# Bidirectional Multiwavelength Ring Networks: Performance Analysis and Experimental Studies

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***Abstract:***

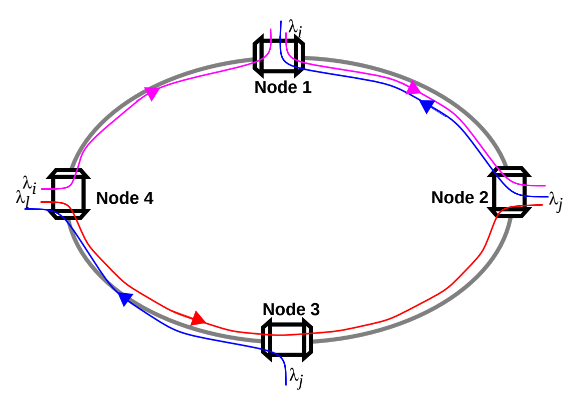
*High-capacity multiwavelength ring networks with bidirectional WDM add/drop multiplexer (WADM) is analyzed and demonstrated. All channels can be added/ dropped independently in each direction. The capacity of a bidirectional ring is found to be approximately twice that of an unidirectional ring. An eight-wavelength WADM is demonstrated for a data rate of 10 Gb/s per channel, providing an overall capacity of 80 Gb/s.*

## 1. INTRODUCTION

Optical networks using wavelength-division-multiplexing (WDM) are powerful technique to exploit the enormous bandwidth offered by optical fibers. A network topology of bus or ring is probably one of the simplest forms to realize such powerful scheme, of which flexibility, scalability and high throughput are some of the advantages. However, most of the investigated WDM optical networks are based on unidirectional transmission [1]-[4], and the full capacity of fiber bidirectionality is largely ignored. Though works on bidirectional transmission of WDM signal were discussed [5-9], the bidirectional WDM optical network is largely unexplored. The bandwidth demand, due to the exponential growth of Internet and Intranet, is increasing at an unproportionally large rate than that of the hardware implementation, investigation on the bidirectional transmission properties of WDM network can be critical, as the bidirectional transmission properties of the optical fiber can be one of the solutions to the demanding growth in network load.

A bidirectional ring network is illustrated in Fig. 1 together with the routing table, showing the traffic can be propagated in two opposing directions within a single fiber. The bidirectional transmission offers smaller number of hops from source to destination for upstream node of the unidirectional transmission ring, resulting in the increase in network capacity. Similar to unidirectional ring network, wavelength add-drop multiplexers (WADM) is required to allow channel addition and termination. This critical requirement usually requires a wavelength channel destined to a certain node is dropped at that node, and new channels can be added at every node as required. However, all existing WADM schemes reported thus far operate in a mode where the added and dropped optical signals must be in the same directions [7-9]. Furthermore, most existing Erbium doped fiber amplifiers (EDFA) with optical isolator restrict the signal propagation in a single direction.

Here, we report the realization of a single-fiber bidirectional WDM ring network based on a new bidirectional WADM. Performance analysis, wavelength assignment, and protocol of the new bidirectional WDM network will be presented along with the experimental results. An eight-channel network, with a capacity of 10 Gb/s per wavelength channel, is demonstrated for a total capacity of 80 Gb/s. The impact of backscattering light which greatly affects the performance of bidirectional transmission is also evaluated experimentally. Numerical simulations are also conducted and shown that, with the same number of nodes and WDM channels, the system capacity of a bidirectional ring is approximately twice that of an unidirectional ring.




Routing Table

| Node | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| $\lambda_i$ | da | dx | xx | xa |
| $\lambda_j$ | xd | ax | xa | dx |
| $\lambda_k$ | xx | xx | xx | xx |
| $\lambda_l$ | xx | dx | pp | xa |

a: add, d: drop, p: pass, x: idle

Fig. 1 A bidirectional multiwavelength ring network with some routing examples and the corresponding routing table.

