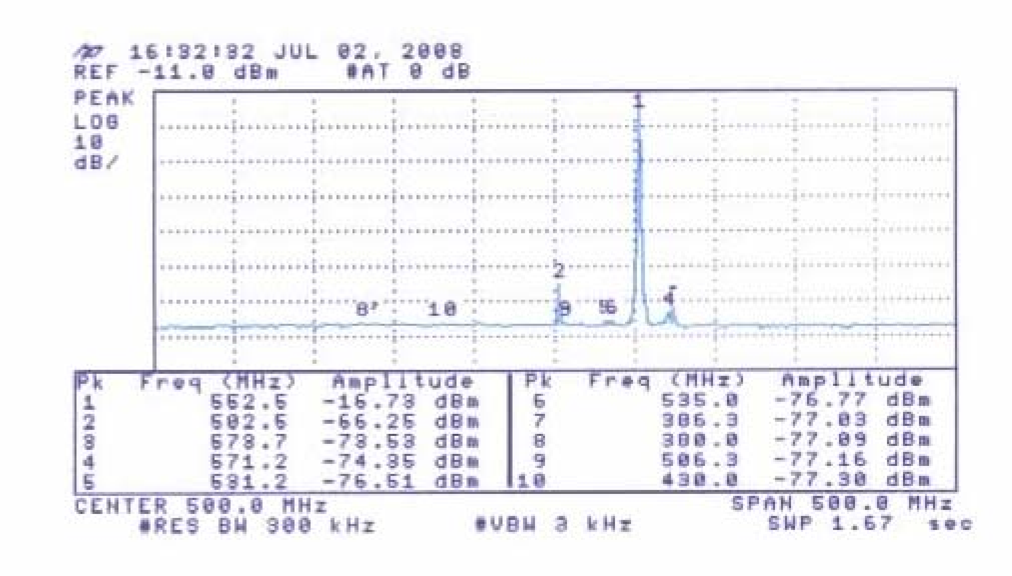
2. Output at RX1 when TX2 with RF power of +0 dB



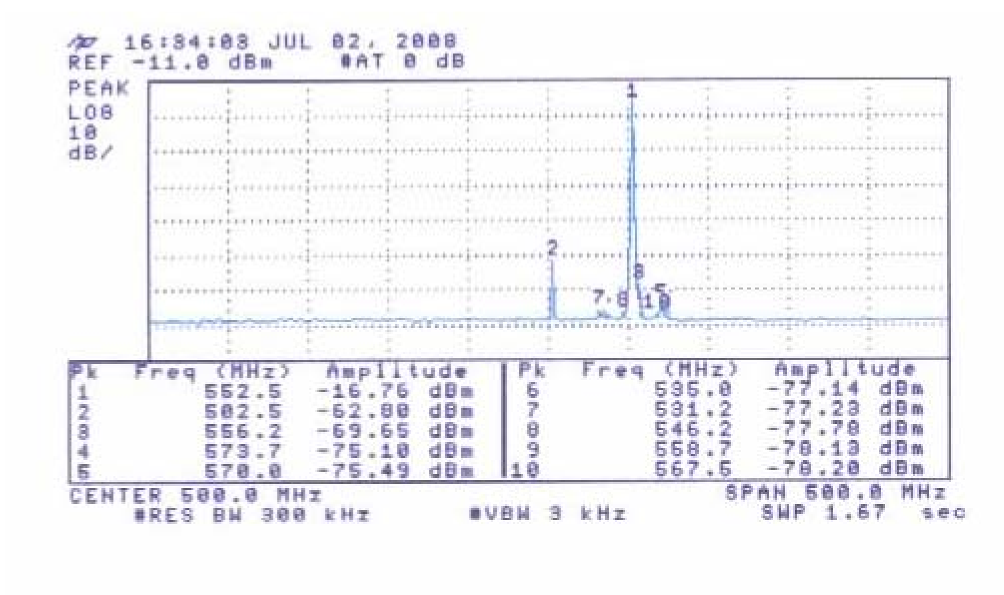
3. Output at RX1 when TX2 with RF power of +5 dB



