Chapter 1

Optical Access Networks

Passive Optical Networks (PONs) are emerging as the ultimate solution for high speed access networks. All-fiber components are ideal for passive optical networks because of many inherent advantages such as low forward and return losses and high power handling capability. This chapter reviews the architecture and optical component technologies used in PON. This chapter also presents the relevance of the research work.

Optical Access Networks

Since its conception [1-3] in late 1980's, Passive Optical Network (PON) is emerging as a promising solution for "last mile" access, because of the potential of optical transmission and the advantages of PON's architecture. PON based broadband access systems have now adopted for wide-scale deployments in Asia, Europe and North America [4], owing to the growing need for broadband access and maturing of the relevant technologies. However, PON technologies are still in the process of evolution to cater to the growing need of economic broadband access.

After a quick overview of access network principles in section 1.1, this chapter continues with a description of optical access network topologies (section 1.2). Section 1.3 introduces the basic architecture of PON, its advantages, optical power budget and the evolution of PON standards. Section 1.4 describes the various optical technologies for power splitting and wavelength division multiplexing.

1.1 Broadband Access Networks: An Overview

Access network is the network between Central Office (CO) and end users and is traditionally called last-mile networks. They are also called first-mile networks in recent years as they are the first segment of the broader network seen by users of telecom services [4]. The "last mile" is the most expensive part of the network because there are far more end users than backbone nodes [5]. Example of access networks are i) twisted copper pairs connecting to each individual household ii) residential coaxial cable drops from community antenna TV (CATV) service providers. Wi-Max is another type of access technology which uses radio waves for last-mile connectivity. Traditionally, optical fibers have been widely used in backbone networks because of their huge available bandwidth and very low loss. However, until the beginning of this century, fiber has not been used as the technology of last-mile connection.

The most widely deployed "broadband" solutions today are Digital Subscriber Line (DSL) and Cable Modem networks. There were 367.7 million broadband subscribers globally at the end of the first quarter of 2008 and 65% of them are using the DSL technology [6]. Although broadband copper-based access networks provide much higher data rate than 56 Kbps dial-up lines, they are unable to provide enough bandwidth for the tremendous growth of Internet traffic, emerging services such as Video-On-Demand, High Definition Television and interactive gaming, or two-way video conferencing. The maximum physical reach of DSL is about 6km @ 2Mbps and

0.3km @ 53Mbps [7]. The physical reach and channel capacity of DSL almost have reached the limitations of the available copper cabling.

In the last decades, optical networks have experienced substantial growth with the deployment of optical fiber in metro and core network segments. DWDM (Dense Wavelength Division Multiplexing) based high capacity systems provide ever increasing bandwidth to meet the growing needs of both voice and data communication [8]. However, optical fiber access networks are far behind and just beginning to penetrate a market largely dominated by copper-based solutions. Local Area Networks (LANs) using emerging fiber technology can provide a high-capacity, high-speed access network system that is inexpensive, simple, scalable, and capable of delivering bundled voice, data and video services to an end-user over a single fiber plant.

1.2 Optical Fiber Access Networks

Local loops using optical fiber for access connections are called fiber-in-the loop systems [9-12]. Fiber access systems are also referred to as fiber-to-the-x (FTTx) system, where ‘‘x’’ can be ‘‘home,’’ “building”, ‘‘curb,’’ ‘‘premises,’’ etc., depending on how deep in the field fiber is deployed or how close it is to the user. In a fiber-to-the-home (FTTH) system, fiber is connected all the way from the service provider to household users. In an FTTC system, fiber is connected to the curb of a community where the optical signal is converted into the electrical domain and distributed to end users through twisted pairs. Therefore, an FTTC system can also be regarded as a hybrid fiber twisted pair system.