## 2. Network Architecture

The network architecture of the bidirectional photonic ring network does not differ much from that of the unidirectional or dual ring configuration, and its basic structure has already been illustrated in Fig. 1. Traffic from node 4 to 1 can be via $\lambda_i$ in clockwise direction, while from node 4 to 2 is achieved via $\lambda_l$ through node 3 in the counter-clockwise direction. Node 3 in the latter case serves as pass-through node in which no wavelength channel is added or dropped. Two way traffic from node 1 to 2 and from node 2 to 1 are via $\lambda_i$ and $\lambda_j$, respectively, can be realized in the same fiber. The bidirectional properties of the ring minimize the number of pass-through nodes before reaching the destination, thus improving the network efficiency. Such bidirectional network relies on the realization of two critical building blocks of bidirectional WADM and bidirectional optical amplifiers.

Fig. 2 shows the architecture of our proposed bidirectional WADM consisting of a WDM multiplexer and demultiplexer. The existing various WDM multiplexer/demultiplexer components are adequate for this purpose, such as the arrayed waveguide grating demultiplexer and interference filter [10]-[12]. The three functions supported by the WADM, namely, channel passing-through, adding and dropping have to be conducted for both propagating directions. In each of these demultiplexed channels, an EDFA is used to compensate for fiber attenuation and other losses in the network. An individual EDFA for each channel is also needed to equalize the gain among all wavelength channels by operating the amplifier in gain saturation regime. The WADM design also requires two optical 2x2 cross switches to perform the bidirectional add-drop and pass-through. High-performance, low-crosstalk (<60 dB) mechanical switches with switching time in the range of millisecond are adequate for the operation, as the ring network of interest is of circuit switching type and the connection setup time can largely be ignored. For the first switch, the two of the ports are connected to the WDM multiplexer and demultiplexer, as indicated by 'left' and 'right' in Fig. 2(b). One of the remaining two ports is connected to an input port of the second optical switch while the other port is connected to the output of an EDFA with its input connecting to the output of the second switch. The added and dropped channels are connected to the respective remaining input and output of the second switch as shown. Figs. 3(a)-(d) show the four modes of operations: channel passing through [Fig. 3(a)] and add/

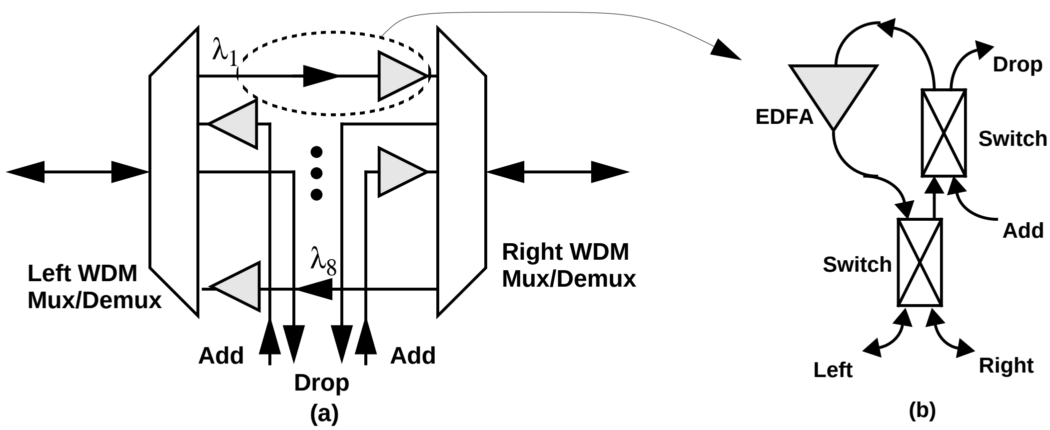



Fig. 2 (a) Architecture of bidirectional eight-wavelength WADM. (b) Structure of the switch fabric at each wavelength port with a directional switch and an add/drop switch.