4. Output at RX1 when TX2 with RF power of +10 dB

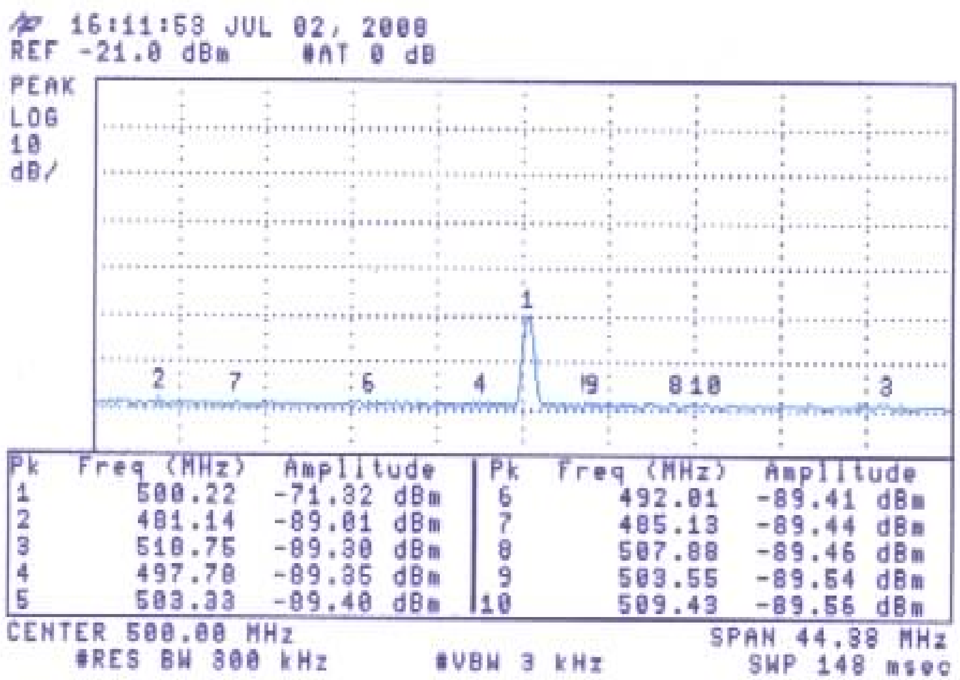


5. Output at RX1 when TX2 with RF power of +13 dB



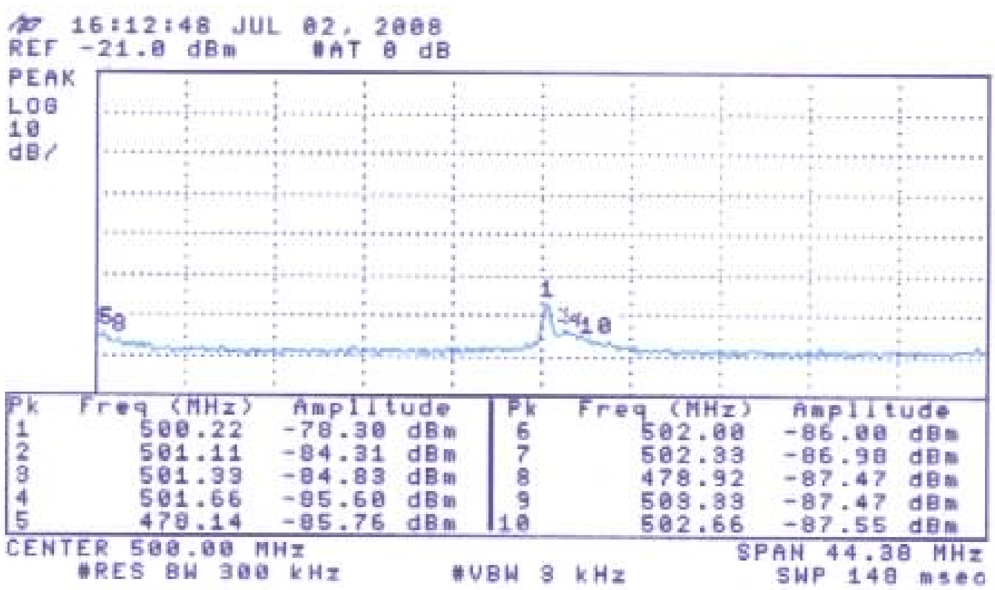
Optical Isolation in the link

- TX1 RF ON (0 dBm), RX1 O/P measured (-17 dBm)
- RX2 O/P measured (-71 dBm) Less by 54 dB



Isolation with Return Link

- TX2 RF ON (0 dBm), RX2 O/P measured (-22 dBm), RX1 O/P measured (-78 dBm), Less by 56 dB

