Optical amplifiers in broadcast optical networks: A survey

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Abstract

Optical data networks are needed to meet ever increasing bandwidth requirements. Broadcast optical networks can provide easy and reliable implementation of optical networks, but due to limited power budget, the number of users supported are limited. The optical amplifiers (OAs) can be used to increase the number of users supported by the network. In this paper use of semiconductor optical amplifiers (SOAs) and doped fiber amplifier (DFAs) is being surveyed in several broadcast topologies, e.g. bus, star, tree etc..

1 Introduction

In the recent past various new types of communication services have been envisaged which require extremely large bandwidth. Few examples of such high bandwidth services are video conferencing, HDTV, video-on-demand, remote surgery and real-time virtual reality via Internet. The bandwidth required by these application is of the order of few 100 Mbits/sec to few Gbits/secs. In the scenario, when such services will be used extensively, the backbone as well as access network have to use optical fiber. Consequently, optical networks have been a topic of immense interest world-wide.

The optical networks can be classified as switched and broadcast networks. In switched networks optical switching is used to route the optical signal [**?**, **?**]. Implementation of such networks requires optical switching techniques. In broadcast optical networks, the transmitted optical signals are received by all the nodes. Therefore in the implementation of braodcast networks passive components can be used for distribution of optical power. Consequently, broadcast optical networks are much simpler to implement. One can look at these networks as the networks where switching is performed at the destination nodes. The nodes for which the optical signal is destined, process the received signal and the remaining nodes ignore the received signal. Therefore, switching complexity lies with the nodes in broadcast networks and within the communication media in switched networks. One of the major limitations of the broadcast networks is the small number of supportable nodes. It happens due to distribution of optical signal which implies splitting of the optical power. If there are N nodes and transmitted optical signal with power P_T watts, each user will receive P_T/N watts. If signal is destined for only one user, $(N-1)P_T$ watts is wasted. But we gain in terms of simplicity of networks while paying in terms of optical power. The above loss of power is termed as splitting loss and causes the limitation in number of users.

The limitation on supportable number of users can be alleviated by using either transmitters with higher power levels or receivers with better sensitivity. There are other options also like opto-electronic regenerators and optical amplifiers. The optoelectronic regenerators are unreliable because of optical-to-electronic (O/E) conversion and vice-versa. Another problem is that in wavelength division multiplexed (WDM) networks separate opto-electronic regenerators are required for all WDM channels. Comparatively, the advantages of using OAs are: (i) signal remains optical (no O/E and E/O conversion), (ii) signal is amplified independently of modulation format and (iii) all the WDM channels can be amplified by a single device.

Consequently, use of optical amplifiers in optical networks has been studied by many researchers. In this paper, use of OAs in broadcast optical network topologies has been surveyed. The paper will give insight in the issues involved in using OAs in various topologies and how the topological optimization is affected? In the next section the basics concepts of OAs are described. In section 3, the focus is put on the placement of OAs in various topologies. In the last section conclusions and various problems for investigations has been posed before the engineering community.

2 Optical Amplifiers

An optical amplifier uses stimulated emmission to amplify the optical signal [**?**]. In the stimulated emission phenomenon an excited ion, atom or molecule emits a photon whenever a photon of same frequency interacts with it. The emitted photon will always have same direction and phase as the stimulating photon. Some of the photons are also emitted spontaneously. In any optical source, generally sponataneous emission is dominant over stimulated emission. In order to create an optical amplifier stimulated emission should dominate sponataneous emission. This will happen when population inversion is created in the medium. Therefore to create an optical amplifier population inversion is needed [**?**] which is created and maintained by a suitable pumping method. The population inversion means that population of excited ion, atoms or molecules is more than the population of ion, atoms and molecules in ground state.

Whenever an optical signal passes through a medium having population inversion, the signal gets amplified. During the process of amplification, the excited ions, atoms or molecules come to ground state. This in turn affects the population inversion and hence amplifier gain. The above is percieved as drop in amplifier gain with increase in input optical power. This drop commonly known as gain saturation is generally modelled by [?]

$$G = G_0 \exp\left(-\left(G-1\right)\frac{P_{in}}{P_{sat}}\right) \tag{1}$$

Here G is saturated gain, G_0, the unsaturated gain i.e, the gain of amplifier when input optical power P_{in} is zero and P_{sat}, the saturation optical power of amplifier.

As mentioned before spontaneous emission is also present in any amplifier. Small amount of this spontaneous emission gets amplified and comes out alongwith signal as amplified spontaneous emission (ASE) noise. The ASE noise is generally modelled as white noise with power spectral density

$$S_{sp} = n_{sp}\left(G-1\right)h\nu \tag{2}$$

Here n_{sp} is spontaneous emission factor, G, the amplifier gain, h the Plank's constant and ν the frequency of optical signal. The value of n_{sp} generally lies between 1.5 and 3.0.

The OAs can be made using different materials and different pumping methods can be used to create population inversion. Two types of OAs which are very commonly used in communication are semiconductor optical amplifiers (SOAs) and doped fiber amplifiers (DFAs) The SOAs are basically semiconductor lasers which operate below lasing threshold [?]. The population inversion in these is achieved by means of electrical energy. An SOA has two end facets, and the reflectivities of these facets decide whether the device will operate as an SOA or a semiconductor laser. When the facet reflectivities are zero, input signal passes through the device only once. Such an amplifier is called travelling wave amplifier (TWA). When reflectivities are non-zero but quite small, the signal passes back and forth through the cavity several times. The small amount of reflectivity of end facets cause ripple in gain profile. If these ripples are small enough the device can be used as optical amplifier with very small degradation. Such an SOA is called Fabry-Perot amplifier (FPA) [?].

In DFAs, optical fiber core is doped by rare earth elements e.g. erbium [?, ?, ?], praseodymium [?, ?] etc.. These amplifiers like SOAs also use stimulated emission for amplifying the optical signals. In contrast to SOAs, population inversion in these amplifiers is achieved by optical pumping. The basic scheme for optical pumping is as shown in Fig.1. A wavelength selective coupler is used for combining the information signal and the pump signal. When these signals travel in a doped fiber, power at the pump wavelength λ_p is absorbed and it creates population inversion. The signal at λ_s, the signal wavelength, amplifies as it passes through the doped fiber core having population inversion. The pump power is generated by semiconductor laser diodes at suitable wavelengths (e.g. 980 nm and 1480 nm for EDFAs). In Fig.1, both pump and information signals propagate in the same direction. Such type of pumping scheme is called forward pumping. It is also possible to introduce the pump power at the second coupler so that pump and information signal travel in the opposite directions. This pumping scheme is referred as backward pumping. Both forward and backward pumping can also be used simultaneously and referred as bidirectional pumping. In forward pumping, as the pump power reduces along the propagation direction, the population inversion also reduces. The signal amplification depends upon the population inversion profile along the length of doped fiber. For higher amplification, more population inversion is desired over the larger length. For a given population inversion profile, there is an optimum length of doped fiber which maximises the overall gain [?].

The gain of OAs reduces when the input signal power increases. This is called gain saturation. As the signal power is different for bit 1 and 0 in an intensity modulated system the gain for bit 1 and 0 is expected to be different. This gain variation for bit 1 and 0 depends on the relaxation time of excited ions/atoms. In DFAs, the relaxation time is of the order of few milliseconds. Therefore, signal at very high bit rate ($\geq 10^3$ b/s) experiences same amplifier gain for both bit 1 and 0. In contrast to this, the relaxation time in SOAs is of the order of few nanoseconds. This means that at high bit rates ($\approx 10^9$ b/s), gain for bit 1 and 0 would be different in SOAs. Due to this, fluctuations in gain for bit 1 and 0 are more in SOAs than in DFAs. Therefore, there is comparatively less crosstalk due to gain saturation in a WDM system with DFAs. The crosstalk arises due to cross-saturation effect in which the gain in desired channel reduces due to the presence of other channels when WDM signals are amplified by OAs.

The most significant application of optical amplifiers is for amplifying the optical signals in communication links. This increases the regenerator spacing in power budget limited optical fiber links. In a point-to-point link, OA can be used as (i) postamplifier, (ii) preamplifier and (iii) in-line amplifier. Postamplifier implies that an OA is used just after the transmitter. It is also possible that OA is integrated with the source to form a high power optical source. In this application, OA with higher saturation power level is desired to reduce the effect of gain saturation. DFAs can be used for this application because of their high saturation power level. However, such a high power optical source would be very bulky. When an optical amplifier is used as a preamplifier, it is placed just before the receiver. This can also be integrated with the receiver to form a high sensitivity receiver module. The OAs in this application must produce low ASE noise. Higher value of saturation power level is not required as in postamplifiers. In-line amplifiers are used in the optical fiber link itself [**?**, **?**, **?**, **?**]. DFAs are better suited for this application because these can be easily spliced in the link resulting in very small coupling loss. There exists an option of remote pumping which will eliminate the need to lay electrical cable to the amplifier's pumping source to supply the required electrical energy. Further, the signal polarisation does not affect the gain of these amplifiers because of their circularly symmetric cross-section. In contrast to DFAs, there is a large coupling loss (≈ 3.5 dB/facet typically) in SOAs and gain varies with input signal polarisation. The gain sensitivity to signal polarisation in SOAs can be reduced by using various techniques. Few of these are mentioned in [?, ?]. The SOAs have two distinct advantages over doped fiber amplifiers. These are: (i) SOAs can be easily integrated in integrated optic transmitter/ receiver modules and (ii) they are available over a wide wavelength range ($0.8\mu m$ - $1.55\mu m$).