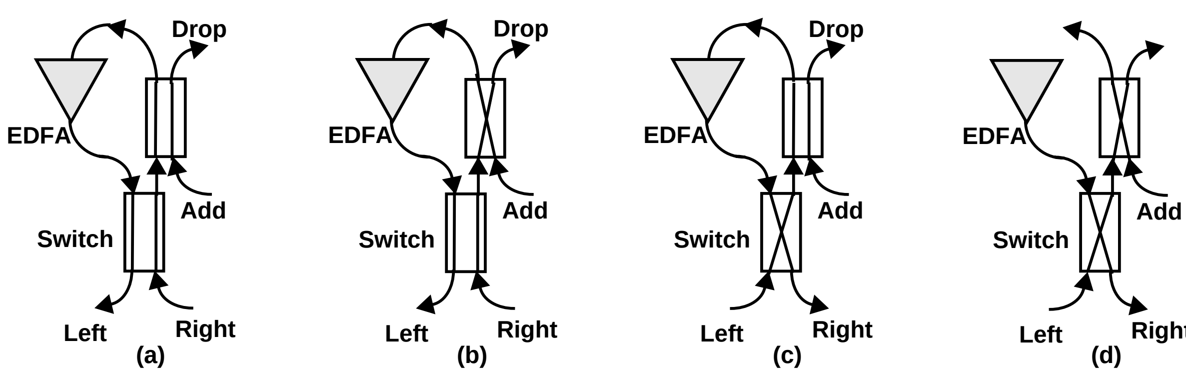



Fig. 3 Four different configurations of the switch fabric: (a) directly from right to left, (b) drop from right and add to left, (c) directly from left to right, (d) drop from left and add to right.

drop [Fig. 3(b)] at the counter-clockwise propagating direction, channel passing through [Fig. 3(b)] and add/ drop [Fig. 3(d)] in the clockwise propagating direction. As shown in Figs. 3, two channels having the same wavelength cannot add to or drop from the same node, and add or drop, if they happen at the same node, must also follow the same direction. All of those are due to hardware constraint. Physically, for the same wavelength in the same fiber, the proposed scheme supports only a single propagating direction at a given time as precluded by Rayleigh backscattering.

One major issue of bidirectional WADM is the backward propagating light generated by Rayleigh backscattering, stimulated Brillouin scattering (SBS), and other reflection effects from various interfaces including fiber splices, connectors, and other optical components. Rayleigh backscattering is a fundamental loss mechanism arising from random density fluctuations frozen into the fiber core during manufacturing. SBS is a nonlinear effect that can generate a backward-propagating Stokes wave which may carry most of the input energy. Unlike Rayleigh backscattering, SBS can be eliminated by broadening the linewidth of the transmitter [13].

With an well-engineered network, all these backscattering light is relatively very small. For example, all reflections effects from various interfaces are required to be smaller than -30 dB, but with many fiber links having much worse back-reflection. However, these backward propagating light which is generated by a strong (about 7 dBm) signal just leaving the WADM contaminates an usually weak (20 to 40 dB weaker) signal coming to the WADM. The WDM multiplexer and demultiplexer in the bidirectional WADM may require higher crosstalk rejection than that in the case of unidirectional ring.

Conventional optical amplifier based on Erbium doped fiber amplifier cannot be used in the fiber link of bidirectional networks because of the isolators in the amplifier module. The WADM in Fig. 2 can also be facilitated as a reconfigurable bidirectional optical amplifier by restricting it to direct passing through without add/drop for all wavelength channels. The optical switches for add/drop functioning is not required as the WADM uses as bidirectional amplifier. Each wavelength channel can be reconfigured to propagate in either direction.