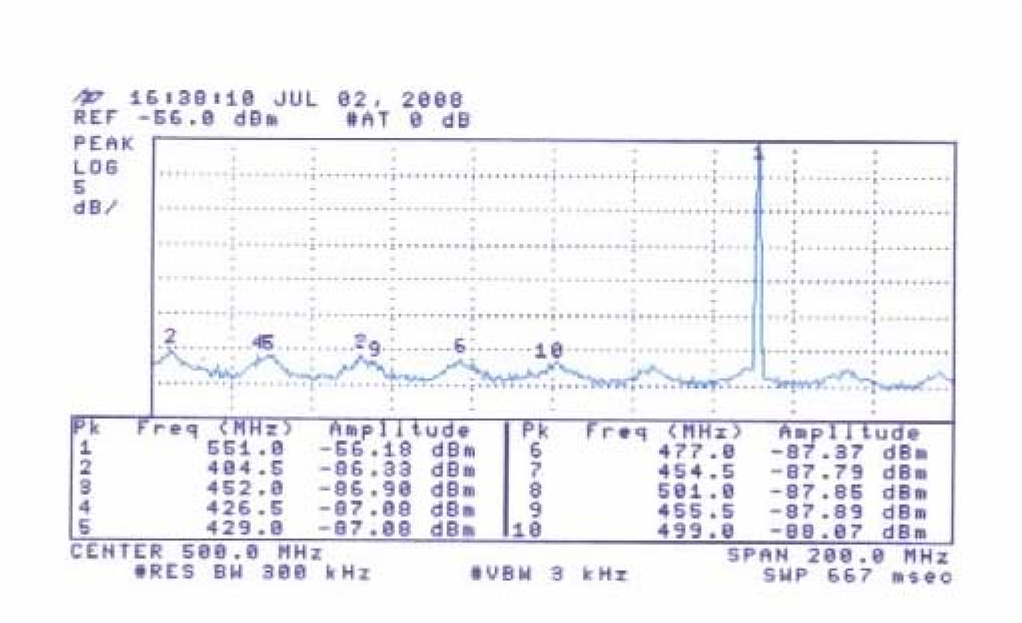


<u>Experiment to check the noise in the link</u>

Condition 1:-

TX1→ RF OFF
TX2→ RF= +0 dB

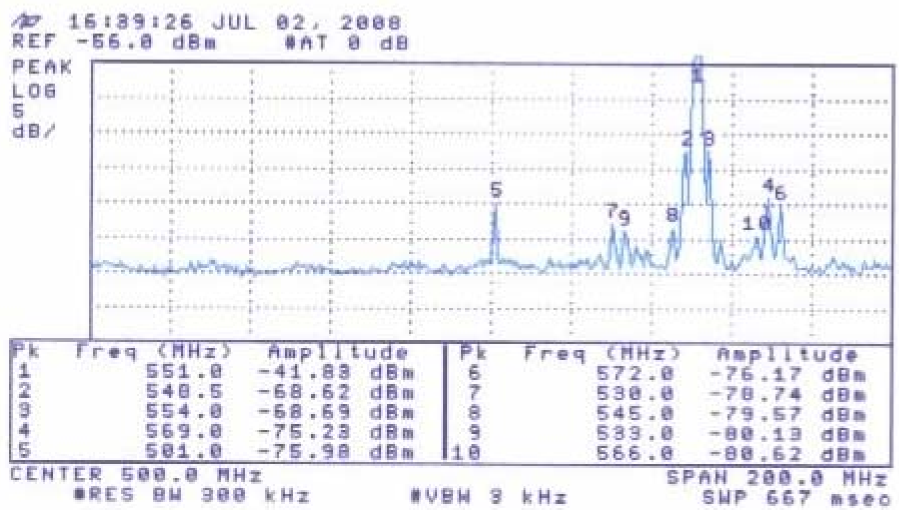
For the above conditions, it was observed that the signal was showing many ripples in the band.



Condition 2:-

TX1→ RF = +0 dB
TX2→ RF= +0 dB

For the above conditions, it was observed that the signal was quite stable with very less ripples.



Hence, both the transmitters should be operated at some higher RF level and both the RF levels should have same value.