Fiber optic broadcast networks also suffer from power budget limitation as the transmitter power is distributed among all the users. Consequently, the number of users are restricted by the transmitter power level. Use of OAs will increase the available power budget and hence the number of users supported.

3 Optical Amplifiers in Broadcast Networks

As mentioned above, OAs can be used in passive broadcast networks for increasing the number of supportable users. Ideally, in a good passive broadcast topology the number of OAs should be minimum for a given number of supportable users. Conversely, number of supportable users can be maximized for a given number of OAs. Both ways should lead to optimal utilization of OAs. The optimal utilization can be achieved by (i) proper placement of OAs in a given network topology and (ii) modifying the existing topologies to utilize the OAs effectively. Many studies have been made to investigate the effective utilization of OAs in various topologies e.g. bus, ring, star and some multilevel topologies. In the following, above studies and their results are surveyed.

3.1 Bus

Bus topology is very popular in copper based networks. It requires less copper cable as compared to other topologies. Further, there are standard media access control protocols e.g. IEEE 802.3 which can be easily implemented on bus. When the bus is implemented using optical fiber, the major problem is non-uniform received power at the nodes. The same signal is received at different power levels at different nodes. Consequently a node can recieve a wide range of optical power levels depending on which node is transmitting. Therefore, receivers with large dynamic range are needed to support more users [**?**]. In a typical bus one cannot support more than twenty users [**?**]. Use of optical amplifiers can keep the recieved power more uniform in bus and hence resulting in support of more number of users.

The SOAs can be placed in a single channel bus with uniformly ditributed nodes such that there are M nodes between two consecutive SOAs (Fig.2) [**?**]. In this topology, M will depend on dynamic range of receivers. The structure (Fig.2) cannot be repeated indefinitely because of noise and gain saturation in SOAs. The number of SOAs which can be used are limited. In order to determine this limit one should consider the signal which is transmitted from one end of bus and recieved at the other end. This will be case of worst case degradation in the signal. When this signal passes through SOAs, the ASE noise accumulates leading to more gain saturation. Consequently the SOAs near the receiver at the other end becomes ineffective. Therefore putting more SOAs is of no use.

Wagner [**?**] has done the analysis and showed that if the bus operates in wavelength range of 1.3 - 1.5 μm with direct detection, noise bandwidth of 10^{12} Hz, $M = 1$ and $\beta = 0.25$, then the number of nodes are limited to less than 500 with the use of InGaAsP base SOAs. This shows the impact of using OAs on a bus topology. There is a large increase in supportable number of users.

3.2 Dual Bus

Dual bus topology is quite popular in high speed networks. One of the popular implementations of dual bus is distributed queue dual bus (DQDB) (IEEE 802.6 protocol) based metropolitan area networks (MANs). DQDB consists of two buses which carry data in opposite directions. The data packets are transferred in time slots which are generated by nodes called Head of the Bus (HoB) (Fig.3). Both the buses use optical fiber for connecting the two consecutive nodes on the bus. The fiber is basically used as point-to-point link (Fig.3). This network has a disadvantage of being unreliable since failure of a node will split the network leaving it unoperational. A solution to this problem is provide by the use of fiber optic bus with passive access. The passive access to bus can be provided to nodes using 2x2 couplers. Since the transmitted power is going to be distributed the number of nodes supported by the network will gets limited. One disadvantage of using passive access is that slot reuse can not be done. Koai and Olshansky [?] have investigated use of OAs in such a passive dual bus in terms of increase in the number of nodes. The scheme is shown in Fig.4. In this figure, NI stands for node interface. In Fig.4a, the square blocks with triangle inside, signifies the attachment of node to fiber. The detail of these blocks are shown in Fig.4b and 4c. Two wavelengths λ_c and λ_d are used in this scheme (Fig.4b and 4c). The wavelength λ_c is used to broadcast the clock signal and λ_d to transmit and receive the data. As the network is supposed to operate at 10 Gb/s, broadcast of clock signal on λ_c is essential. This is because at such a high bit rate, clock recovery and synchronisation is very difficult. Use of clock at λ_c and data at λ_d, requires compensation of phase delays due to environmental variations (e.g. temperature). The noise and gain saturation of SOAs have been considered in the above. It has been shown that a photonic dual bus using OAs with unsaturated gain of 12 dB and saturation power level of 4 dBm can support 100 nodes spanning hundreds of kilometres [?]. Therefore, such a network is suitable for implementing wide area networks (WANs) or metropolitan area networks (MANs) applications. The study can be extended to WDM dual bus networks which can support multiple data channels.

3.3 Ring

Point-to-point links with optical fibers have been used in ring topology for about two decades. Fiber distributed data interface (FDDI) is such a high speed ring network designed with fiber as the transmission medium [?, ?, ?]. Ring has also been proposed for self healing synchronous optical network (SONET) architectures. In these self healing rings, reliability is increased by creating alternate paths and providing isolation of faulty links. FDDI uses two counter rotating rings. It employs a loopback mechanism in case of node failures for high reliability. In all these ring networks, the fiber is used as point-to-point link. One can also use passive optical rings since these can provide high reliability because failure of a node will not break the ring. But these have power budget constraints, limiting the number of nodes which can be used on it. This problem can be overcome to a great extent by using optical amplifiers. Such a passive ring using distributed erbium doped fiber amplifier has been proposed by Goldstien [?]. The scheme is shown in Fig.5. The ring uses erbium doped fiber throughout its length. The nodes are connected to the ring using 2×2 couplers. The pump power is inserted in the ring through a WDM coupler. In the analysis of this ring structure, g/α is considered to be a constant along the ring. Here, g is the gain coefficient and α the attenuation coefficient of the fiber in the ring. It was shown that when g is less than α, ASE noise power spectral density within the ring attains a constant value which is quite low even when $\alpha - g \ll 1$. Thus distributed optical amplification can be used in the ring to increase the supportable number of users. It has been shown by Goldstien [?] that a 300 km ring at 2.5 Gb/s cannot support even a single user without amplifier, but with the distributed amplification over 450 users can be supported. In the above study, following assumptions have been made. Pump power is assumed to cause such a population inversion profile that g/α is constant throughout the ring. Some other factors which restrict the number of users are ignored e.g. (i) dynamic range of receivers, (ii) back reflection at various points and (iii) remnants of recirculating optical signals. The analysis given by Goldstien can be extended to include all these factors to determine exact performance. Further, on can do the analysis for the WDM systems.

3.4 Star

Ideally, star topology distributes optical power equally at output ports. Therefore, it can support maximum number of users without OAs as compared to any other topology. At the present level of technology, number of users supported by star is small (typically ≤ 64). Detailed study on the use of SOAs in star topology for WDM network has been made in [?, ?, ?]. In the above, two placement options of SOAs i.e., postamplifiers and preamplifiers in a star network (Fig.6) are analyzed and compared. In postamplifier scheme SOAs are placed after the transmitter and in preamplifier scheme just before the receiver. The star coupler in Fig.6 is a multistage star coupler made of many 3 dB 2×2 couplers. It is assumed in the study that each user transmits on a dedicated wavelength. All the transmitted signals are broadcast to all the receivers. The receivers use optical filters to select the channel to be received.

When the two placement options are compared it is seen that the different degrading factor exist in both the schemes. In postamplifier scheme, the gain saturation effect is more prominent as compared to preamplifier scheme. The effect of ASE noise is less in postamplifier scheme as it suffers more attenuation. In preamplifier scheme, multiple channels are amplified but as these channels are statistically independent, the gain saturation effect is less, but crosstalk due to gain saturation is present. The effect of echoes due to reflection has also been studied and it was found that with increasing number of users, the degradation due to echoes reduces. In preamplifier scheme, degradation due to reflection is more as the amplifier reflection coefficient will be higher because of less gain saturation as compared to postamplifier scheme.

The SOAs in the above have been assumed to be travelling wave amplifiers (TWAs), gain saturation and ASE noise has been considered in these amplifiers. The study shows that use of SOAs increases the number of users in both the schemes, and the preamplifier scheme is better as it can support more number of users as compared to postamplifiers scheme for a typical WDM star network. There is one drawback that number of SOAs are always equal to number of users in the scheme.