## 3. Protocol and Wavelength Assignment

The controlling protocol and wavelength assignment is a simple job for central control. The control center can periodically poll each node for connection/disconnection request. The switches in each node can be functioned according to the command from the control center. One copy of the routing table in Fig. 1 is required to be stored in the control center and update accordingly. The routing table indicates whether each wavelength channel is idle (x), add (a), drop (d), or pass (p) at each node. A connection table to record each connection may or may not required. Very simple scheme can be used for wavelength assignment, for example, the control center searches the routing table from the first to the last wavelength channel to find an empty wavelength slot for clockwise direction and searches from the last to first wavelength for counter-clockwise direction. Assuming a function of establish(i, j, channel, direction) is available to establish a connection from node *i* to node *j* though specific channel and direction, the wavelength assignment procedure may function as following:

```
connection(i, j) To make a connection from node i to node j
    if ( i == j),
        error(add and drop node cannot be the same);
    channel = no_channel;
    if (|i - j| < N - |i - j|) & (i > j) || (|i - j|  ≥  N - |i - j|) & (j > i),
        if (channel = empty(i, j, counter_clockwise)) != no_channel,
            establish(i, j, channel, counter_clockwise);
        else if (channel = empty(i, j, clockwise)) != no_channel,
            establish(i, j, channel, clockwise);
    else
        if (channel = empty(i, j, clocwise)) != no_channel,
            establish(i, j, channel, clockwise);
        else if (channel = empty(i, j, counter_clockwise)) != no_channel,
            establish(i, j, channel, counter_clockwise);
    if channel == no_channel,
        return (no empty channel);
end /* connection */

empty(i, j, direction) To find empty channel slot
    if (direction == clockwise),
        for (channel = 1 to channel = N) do
            if (empty slots for clockwise direction from i to j)
                        return channel;
    if (direction == counter_clockwise),
        for (channel = N to channel = 1) do
            if (empty slots for counter_clockwise direction from i to j)
                        return channel;
    return no_channel;
end /* empty */
```

There are other controlling signals transmitting between the control center and each node, most of them are trivial and we will not elaborate here. For circuit switching, the signalling network can be slow links to each node, there are numerous choices for the signalling network, to name a few: embedded in the signal, a separate wavelength, telephone network, wireless network,...

The distributive control of the network is more challenging. In order to control the functioning of the network, each node must keep a routing table and related information. In order to eliminate the case in which two nodes want to establish a connection at the same time, the controlling protocol may use a token passing scheme such that a node can establish a connection and transmit other controlling information if and only if the node has a token. In other words, the distributive control mechanism allows each node functioning as a control center in turn.

## 4. Analysis of Multiwavelength Bidirectional Ring Networks

An multiwavelength optical ring network can transmit in both directions even when a single fiber is used. This section shows that the system capacity of a bidirectional ring is approximately twice that of an unidirectional ring.

Assume a ring network with $N$ nodes. In an unidirectional architecture, signal transmits from node $i$ to $i + 1$ but not the reverse, for a connection from node $i$ to node $j$, the signal needs to pass through $j - i$ links if $j > i$ or $N + j - i$ links if $j < i$. If the network has identical connection probability between nodes, the average number of links that a connection goes through is

$$\bar{L} = N/2 \text{ for unidirectional ring.} \qquad (1)$$

If the connection is from node $i$ to $i + 1$, the connection just occupies a wavelength channel on one single link. However, if the connection is from node $i + 1$ to $i$, the connection needs to pass through $N - 1$ links and all $N$ nodes to reach the destination.

In a bidirectional architecture, without congestion, the connections from node $i + 1$ to $i$ or from node $i$ to $i + 1$ require only one link in different direction. For a connection from node $i$ to $j$, without congestion, the signal needs to pass through $\min\{|i-j|, N-|i-j|\}$ links. If the network has identical connection probability between nodes, the average number of links of each connection is

$$\bar{L} = \begin{cases} \dfrac{N^2}{4(N-1)} & N \text{ even} \\ \dfrac{N+1}{4} & N \text{ odd} \end{cases} \quad \text{for bidirectional ring.} \qquad (2)$$

Note that the expression in (2) can be well approximated by $N/4$. If all WDM channels in the direction with smaller number of links are occupied, the direction with more number of links can be used.