FTTx which brings high-capacity optical fiber networks closer to the end users, appears to be the best candidate for the next-generation access network. FTTx is considered an ideal solution for access networks because of the inherent advantages of optical fiber in terms of low cost, huge capacity, small size and weight, and its immunity to electromagnetic interference and crosstalk. Today, the maximum demonstrated information capacity of an optical fiber exceeds 100 Tb/s for a typical DWDM system with coherent detection [8]. Because of the costs involved, such systems probably will be limited to core and backbone networks. Since optical fibers are widely used in backbone networks, Wide Area Networks, and Metropolitan Area Networks, the implementation of the FTTx in access networks will complete the all-optical-network revolution.

Fiber access systems can be point-to-point (P2P) or point-to-multi-point (P2MP). Moreover, they can use an active remote distribution node such as an Ethernet switch or a simple passive splitter as the remote distribution node used in power splitting PONs. Figure 1.1 depicts different architectures of fiber access networks, assuming a number of N end nodes:

a. In the first architecture, there is a direct Point-to-Point (P2P) link between the CO and each end user, so N fibers and 2xN transceivers are needed to support N customers. The speed of the terminal equipment equals to the data rate for end users.
b. In the second architecture, there is a P2P link between the CO and the curb switch while the links between the curb switch and the end users are also P2P. So the link between the CO and the curb switch is now shared between the N end users. This approach needs 2x(N+l) transceivers (1 at the CO, N+1 at the curb switch and N at the end user side). The speed requirement of the terminal equipment also is the data rate for end users;
c. In the third architecture, the CO and end users are connected by a Point-to-Multi-Point (P2MP) link. Compared with the second architecture, the curb switch is now replaced by a wavelength multiplexer/demultiplexer. As each user has its own corresponding transceiver at the CO side, this architecture needs 2xN transceivers. The required speed of the terminal equipment is the same as a and b;
d. The last architecture shares the same topology as the previous one with a passive optical splitter/coupler instead of the WDM and it reduces the cost further by sharing a single transceiver at the CO side among all the end users. Then only N+1 transceivers are needed in total. The speed of the terminal equipment equals to the sum of data rate for all end users.

The network topology of the last two architectures is normally referred as a PON, where only passive optical devices are used, namely fibers and splitters or combiners. Various solutions based on a shared PON network architecture are adopting different transfer technologies, to support integrated services and multiple protocols. The PON architecture was proposed as a way to share the large fiber bandwidth among many users through a passive splitter, and hence improve the per user cost of FTTH. In fact, NTT adopted P2P architectures in some early FTTH trials [13]. Another type of PON called WDM-PON uses a wavelength multiplexer as the remote distribution node [12]. PON architectures will be described in detail in the following sections. Although FTTH was in trial for a long time since its proposal, the high cost of fiber-optic components and lack of killer applications for the high bandwidth offered by optical fibers have been barriers to its real applications.