In the literature, many modified topologies which utilize star couplers and OAs have also been proposed [?, ?, ?]. These can support higher number of users as compared to a passive star topology. The star couplers in the above can be either transmissive or reflective or both. In reflective star coupler, input and output ports are same. The user transmits the signal in a given port and receives the signal from all other users at the same port [?]. The propagation direction of transmitted and received signals are opposite in the port. Two schemes of distributed reflective star couplers which use erbium doped fiber amplifiers (EDFAs) to increase the supportable number of users have been proposed in [?]. In both the schemes, 4×4 couplers having an EDFA as shown in Fig.7 is used as basic element. An 8×8 star coupler can be made using these 4×4 couplers and 2×2 couplers as shown in Fig.8. Following the same approach, star coupler of larger size can be constructed using smaller size couplers. In the first scheme (Fig.9), m number of $m \times m$ star couplers are used. Implementation of each $m \times m$ coupler requires $m/4$ EDFAs and $6m/4 + (m/2)\log_2(m/4)$ number of 2×2 couplers [?]. It can be seen from Fig.9 that the reflective star made of m number of $m \times m$ star couplers can support $N_u = m^2$ number of users. In this scheme, one output port of each $m \times m$ coupler is terminated with a mirror and other $(m-1)$ ports are connected to remaining $(m-1)$ number of $m \times m$ couplers. A 16×16 distributed reflective star coupler based on this scheme is shown in Fig.10.

In the second scheme (Fig.11), $2m$ number of $m \times m$ couplers are used to implement a distributed reflective star coupler which can support $N_u = 2m^2$ number of users [?]. The $m \times m$ couplers are being grouped to form m pairs. In each pair, one output of each $m \times m$ coupler is connected using 2×2 reflective star coupler (shown by hashed block in Fig.11). Each pair of $m \times m$ couplers is connected to every other pair by a 2×2 transmissive coupler. A 32×32 reflective star coupler based on this scheme is shown in Fig.12. In these star couplers, less fiber is required as compared to a centralized star coupler. The EDFAs are shared by all the users. In the above proposition, no mention has been made regarding the utility of these stars in a WDM system. The use of above star in a WDM system will require wide bandpass filters in EDFAs. Further, the required gain of EDFAs for a given number of users is not given, which is needed in the design of such systems. Also the injection of pump in EDFAs will require wavelength selective coupler.

Another star coupler configuration using EDFAs in WDM/FDMA network (Fig.13) has been proposed in [**?**]. WDM/FDMA network means that the signal spectrum consists of many frequency band at different wavelengths. Each band contains many channels which are wavelength multiplexed with very narrow spacings. In this scheme, there is one central coupler of dimension $m_c \times m_c$. All other couplers are auxiliary couplers and can have any dimensions. There are m_c wavelength bands and an unique wavelength band is allocated to the users on an auxiliary coupler. Each wavelength band has multiple channels to be used for transmission by the users on the corresponding auxiliary coupler. When an user on the auxiliary coupler AC1 transmits the signal on a wavelength channel in the assigned band W_1, it is broadcast to all the users on the same coupler. A part of the signal is transmitted to central coupler. At the input, only the wavelength band W_1 is allowed to pass through by means of an optical bandpass filter (BPF). This filter allows only the signals from users on AC1 to be passed, which are then amplified and broadcast to the other auxiliary star couplers. The output fiber connected to AC1 from central star coupler contains a bandstop filter (BSF) for wavelength band W_1. Ideally, the use of BSF prevents the recirculation of the optical signal in wavelength band W_1. One of the output ports of $m_c \times m_c$ central star coupler can be used as an input for the pump power for all the EDFAs. This scheme has the advantage that existing networks on auxiliary stars can be easily interconnected. The network size can be easily increased by using auxiliary stars until all the ports of the central star are occupied. Sharing of pump source, amplification of a part of spectrum by EDFAs are the main features of the scheme. The disadvantage is that recirculating signals can produce interference in practical BSFs, which can be minimized by suitably matching the BPFs and BSFs. The $m_c \times m_c$ star coupler must be wideband as the pump signal also traverse through the central coupler.

A few other configurations using star couplers with OAs have been reported in [?, ?]. The star coupler proposed in [?] uses BPFs and BSFs for each wavelength band. This coupler is modified by Yung-Kuang *et. al* [?] and the modified version is shown in Fig.14. This is a $mm_c \times mm_c$ centralized star coupler. The $1 \times m$ and $m \times 1$ couplers can be made using $(m-1)$ number of 3 dB 2×2 couplers as shown in Fig.15. The $m_c \times m_c$ coupler is a transmissive star coupler made of $(m_c/2)\log_2(m_c)$ number of 3 dB 2×2 couplers. Each OA is a forward pumped EDFA as shown in Fig.16. This scheme supports more number of users than $m(m_c-1) \times m(m_c-1)$ coupler [?]. The number of required 2×2 couplers is less than that of star coupler [?] for $m \geq 32$. This coupler does not require dedicated BPF and BSF as in [?].

As each user must be connected to the centralized star coupler, there is a large fiber requirement. The fiber requirement can be reduced by making the above star coupler distributed. This can be achieved by putting the $1 \times m$ and $m \times 1$ couplers with the group of m users. It implies that fiber is required only to connect the $1 \times m$ and $m \times 1$ couplers to $m_c \times m_c$ star. This saves the required fiber as well as the required conduit length for fiber layout. Further, the number of $1 \times m$ couplers can be reduced by using reflective $m_c \times m_c$ star coupler. The resulting $mm_c \times mm_c$ coupler is shown in Fig.17. The above modification also reduces the required fiber to half as compared to the star shown in Fig.14 as the transmitted signal and signal to be received share the same fiber while propagating in opposite directions. These signals can be separated by using diplexers at the user ends. The $m_c \times m_c$ reflective star coupler can be made by using a $m_c \times 1$ coupler whose single port is terminated by a mirror (Fig.18). There are also two other possible ways to form a $m \times m$ reflected star coupler. These are already shown in Figs.9 and 11.

3.5 Tree

A broadcast tree topology was first proposed by Gerla [?] and is named as tree-net. It is more general than star and can be considered as two level topology made of star and folded bus. The SOAs have been considered in this topology for increasing the supportable number of users [?, ?]. The SOAs are placed in the star portion of the tree-net (Fig.19).

The tree-net under consideration is assumed to support WDM channels. Users on each branch use a dedication wavelength for transmission allocatted to the branch. Therefore there are b wavelength corresponding to b branches in the topology. To place the amplifiers it is assumed that signal will pass through only one amplifier while going from source to destination. Due to the above condition, maximum number of amplifiers that can be placed are equal to b. There are two possilities to place the SOAs: (i) before the root and (ii) after the root. This study considers the placement after the root as shown in Fig.20. If number of amplifiers (N_a) to be used in the topology is less than b, a star coupler made of $log_2(N_a)$ stages of 3 dB couplers is used. The amplifiers are placed at the output of the resulting N_a x N_a star coupler. The size of this coupler is increased to b xb by using 3 dB 2x2 couplers as combiners and splitters at the input and output. An example of $8x8$ coupler with four amplifiers is shown in Fig.20. In this study [?, ?], three cases were considered i.e., (i) unsaturated SOAs, (ii) average gain saturated SOAs and (iii) average gain saturated SOAs with gain fluctuations.

The results for a typical tree-net were computed [?, ?] and it was observed that use of SOAs increases the supportable number of users. Further one will expect that increasing number of SOAs will correspondingly increase the supportable number of users, but this does not happen always. Comparison of tree-net with star shows that tree-net can support same number of users for less number of SOAs. For example, star topology requires 256 SOAs for supporting 256 users, while the tree-net requires only 64 SOAs. It is also observed that tree-net had wider choice of supportable number of users. This is because the tree-net topology is a multilevel topology.

4 Conclusions

In this paper, configurations of various topologies which use the OAs have been reviewed. In most of the studies, degrading effects due to OAs have not been considered. Therefore, these give an upper bound on the supportable number of users. There are studies which have incorporated the various degrading factors in SOAs [?, ?, ?, ?]. In [?, ?], it is seen that tree-net uses SOAs more effectively than star. From the above it is deduced that multilevel topologies are expected to use OAs more efficiently. Some new schemes have also evolved in last few years to use the OAs more efficiently. But their practical implementation require some specialized devices e.g. mirrors for terminating the ports and 2×2 reflective star couplers.

It is concluded that more accurate analyses are needed to compute the supportable number of users in most of the studies done so far. Since all the studies use very wide range of parameters and devices it is extremely difficult to make the quantitative comparison. Therefore, only a qualitative comparison can be done for the schemes using similar kind of devices. One can observe that most of the recent studies are use EDFAs. This is because i) EDFAs can provide very high gain, ii) have less cross gain modulation and iii) are more compatible with fiber. Doped fiber amplifiers are well suited to distributed star coupler, bus and ring based networks. In centralized star couplers, SOAs are better options because they can be embedded within the integrated optic implementation of star coupler blocks. The SOAs are also better suited as post or preamplifiers since these can be integrated with either the transmitter or the receiver chips. Finally, it is concluded that OAs will form very important component in all the future optical networks and their characterization and performance evaluation in networks need further investigations. Wherever we can embedd the OAs within integrated optic block, SOAs will be preferred and when it has to be inserted in a fiber link, DFAs will be preferred. Moreover future seems to be heading towards multilevel topologies with OAs in them for implementing broadcast optical networks.