Comparing (1) and (2), the average number of links that a connection goes through in a bidirectional ring is approximately half of that of an unidirectional ring. In a rough estimation, the bidirectional ring may accommodate twice more connections and thus twice more throughput. If all connections in the network are permanent connections, the best routing scheme may be found to utilize all links and WDM channels in the system. In the optimal case that all resources of links and WDM channels are utilized, with the same number of nodes and WDM channels, the total number of connections is inversely proportional to the average number of links in each connection. Therefore, the bidirectional ring can accommodate approximately twice more connections.

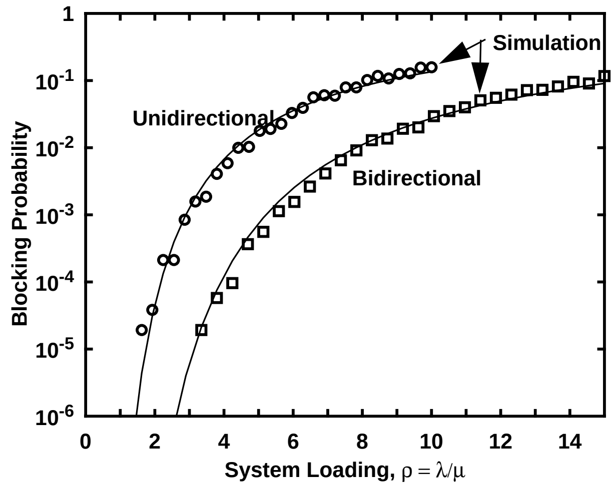



Fig. 4 Blocking probability as a function of system loading for an eight-wavelength ten-node unidirectional or bidirectional multiwavelength optical ring network.

For a circuit switched multiwavelength ring network with connection coming in randomly, a simulation is conducted for an eight-wavelength ten-node unidirectional and bidirectional ring network. Assuming circuit switching with negligible connection setup time, Fig. 4 shows blocking probability as a function of system loading. The system loading is defined as $\rho = \lambda/\mu$, where $\lambda$ is the call arrival rate and $\mu$ is the call service rate. In other words, $\lambda$ is the number of connection request per unit time and $\mu$ is the number of connection served per unit time. The average number of connections in the network is approximately equal to $\rho$ with the difference due to blocking.

In the simulation, both arrival process and service process are assumed to be Poisson process. When a connection is blocked, the request user will not attempt to establish the same connection again. All connections are routed as Section 3.

With the same blocking probability, the system loading of the bidirectional ring is approximately twice the system loading of the unidirectional ring. The simulation results can be accurately fitted to an empirical formula of $\exp(-a/\rho)$. The empirical curve fits are also shown in Fig. 4. Further studies are conducted in progress to find the dependency of $\alpha$ on number of wavelength channels and number of nodes. Further numerical results show that the ratio of $\alpha$-parameters of unidirectional and bidirectional ring is approximately equal to the ratio of average number of links each connection is passed through.

## 5. Demonstration and Experimental Study of Bidirectional WADM

The multiwavelength bidirectional WADM was constructed with a configuration similar to that shown in Fig. 2. The multiplexer/demultiplexer used is an eight-channel interference filter having a channel separation of 200 GHz and an insertion loss of 2.5 dB, similar to those for MONET project [10]-[12]. The channel wavelengths are the same as that of MONET, confined to ITU standard. The demultiplexed channels are boosted by EDFAs with saturated output power of +10 dBm. To avoid SBS, the laser frequency is modulated with a small amplitude sinusoidal tone to broaden the linewidth [13]. The data are encoded by an external intensity modulator modulated at 10 Gb/s NRZ $2^{23}$-1 PRBS. At this bit rate, the receiver sensitivity is found to be -17 dBm at a BER of $10^{-9}$, and the link budget is about 23 dB.