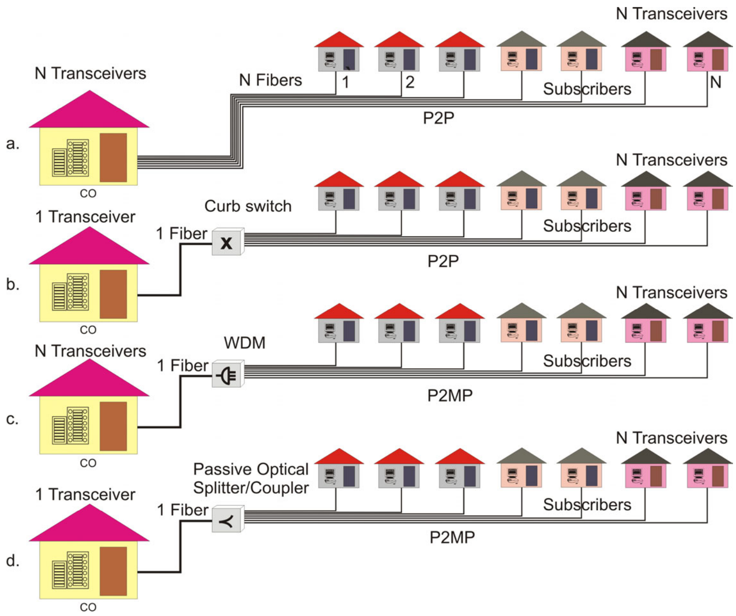

Figure 1.1: Different architectures of access network

1.3 Basic Architecture of a PON

Figure 1.2 depicts a common PON architecture supporting different FTTx scenarios. The optical elements used in such networks are only passive components, such as fibers, splitters/couplers and connectors. The optical path that consists of these components is called the Optical Distribution Network (ODN). The Optical Line Terminal (OLT) resides in the CO, connecting the optical access network to an IP, ATM, or SONET backbone. An Optical Network Unit (ONU) is located at the curb (FTTC solution), or an Optical Network Terminal (ONT) is located at the end user location (FTTH, FTTB solutions), to provide broadband voice, data, and video services with guaranteed Quality of Service. While FTTB and FTTH solutions have fiber reaching all the way to the customer premises, FTTC may be the most economical deployment today [14], leaving room for alternative technologies such as DSL or even wireless to implement the last drop.

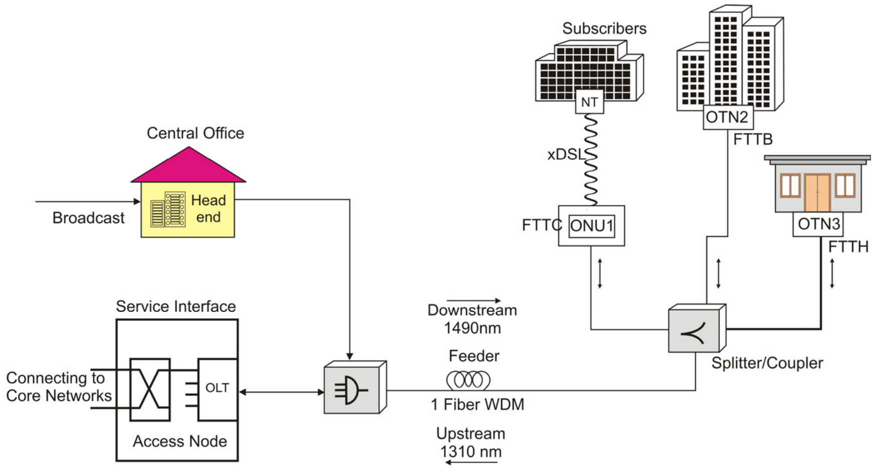

Figure 1.2: PON Architecture (FTTx Scenario)

All transmission over the ODN of the PON occurs from or towards the OLT, as ONUs or ONTs do not communicate directly with each other. The P2MP transmission from the OLT to ONUs/ONTs is called Downstream, and the P2MP transmission from ONUs/ONTs to the OLT is called Upstream. In most PON implementations, the downstream and upstream optical signals in the drop section, close to an ONT, are shared over a single fiber for cost reasons. Closer to the OLT, in the feeder section, it is more common to use separate fibers for up- and downlink. The wavelengths of uplink and downlink signals can be the same, but usually separate wavelength bands are used, as this makes the network more robust against optical reflections, and reduces the losses associated with up- and downlink combination and splitting. Upstream and downstream signals are multiplexed (combined) or demultiplexed (split) from the fiber using coarse WDM filters at the CO and the subscriber premises.

1.3.1 Advantages of PON Architecture

PON technology is getting more and more interest from the telecom industry as a future-proof "last mile" solution. The benefits of using broadband PON local access networks are numerous, and list a few:

- A PON allows for longer physical reach. While the DSL maximum physical reach is about 6 km, a PON local loop can operate at distances of over 20 km without amplification, as today's optical fiber has much less attenuation than any copper wire.