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Fig.14 Star coupler with amplifiers and without bandpass and bandstop filters.

Fig.15 8×1 coupler based on seven 2×2 couplers.

Fig.16 Forward pumped EDFA.

Fig.17 $mm_c \times mm_c$ reflective star.

Fig.18 $m_c \times m_c$ reflective star coupler based on $m_c \times 1$ tree coupler.

Fig.19 Tree-net topology.

Fig.20 8x8 amplified star coupler using four amplifiers.

Biographies of the Authors

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Yatindra Nath Singh was born in Delhi in 1969. He obtained B.Tech. in Electrical Engineering with honours from Regional Engineering College, Hamirpur, Himachal Pradesh in July 1991, M.Tech. in Optoelectronics & Optical Communications from Indian Institute of Technology, Delhi in December 1992 and Ph.D. from department of electrical engineering, Indian Institute of Technology, Delhi in 1997. He was with the department of electronics and computer engineering, University of Roorkee, Roorkee, India as faculty from Feb'97 to July'97. He is currently working as faculty in the department of electrical engineering, Indian Institute of Technology, Kanpur. He is a member of Institution of Electronics and Telecommunication Engineers (IETE), India and The Institution of Electrical and Electronics Engineers, Inc., (IEEE) USA. His academic interests include Optical Computing, Optical Networks, Photonic Switching and Optical Communications. He is also interested in MAC Protocols and Philosophy of Science.

2. Hari Mohan Gupta

Hari M. Gupta received the B.E. degree in Electronics and Communication Engineering from the University of Roorkee in 1967, the M.Tech. degree in Electronics and Electrical Communication Engineering from the Indian Institute of Technology, Kharagpur in 1969, and the Ph.D. degree in Electrical Engineering from the Indian Institute of Technology, Kanpur in 1974. He has been with the Department of Electrical Engineering, Indian Institute of Technology since 1973, and a Professor since 1986. He was a Visiting Associate Professor at the Department of Electrical Engineering, McGill University, Montreal, Canada during September 1979–August 1980, and at the Department of Electrical and Computer Engineering, Drexel University, Philadelphia, U.S.A. during September 1984–December 1985.

He established Photonic Systems research and initiated Telematics Programme at IIT, Delhi. His academic and research interests are Computer Communication Networks, Photonic Information Systems and Networked Multimedia Systems.

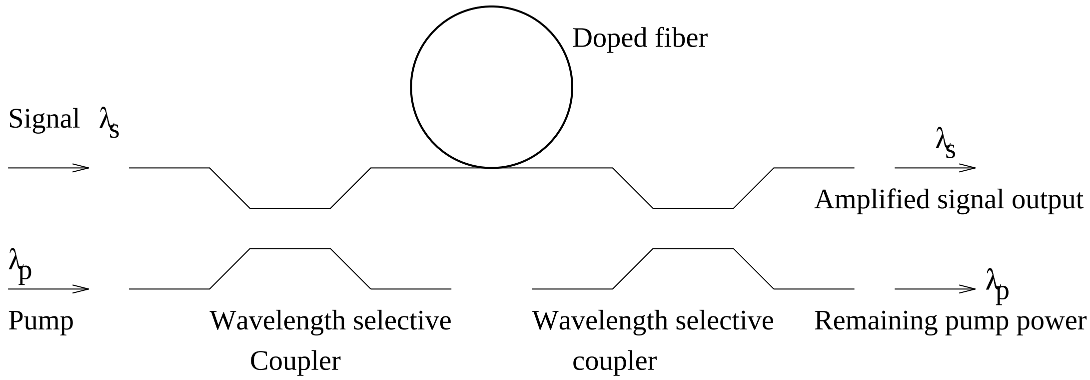
He is a fellow of the Institution of Electronics and Telecommunication Engineers, a fellow of Institution of Engineers (India), senior member of the Computer Society of India, member of the Systems Society of India and a member of the Indian Society for Technical Education. He has been India's representative in International Federation of Information Processing (IFIP)-TC-6 Committee on Communication Systems, and the Vice-President of the Systems Society of India. Currently, he is a member of IETE council.

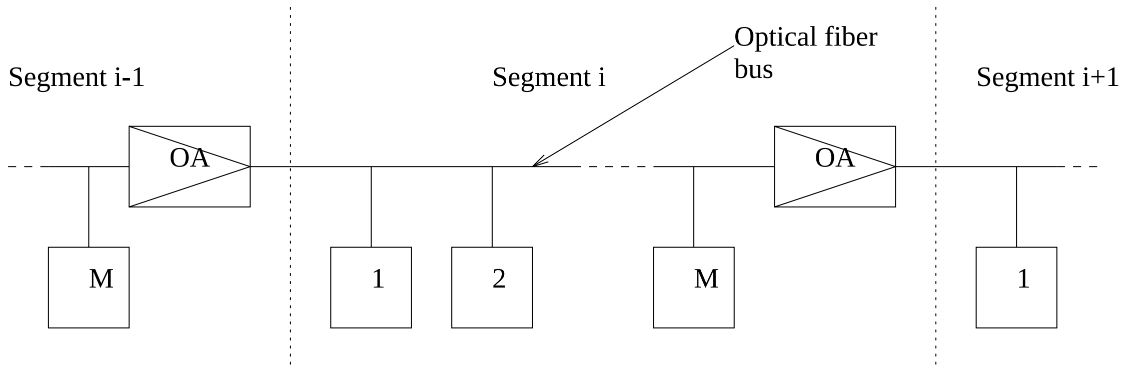
3. Virander Kumar Jain

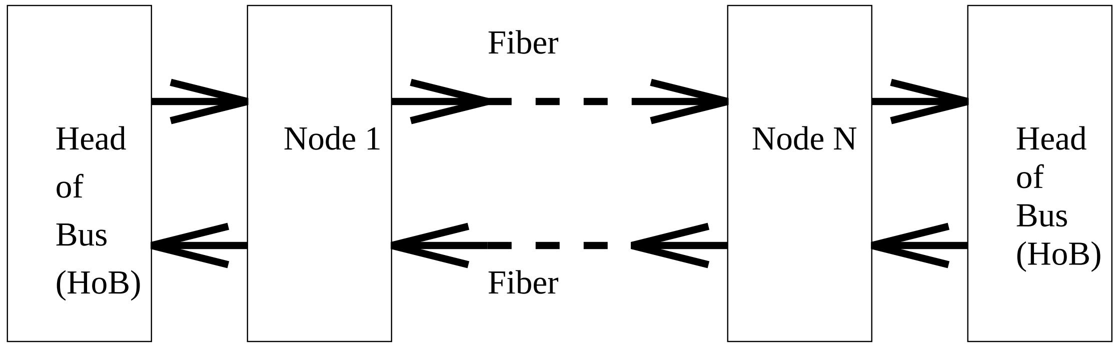
Virander K. Jain obtained M.Sc.(Tech) in Electronics from BITS Pilani in 1975 and Ph.D. in Digital Communications from IIT Delhi in 1982. During 1978-82, he worked as a Research Officer with the Research Department, All India Radio, New Delhi. Since December 1982, he has been on the faculty of the Electrical Engineering Department, IIT Delhi and currently he is Professor. He has worked at the British Telecom Research Laboratories, Ipswich, U.K. for six months (January–June'88). He has also worked at the Institute for Communication Technology, German Aerospace Research Establishment, Germany (February'91–January'92 and March–June'95) and Fachbereich Elektrotechnik, Fachhochschule Düssledorf, Düssledorf, Germany (January–March'95) as an Alexander von Humbolt research fellow. He visited the International Centre for Theoretical Physics (ICTP), Trieste, Italy in February–March'86 to attend a workshop on Optical Fiber Communications. He visited ICTP again in May–July'89 and May–June'95 as an Associate Member.