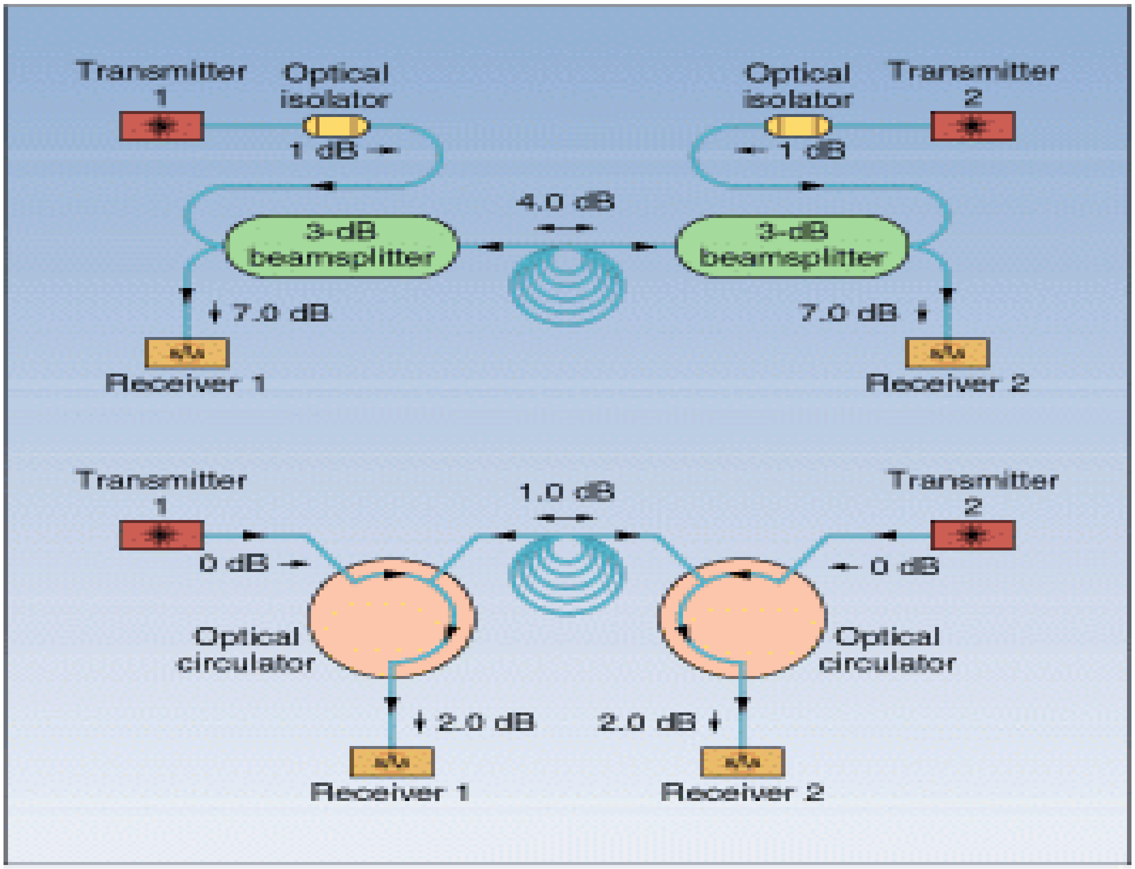
6. Comparison between the Bidirectional link consisting of circulators and that consisting of the beam-splitters.

By operating as a one-way revolving door, an optical circulator separates incoming and outgoing signals without beamsplitters and isolators, decreasing system loss.

Fiberoptic communication systems, sensors, amplifiers, and instruments such as optical time-domain reflectometers (OTDRs) often transmit and receive signals along the same optical path. These signals then must be separated and redirected to be useful. The traditional separation method, relying on 3-dB beamsplitters and (sometimes) isolators, typically imposes more than 6 dB of signal loss. In contrast, signal separation with optical circulators reduces these losses to nominally 2.0 dB.

To illustrate, consider a single-fiber, bidirectional communication system using 3-dB beamsplitters (see Fig. 1, top). Each path includes two 3-dB beamsplitters and two isolators (the latter to avoid interference with the transmitter). Only 25% of the transmitter signal reaches the receiver—and that is before the inevitable scatter, absorption, splice, and isolator losses. Each splitter passes only 50% of the input signal; the isolator adds its own 1-dB signal loss. This familiar design may well require signal amplification or enhanced detection sensitivity for acceptable performance, especially in long-haul service.

Optical circulators offer an alternative configuration . In Fig. 1, bottom, an optical circulator at each terminal replaces the isolator and 3-dB splitter. Path loss drops to about 2.0 dB; components and connectors are eliminated and device specifications are relaxed. Intermediate amplifiers may be unnecessary, and overall system noise may be reduced.



11-FEA-6 Fig. 1

FIGURE 1. Conventional bidirectional communication system incorporates isolators and beamsplitters (top). Cumulative losses are noted as the signal progresses through the system. Up to 7-dB loss is imposed on each circuit by the signal-separation components. In bidirectional communication system with optical circulators, signal separation is achieved with only 2.0-dB loss in each circuit (bottom).

7. Conclusions

The bidirectional link designed using circulators introduces a very low loss and hence improves the bidirectional system.

The bidirectional link designed produces the desired results by using the uncooled DFB laser with central wavelength at 1550 nm. It is observed that by using a single mode optical fiber of length 1.3 Km between the port 2 of both the circulators, the lossess are minimized.

The transmitters are operated at the frequencies separated by some amount. This is because, when same frequency was used the phenomenon of production of beats was observed and the ripples were seen. But when different frequencies were used, the ripples were reduced to a great amount.

Also, it is concluded that both the transmitters should be operated at some higher RF level and both the RF levels should have the same value. Due to this, the ripples in the signal were reduced to a great extent. Aalso there was some degradation in the isolation of the system.

The cost of circulator is very high as compared to that of WDM Couplers. Hence to make the system cost effective couplers instead of circulators is preffered.

8. References

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