- Since numerous end nodes share the feeder section fiber(s) between the CO and the passive optical splitter/combiner, a PON minimizes fiber deployment in both the local exchange and the local loop.
- In a PON, E/O components and electrical devices at the CO are shared amongst a large number of subscribers, saving expensive high-speed electrical and optical equipment.
- Due to the high data capacity of fiber, a PON can provide much higher line rates than alternative access technologies. The standardized maximum downstream and upstream line rate of an FSAN PON today is standardized at 2488 Mbps
- Since the bandwidth of a PON is shared by all subscribers, it provides the possibility to use the bandwidth more efficiently by Dynamic Bandwidth Allocation [15, 16]. Hence, the line rate exceeds the available average bandwidth of each PON subscriber by nearly the PON splitting factor. This is especially valuable for accommodating burst traffic, as a single subscriber can communicate at the full line rate during limited time intervals. In contrast, DSL assigns *a* complete P2P link to a single subscriber, so a subscriber cannot exceed the peak subscriber rate and free CO transmission capacity, due to inactive subscribers, cannot be reused.
- As a P2MP network, a PON allows for downstream video broadcasting.
- A PON can reduce the cost of maintenance dramatically, because it eliminates the necessity of installing multiplexers and demultiplexers in the splitting locations, thus relieving network operators from the gruesome task of maintaining and providing power to electrical devices in the field. Instead of active devices in these locations, a PON has optical passive components that can even be buried into the ground at the time of deployment:
- A PON easily upgrades to higher bit rates or additional wavelengths. If a new subscriber wants to join the PON, there is no need to add extra hardware at the CO side, while DSL requires the installation of a new transceiver in the local exchange. When new technologies that support higher bit rates become available, only the end equipment like OLTs and ONTs needs to be extended or replaced.

1.3.2 PON Multiple Access Technology

In the downstream direction, the OLT laser is modulated with a mix of broadcast (all ONTs), narrowcast (some ONTs) and P2P information using a suitable multiplexing mechanism. In fact, PON downstream technology borrows a lot from other continuous, single talker fiber networks. Sharing the feeder section of a PON for upstream communication however is a much more uncommon and difficult task, as a multiple access technology is required that avoids collision between signals transmitted by the different ONTs. Collisions cannot be permitted as the high network delay and data rates would cause excessive network time-outs. The available solutions for multiple access are Wavelength Division Multiple Access, Time Division Multiple Access (TDMA), Sub Carrier Multiple Access and Code Division Multiple Access [17-20].

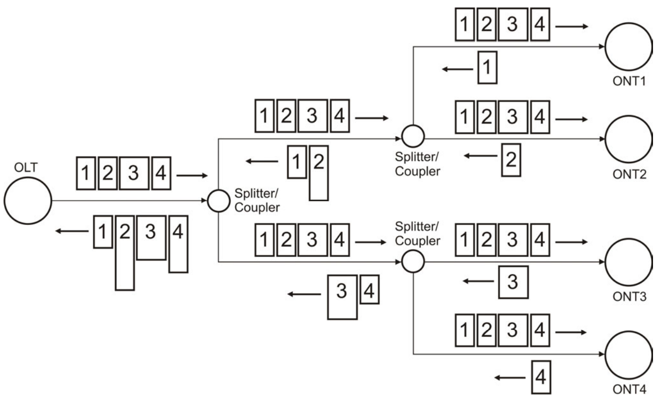

Figure 1.3: Signal transmission in a TDM/TDMA PON

TDMA is the most efficient and most adopted PON multiple access technology today, and allocates the upstream communication of each ONT into time slots that are separated in time upon arrival at the OLT. An ONT can only transmit data within the time slots allocated to it. TDMA gives each ONT a pre-allocated but variable fraction of the single wavelength upstream capacity. Only one transceiver is needed in the OLT (Figure 1.1 d), no matter how many ONTs are connected to it, as long as the downstream optical power budget is not exhausted. Hence TDMA PONs provide an economical solution for the "last mile problem". The signal transmission over a TDM/TDMA PON is illustrated in Figure 1.3. In downstream the data is broadcast across the P2MP ODN from the OLT at the CO side to the ONTs receiving a single wavelength. As each ONT receives all the data, the OLT must label each packet with the ID of the intended recipient. The signal received by each ONT is in