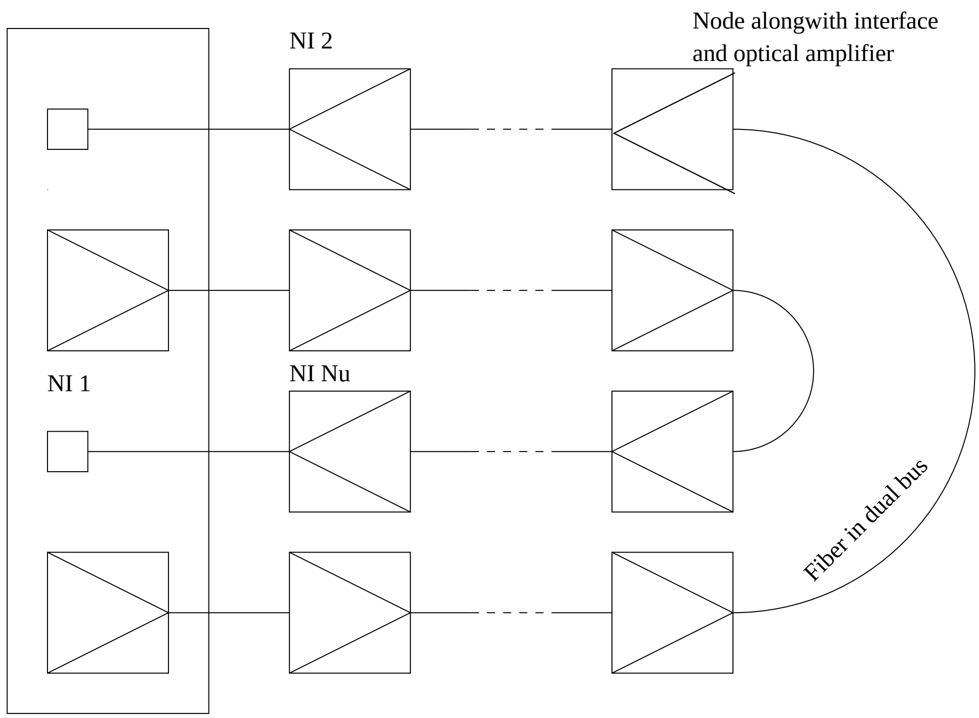
Dr. Jain's research interests include Digital Communication Systems, Signal Detection in Noise and ISI, Optical Communications, Computer Networks etc.. He has published 55 research papers/reports in various national and international journals. He has co-authored a book on Optical Communication Systems published jointly by Narosa Publishing House and John Wiley & Sons.

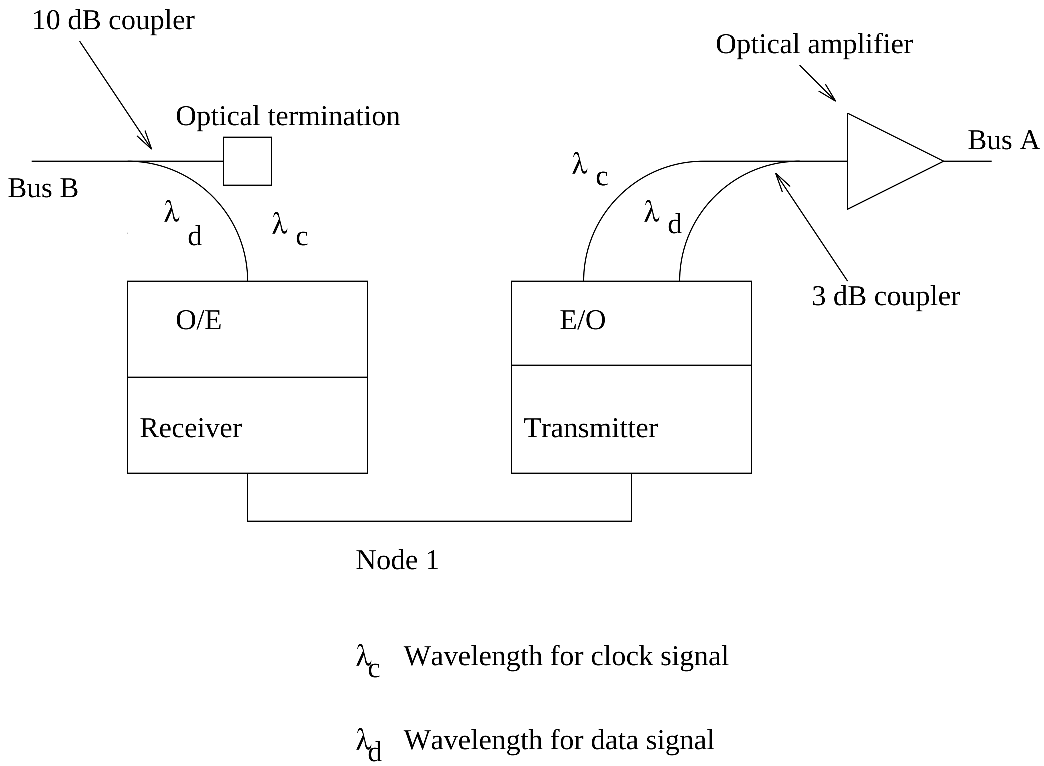
He is a life member of Indian Society for Technical Education (ISTE) and a Fellow of Institution of Electronics and Telecommunication Engineers (IETE), India.

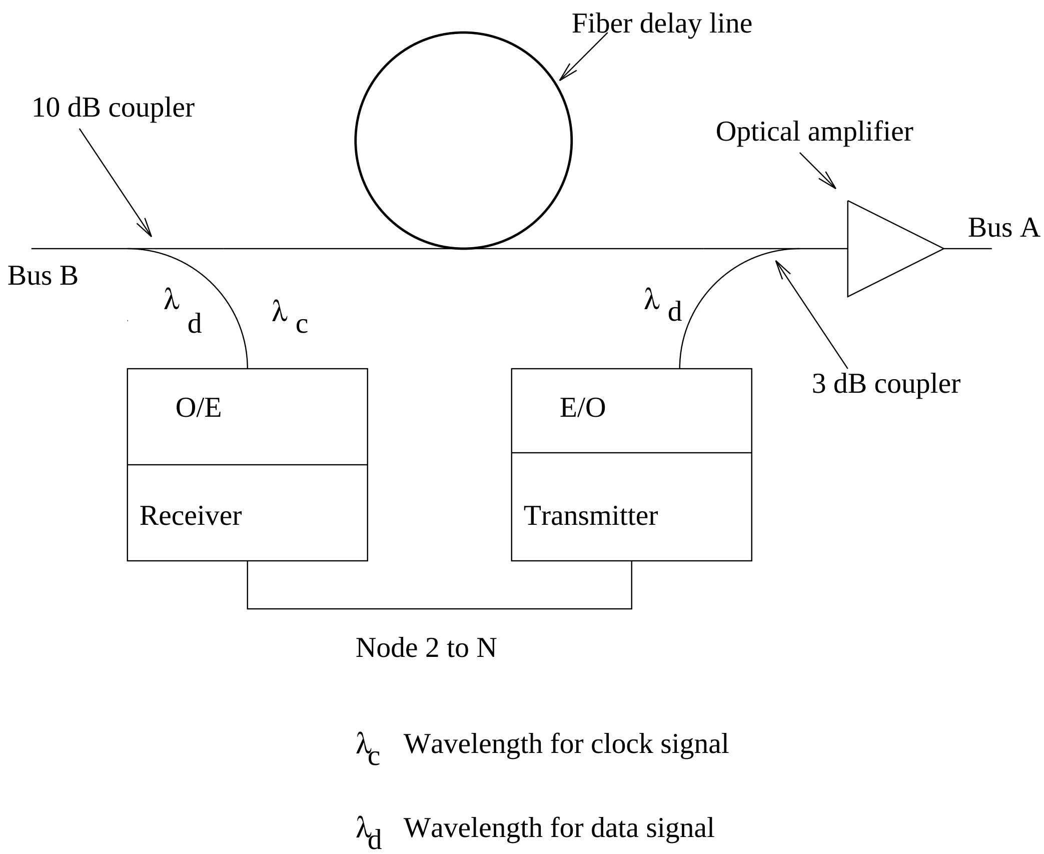

Doped fiber
Signal λ_s
λ_s
Amplified signal output
λ_p
λ_p
Pump
Wavelength selective Coupler
Wavelength selective coupler
Remaining pump power