An experiment was designed to simulate the influence of backscattering of neighboring channels and other reflection effects on the transmitting channel. Three independent channels, locating at $\lambda_2$ = 1550.92 nm, $\lambda_3$ = 1552.69 nm, and $\lambda_4$ = 1554.25 nm and all modulated independently at a 10 Gb/s NRZ PRBS by means of delay, were launched with channel at $\lambda_3$ propagating in the forward direction from the headend while channels at $\lambda_2$ and $\lambda_4$ in the backward propagating direction from the added channels in the WADM, as shown in Fig. 5. The transmitter at $\lambda_3$ was connected to the WADM through a 50 km of dispersion shifted fiber. An optical attenutaor was placed near the transmitter end for sensitivity control. The resultant optical spectra at the dropped channel of $\lambda_3$ measuring at a BER of $10^{-9}$ at 10 Gb/s was recorded and displayed in Fig. 5. The crosstalk channels deriving from counter-propagating directions are prominent, and was found to be at -18 dB below the main channel at the worst case at $\lambda_2$ and -33 dB below the main channel at $\lambda_4$. Note that the intensity of the crosstalk channels are not symmetric, owing to the asymmetric properties of the WDM multiplexer and demultiplexer. The BER measurements of the main channel in the presence of crosstalk channels were displayed in Fig. 6, showing little penalty experienced by the data transmission.

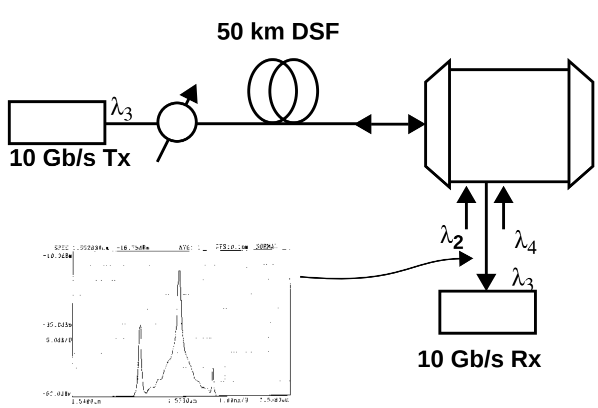



Fig. 5 Experimental setup to evaluate the impact of backward propagating light on the performance of the WADM. The optical spectrum is taken when the BER of the 10 Gb/s signal is around $10^{-9}$.

We also studied the case for all the interfering channels co-propagating with the main channel. The crosstalk level was found to be smaller than -25 dB below the signal channel, giving that all channels have the same intensity. Comparing the crosstalk level of -25 dB in unidirectional operation with that of -18 dB in bidirectional operation, bidirectional WADM may require higher crosstalk rejection in the WDM multiplexer and demultiplexer.

The bidirectional WADM structure can be modified as a bidirectional amplifier module to pass through channels but without channel add/drop function. Fig. 7 shows the demonstration of bidirectional amplification for a 150 km DSF optical link in which the bidirectional amplifier was inserted at the halfway of the system. Similar previously described add/drop experiment, the transmitting channel at $\lambda_3$ was launched in the head node in the forward direction while two wavelength channels at $\lambda_2$ and $\lambda_4$ were transmitted in the end node propagating in the backward direction. Experimental results show that adjacent counter-propagating channels have very small effect on the forward transmitting channel at $\lambda_3$, generating a power penalty smaller than 0.3 dB. An optical spectrum measurement in the forward direction by inserting an optical splitter at the output of the amplifier module was also shown in Fig. 7. The amount of crosstalk was found to be minimal. BER measurements were also performed with and without the adjacent channels, and the results are shown in Fig. 8.

In our experiment, each EDFA in the WADM is individually pumped by a pump laser. The cost of the WADM can be reduced by using shared pump source [14].