Continuous-Wave mode as in a P2P link, since the OLT is always the only talker. There is no rapid change of the signal amplitude and phase. From this CW downstream, a system clock is extracted from the downstream receiver that is used to synchronize the ONT upstream transmission. During normal operation of a TDMA-PON, each ONT only turns on its laser and transmits a burst of data in its granted time slot, and then quickly shuts its laser off to avoid interfering with other ONTs. This is referred to as burst mode operation. Because the ONTs are at different locations, the drop sections show different fiber lengths with different optical loss, and the amplitude and phase of the upstream signals vary rapidly, from burst to burst, upon arrival at the OLT. In a TDMA-PON each upstream burst is preceded by a burst preamble, allowing the OLT receiver circuits to perform on-the-fly amplitude, clock phase and data recovery. The intervals between bursts also contain guard times to account for the finite switch on/off times of the ONT laser sources.

1.3.3 Optical Power Budget of a PON

The upstream optical power budget of a PON is the difference in dB between the (worst case) upstream optical power launched into the fiber by an ONT and the receiver sensitivity of the OLT. In practice, the minimum and maximum loss an optical signal may experience on its way from OLT to ONT, or when traveling in the opposite direction, is clearly specified. For class A, B and C optical distribution network, the minimum/maximum path loss are 5~20, 10~25 and 15~30 respectively. These losses are mainly due to fiber attenuation, which increases with fiber length, and the 1xN power reduction in each broadband 1xN splitter or combiner. When the PON splitting factor is made high, to support a large number of ONTs from a single OLT the optical losses due to the power splitting and combining will consume most of the optical power budget. So typically a PON may have a high split, but then the maximum range is limited or vice versa. In Equation 1.1, α is the fiber attenuation factor and L is the length of fiber.

$$P_{transmitted} - P_{sensitivity} \geq P_{penalty} + \alpha L + P_{splitter} \quad (1.1)$$

1.3.4 Wavelength Plan in PON

FSAN (Full Service Access Network) study group standardized PONs specifying the 1490 nm wavelength band for downstream signal transmission, the 1310 nm wavelength band for upstream transmission, and 1550 nm as an enhancement band for broadcast services such as CATV (Community Antenna Television) via this broadband overlay. The schematic of the wavelength allocation plan is shown in Figure 1.4. The network installers normally use an out of band test wavelength at 1625nm, for trouble shooting the network.