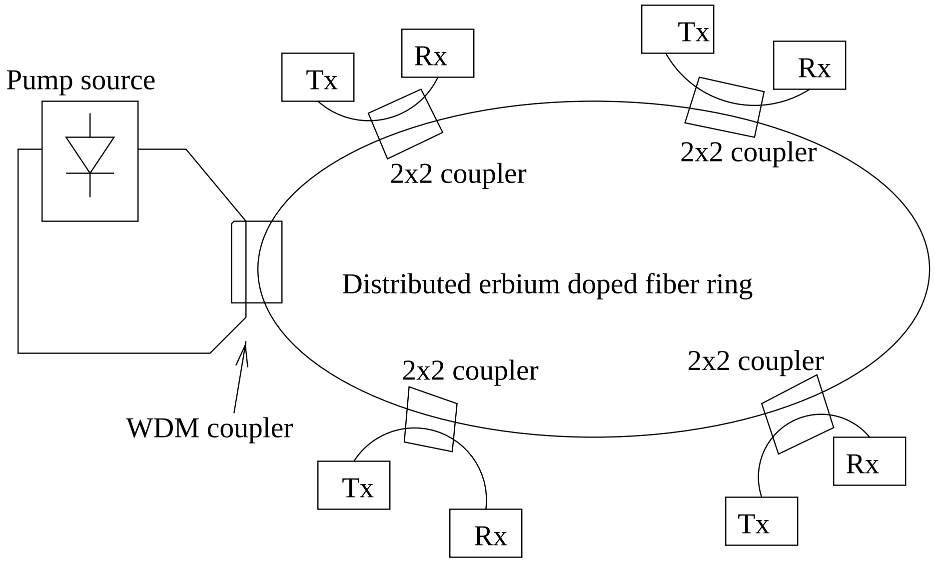

Segment i-1
Segment i
Optical fiber bus
Segment i+1
OA
OA
M
1
2
M
1

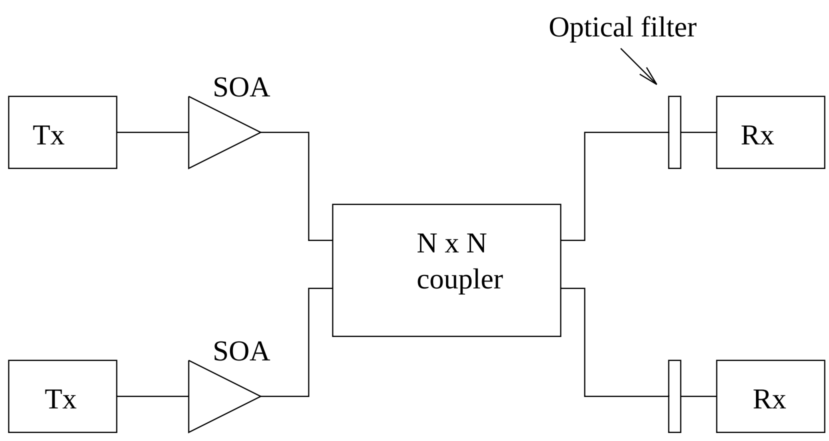

Fiber
Head of Bus (HoB)
Node 1
Node N
Head of Bus (HoB)
Fiber


Node alongwith interface
and optical amplifier
NI 2
NI 1
NI Nu
Fiber in dual bus

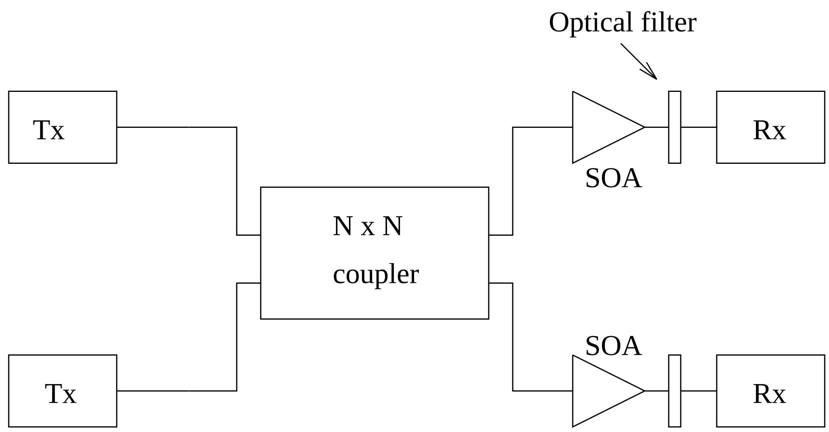

10 dB coupler
Optical termination
Optical amplifier
Bus A
Bus B
λ c
λ d
λ c
λ d
3 dB coupler
O/E
Receiver
E/O
Transmitter
Node 1
λc Wavelength for clock signal
λd Wavelength for data signal


Fiber delay line
10 dB coupler
Optical amplifier
Bus A
Bus B
λ d
λ c
λ d
3 dB coupler
O/E
Receiver
E/O
Transmitter
Node 2 to N
λc Wavelength for clock signal
λd Wavelength for data signal

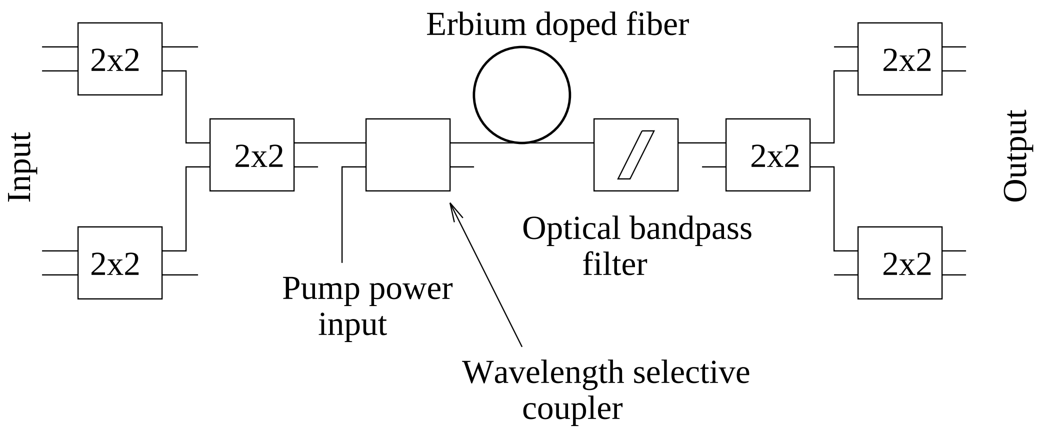

Pump source
Tx
Rx
Tx
Rx
2x2 coupler
2x2 coupler
Distributed erbium doped fiber ring
2x2 coupler
2x2 coupler
WDM coupler
Tx
Rx
Rx
Tx