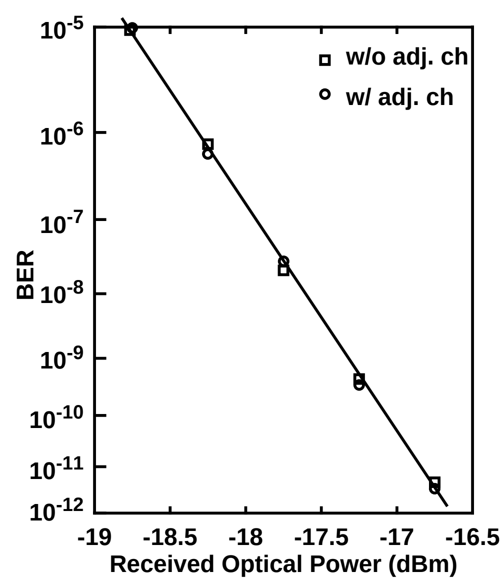



Fig. 6 BER as a function of received optical power for a 10 Gb/s signal at $\lambda_3$ with and without counter-propagating adjacent channels. The setup is Fig. 5 for evaluating the effect of back-propagating light.

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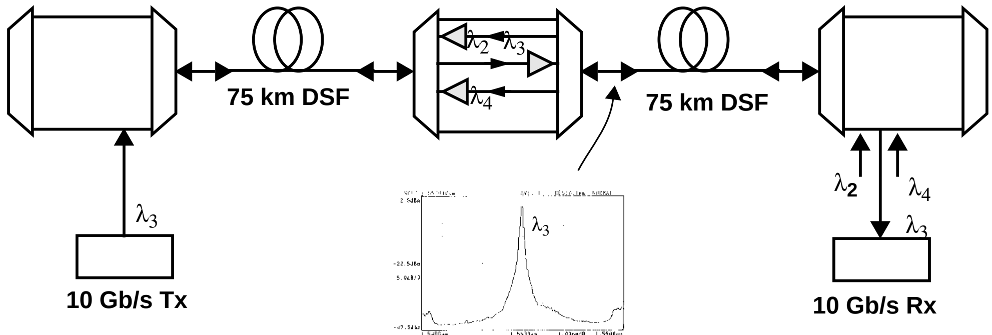


Fig. 7 Experimental setup to demonstrate the application of the WADM as a bidirectional optical amplifier for a 150 km system.

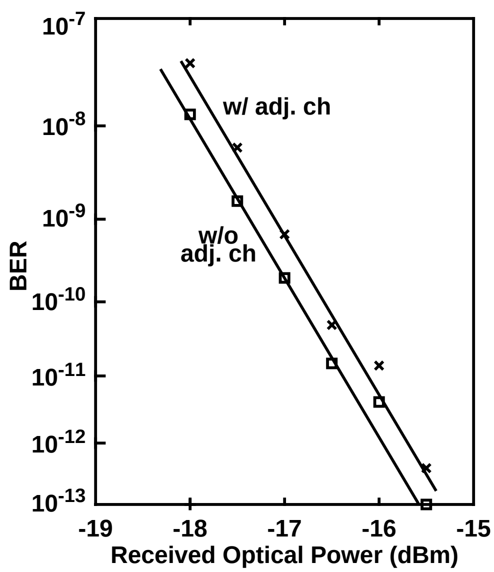


Fig. 8 BER as a function of received optical power for a 10 Gb/s signal at $\lambda_3$ with and without counter-propagating adjacent channels for a 150 km bidirectional system shown in Fig. 7.

## 6. Summary

Bidirectional WDM network could be of interest because of its unique capability of utilizing the bidirectional propagation feature of the optical fiber. Simple estimate suggests that bidirectional ring network offers twice the capacity when compared with traditional unidirectional ring network, which is confirmed by detailed simulation based on an eight-channel system. A bidirectional WADM was designed and demonstrated with a 10 Gb/s data transmission per channel in an eight channel system. The performance of the bidirectional WADM is shown not to be suffered from the backward propagating light induced by Rayleigh backscattering, stimulated Brillouin scattering, or other reflection effects. Slight modification can change the bidirectional WADM to bidirectional optical amplifier module, providing optical amplification and gain equalization for each individual wavelength channel.

## 7. References


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