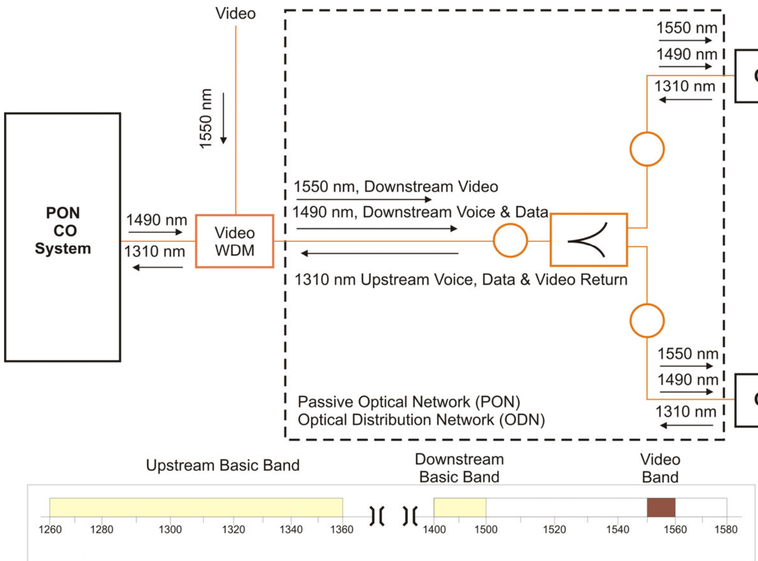

Figure 1.4: ITU-T G.983.3 PON Wavelength Allocation Scheme

1.3.5 Signal Splitting in TDM-PON

The purpose of power splitting include: (1) sharing the cost and bandwidth of OLT among ONUs and (2) reducing the fiber mileage in the field. Apart from the simple one-stage splitting strategy (Figure 1.5 (a)), splitters may also be cascaded in the field as shown in Figure 1.5 (b). In the most extreme case, the feeder fiber forms an optical bus and ONUs are connected to it at various locations along its path through 1:2 optical tap splitters as shown in Figure 1.5 (c). The actual splitting architecture depends on the demography of users and the cost to manage multiple splitters. In a bus or tree architecture like Figure 1.5 (c), if all the splitters have the same power splitting ratio, the furthest ONU will suffer the most transmission and splitting loss and become the system bottleneck. Splitters with uneven splitting ratios may be used to improve the overall power margin. However, such optimization requires stocking non-uniform splitters and is hence difficult to manage. From a management point of view, it is usually simpler to have a single splitter for distribution in the field, which makes splicing easier and minimizes connector and splicing losses. However, distributed splitting architecture is more advantageous when serving clusters of customers, randomly distributed. An example of a distributed splitter solution would be the 1x8 split at the local convergence points with a 1x4 split at each of the network access points.

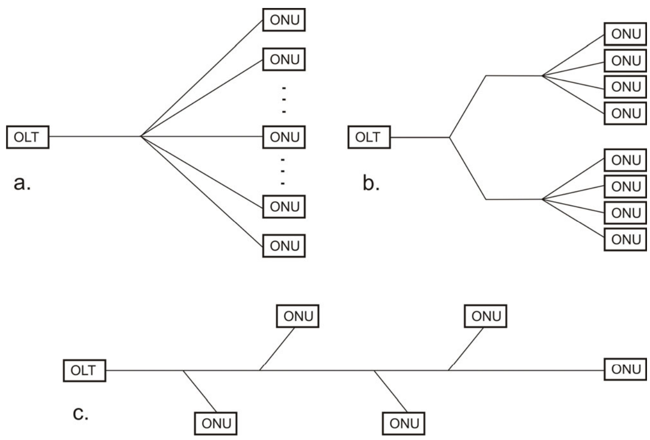

Figure 1.5: Splitting strategies in a TDM-PON: (a) one-stage splitting b) multi-stage splitting and (c) optical bus

Most of the commercial PON systems have a splitting ratio of 1:16 or 1:32. A higher splitting ratio means that the cost of the PON OLT is better shared among ONUs. However, the splitting ratio directly affects the system power budget and transmission loss. The ideal splitting loss for a 1:N splitter is 10*log(N) dB. To support large splitting ratio, high power transmitters, high sensitivity receivers, and low-loss optical components are required. Higher splitting ratio also means less power left for transmission fiber loss and smaller margin reserved for other system degradations and variations. Therefore, up to a certain point, higher splitting ratio will create diminishing returns. Studies showed that economically the most optimal splitting ratio is somewhere around 1:40 [12].

A high splitting ratio also means the OLT bandwidth is shared among more ONUs and will lead to less bandwidth per user. To achieve a certain bit error rate (BER) performance, a minimum energy per bit is required to overcome the system noise. Therefore, increasing the bit rate at the OLT will also increase the power (which is the product of bit rate and bit energy) required for transmission. The transmission power is constrained by available laser technology (communication lasers normally have about 0–10 dBm output power) and safety requirements issued by regulatory authorities [13].

1.3.6 Evolution of PON Standards

Today's PON standards represent the different views and attitudes of two distinct standardization groups looking at problems and finding solutions towards the future of the telecommunication market. Broadband PON (BPON) and Gigabit PON (GPON) are mainly motivated by groups of network providers, who want a high performance platform that can provide full services to end users. Ethernet PON (EPON), which optimizes simplicity rather than performance, presents the consideration of some equipment vendors. The strengths and weakness of the respective standards result from the different considerations.