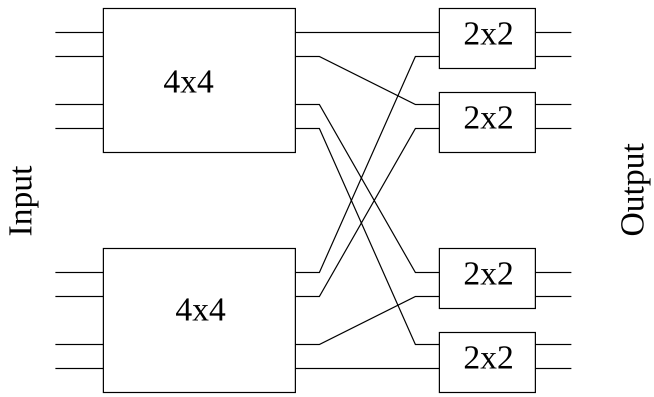
SOA - Semiconductor Optical amplifier

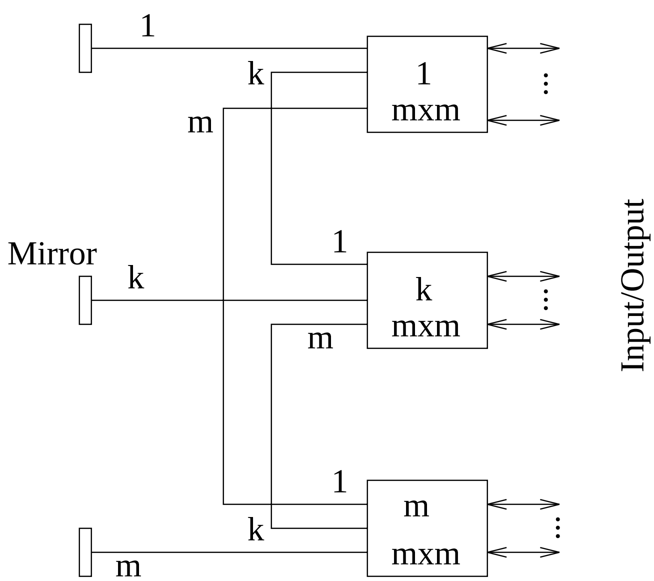


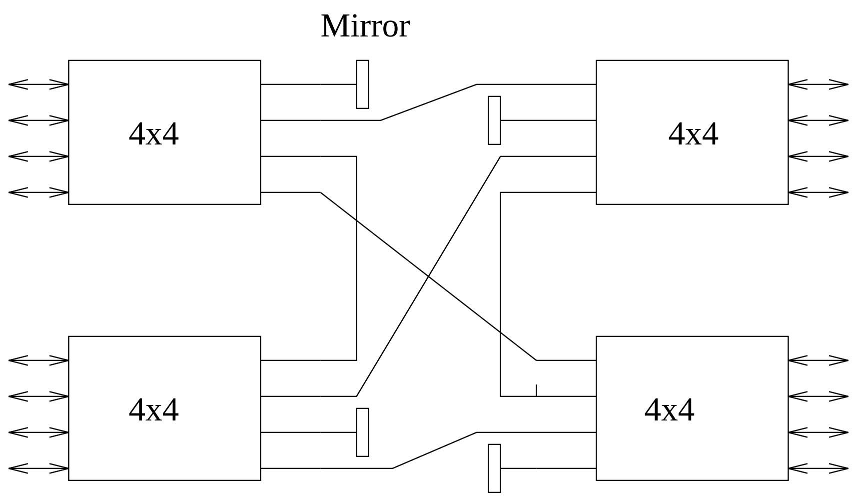
SOA - Semiconductor Optical amplifier

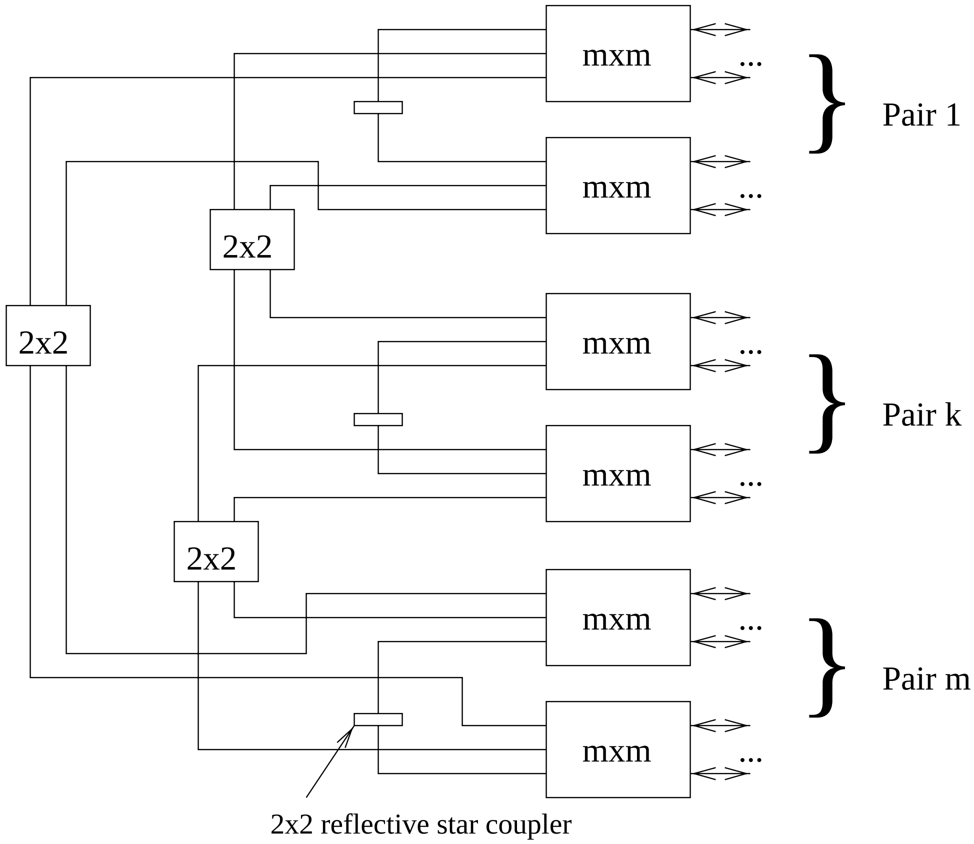


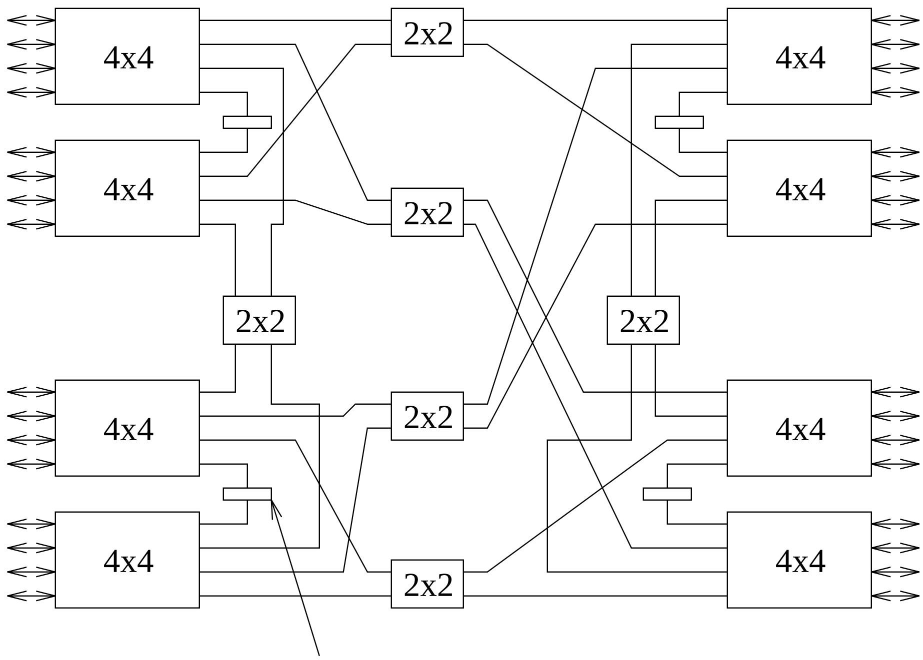
Erbium doped fiber
2x2
2x2
2x2
Input
Pump power
input
Optical bandpass
filter
Wavelength selective
coupler
2x2
2x2
2x2
Output