In 1998 ITU-T released G.983.1, the first in a series of G.983.x recommendations commonly referred to as ATM-PON or Broadband PON (BPON), and drafted by the FSAN study group [21]. It was a first attempt at a PON standard. Various physical layer parameters have been specified in G.983.1 [21], such as the line coding (NRZ with scrambling), minimum receiver sensitivity, minimum and maximum transmit power values both in upstream and downstream. The next-generation ITU-T PON standard is GPON and was designated ITU-T G.984.x. GPON retains the strengths of BPON, corrects its weaknesses, and increases the bit rate to the gigabit range. Concurrent in time, the IEEE has developed an Ethernet-based protocol referred to as EPON [22]. EPON is part of the IEEE Ethernet in the Last Mile initiative and was designated 802.3ah. Although the transport mechanism for EPON is based on Ethernet, there are substantial differences imposed by the very nature of an access network.

1.4 Optical Technologies and Components of PON

The optical technologies for access network have been advancing at a rapid rate, with goals of achieving performance and high reliability in addition to manageability, ease of installation, and upgradeability. Each of these goals bears a direct contribution to the overall capital and operational expenditures of the network. For widespread uptake and deployment, it is imperative that the network be cost competitive to current access technologies. In this section, optical technologies that have been developed to achieve these goals are compared.

Optical power splitter is the central component in a power-splitting passive optical network where its primary function is to split the optical power at the common port equally among all its output ports. The major technologies used to make power splitters include fused fiber technology and planar lightwave circuit (PLC) technology. High reliability, low cost per port, low insertion loss, and high splitting ratio uniformity are essential for splitters for use in passive optical networks. Many leading service providers and component manufacturers consider wavelength division multiplexing (WDM) network as the preferred upgrade solution in order to satisfy high and increasing bandwidth demands. In a WDM-PON, each user is assigned with their own downstream/upstream wavelength channels, enabling dedicated and potentially symmetric downstream/ upstream bandwidths. An arrayed waveguide grating (AWG) serves as the passive WDM mux/demux or a passive WDM routing component at the remote node, replacing the optical power splitter in a power-splitting PON.

1.4.1 Power Splitting Technologies

In a power-splitting PON, an optical power splitter in the outside plant is physically connected to the CO, with a feeder fiber. It also connects to a number of ONUs via a series of distribution fibers. There are different technical technologies used for signal splitting in FTTH system [23]:

- Fused or fused biconical taper (FBT) couplers
- Planar splitter or planar lightwave circuits (PLCs)
- Fused coupler arrays
- Monolithic fused couplers

In a PON-FTTH network, in order to split the incoming signal from the central office to subscribers, regardless of the fabrication technology used and/or the protocol adopted (B-PON, E-PON or G-PON), the passive optical splitter has to guarantee at least four key parameters: broad operating wavelength range, low insertion loss and uniformity in any operating conditions, small footprint and long-term reliability. Aside from uniform loss, the insertion loss of splitters is an important parameter in network implementation that influence system performance and the overall cost per drop. Lower insertion loss splitters will extend the reach and number of customers that can be accommodated within the same PON, yielding higher revenue per PON for service providers.

1.4.1.1 Fused Fiber Technology

A fused coupler is a structure formed by joining two independent optical fibers [24], as shown schematically in Figure 1.6. The claddings of the fibers are fused in a small region. FBT devices work as a result of an energy transfer by coupling between optical fiber cores [25]. Consider two parallel single-mode optical fibers in close proximity. If the evanescent tails of each waveguide have considerable overlap, it can be shown that there are two possible solutions for mode propagation in the two waveguide structure. These are the so-called supermodes or Eigenmodes. The two solutions have symmetric and non-symmetric energy distributions and differing propagation constant values. As the relative phases of the modes change, the energy is shared between the two fibers. At matching and mismatched phases, the energy is alternately maximized in each fiber core, i.e. the energy pulses back and forth between the waveguides. In other words, the energy can be split evenly or unevenly down the fibers. The energy transfer is dependent on the core separation (2r) and the interaction length (z).