Input
4x4
4x4
2x2
2x2
2x2
2x2
Output

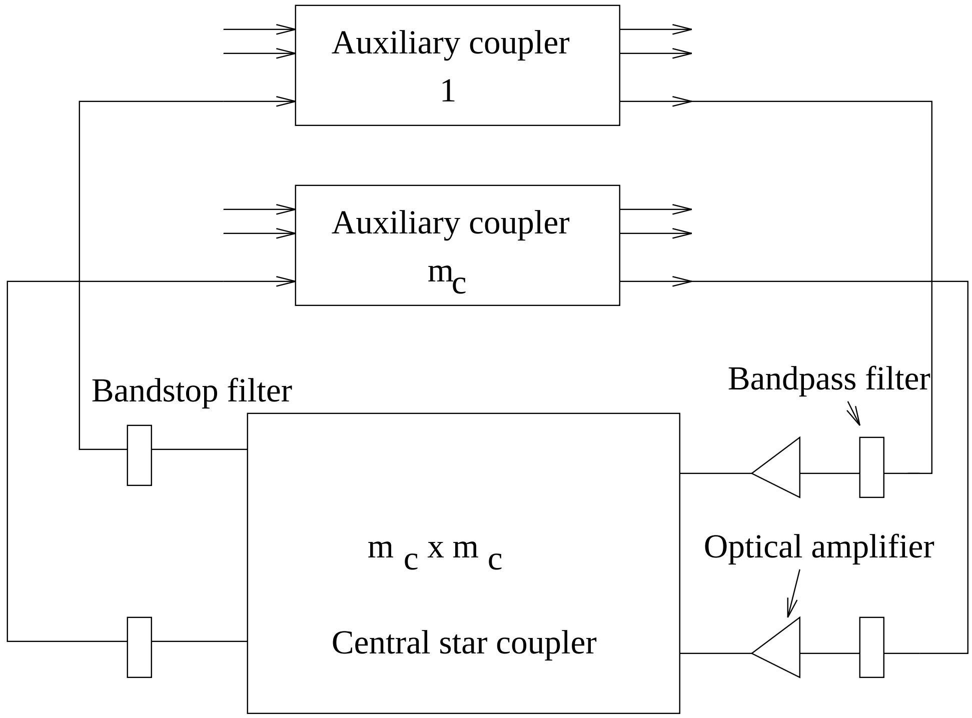

1
k
m
1
mxm
Mirror
k
1
k
mxm
m
Input/Output
1
m
mxm
k
m

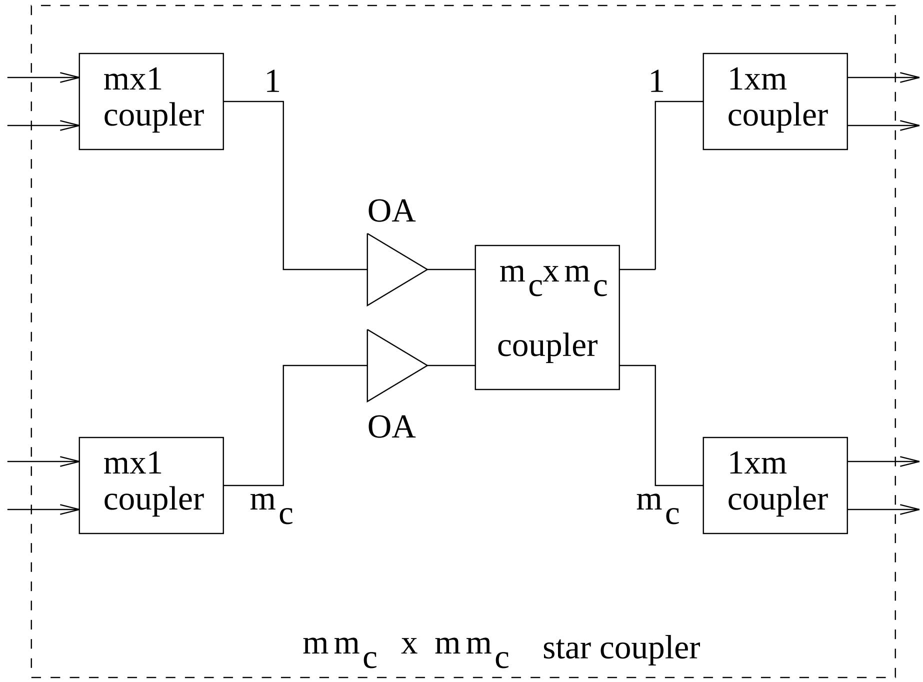

Mirror
4x4
4x4
4x4
4x4

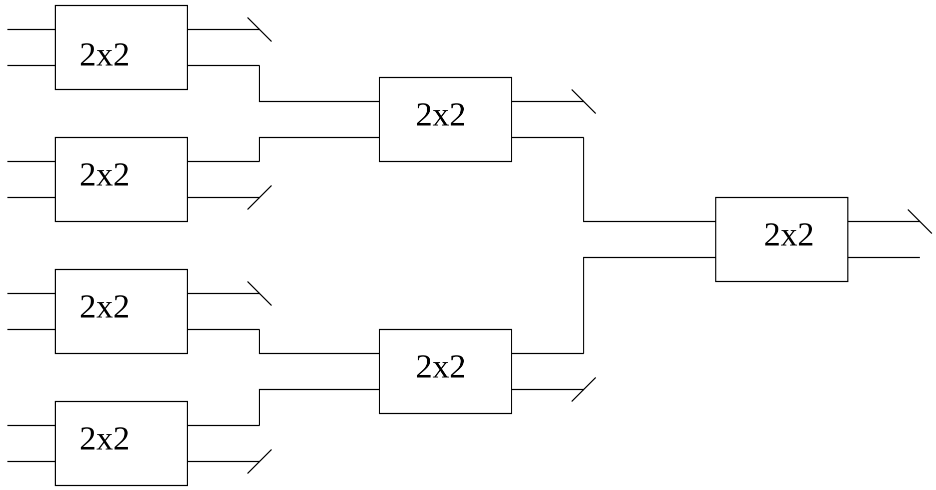

mxm
mxm
mxm
mxm
mxm
mxm
2x2
2x2
2x2
Pair 1
Pair k
Pair m
2x2 reflective star coupler

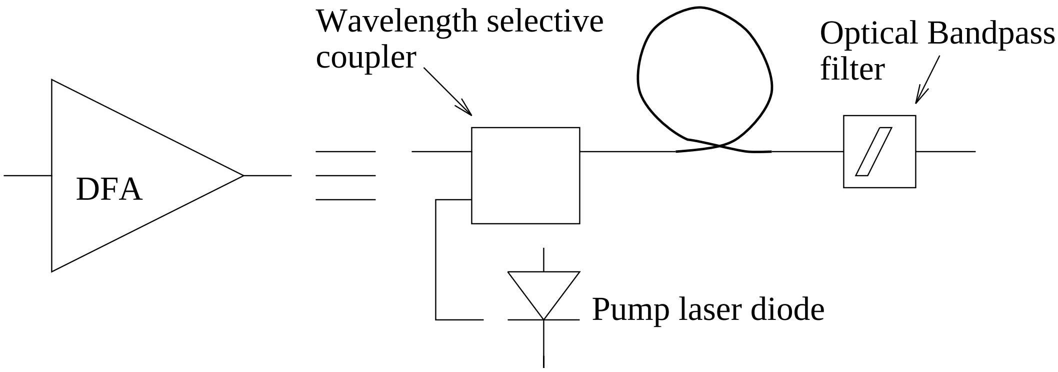


2x2 reflective star couplers

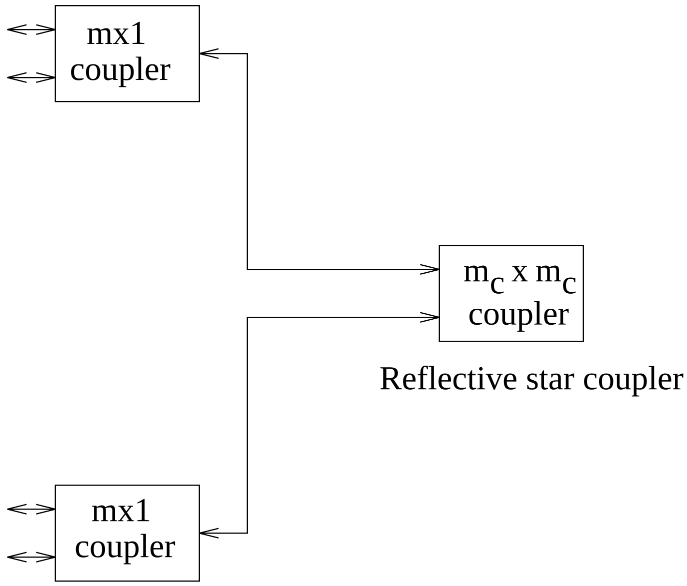

Auxiliary coupler
1
Auxiliary coupler
mc
Bandstop filter
Bandpass filter
m c x m c
Central star coupler
Optical amplifier

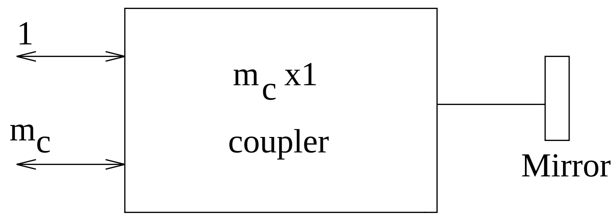

mx1
coupler
1
mx1
coupler
m c
OA
OA
m c x m c
coupler
1
1xm
coupler
m c
1xm
coupler
m m c x m m c star coupler

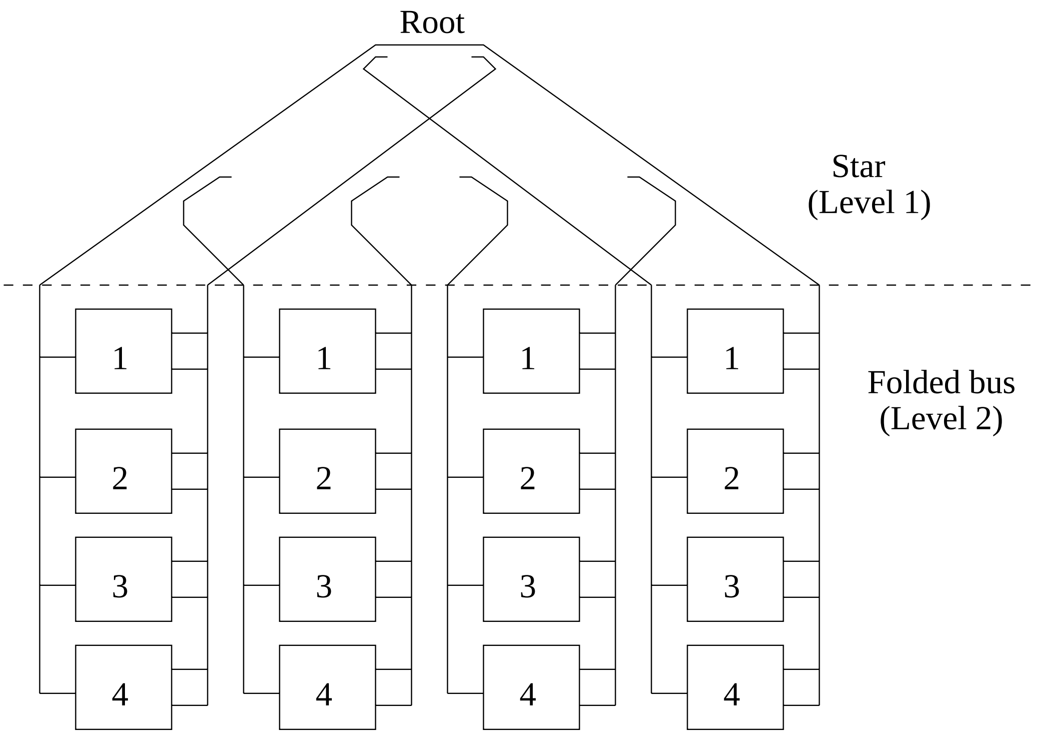

2x2
2x2
2x2
2x2
2x2
2x2
2x2



DFA - Doped fiber amplifier


mx1
coupler
m_c x m_c
coupler
Reflective star coupler
mx1
coupler


1
m_c
m_c x1
coupler
Mirror


Root
Star
(Level 1)
Folded bus
(Level 2)
1
1
1
1
2
2
2
2
3
3
3
3
4
4
4
4