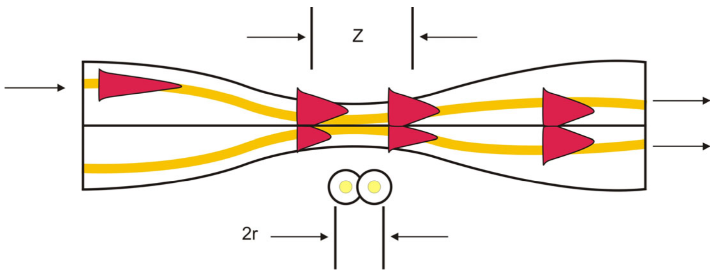

Figure 1.6: Fused coupler technology

A 2x2 coupler is formed, since two separate fibers are fused. To obtain a 1x2 coupler (or splitter) one of the input fibers is cut and terminated suitably to avoid back-reflections from that end. The 1x2 coupler is then mounted on a glass or quartz plate (see Figure 1.7) and put into a metal tube [24], typically of 3 mm diameter. The advantage of this optical coupler type is that the optical signal is always traveling through the same material and therefore offers a reduced loss.

Figure 1.7: Photograph of a 1x2 Fused Coupler

1.4.1.2 Planar Lightwave Circuit Technology

The second type of splitter is made up of integrated optical circuit assembled with an input and an output fiber array as shown in Figure 1.8 [26]. Central to the splitter is a

PLC chip comprising of optical waveguides fabricated on a planar substrate, typically made of silicon or quartz, to form a cascade of Y-branches. For a 1xN splitter, one side of the PLC chip is aligned to a fiber whereas the opposite side is aligned to an array of N fibers, as shown in Figure 1.8. The number of power-splitting fan outs in a PON is typically 16 and 32, but with an increasing demand of up to 64, makes the alignment of the fiber array to the PLC chip more challenging [27].

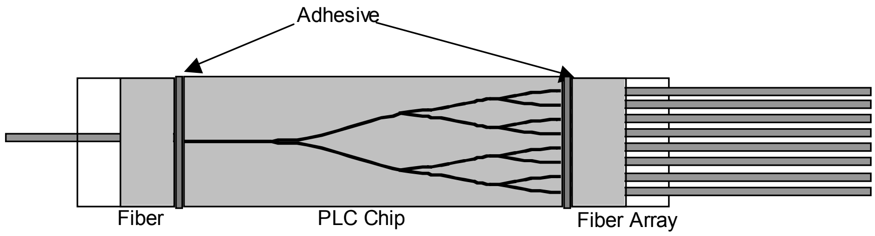

Figure 1.8: Internal structure of a 1x8 PLC splitter

There are three principal fabrication processes for Planar Lightwave Circuits (PLC) [28-33], Ion exchange with glass substrate, Plasma-enhanced chemical vapor deposition and Flame hydrolysis deposition. The differences between the three processes lie in the “generation” or building-up of the waveguide in which the light will propagate. The principle outcome of all these technologies is ultimately the same: to generate a structure in which light can propagate without loss and still behave like an optical fiber. All processes mentioned have a structure at the end (doped glass), which has a different refractive index than the surrounding material (also Glass). The difference in the refractive index allows the waveguide to mimic the performance of an optical pure fiber which is also constructed with glass having a different refractive index.

Compared to fused biconical-taper-based splitters, PLC technology allows for chip-size devices with the potential of integrating multiple functions, e.g. WDM coupler, onto a single chip. It also enables a uniform loss over a wide operating range of wavelengths from 1250 nm to 1625 nm [27, 34-37]. A PLC-based splitter suffers excess insertion loss from fiber array alignment to the PLC chip, fiber array uniformity caused by pitch and depth inaccuracies in the v-grooves of fiber array block that holds the fiber array, splitting ratio uniformity caused by imperfections in the PLC chip due to manufacturing, inherent chip material loss, and connector loss.

1.4.1.3 Fused Fiber Arrays

To create a more complex structure than 1x2 or 2x2 configurations, 1x2 fused coupler components are concatenated by splicing the output arms of the first coupler to the input arm of the second one and so forth [38]. This is done repeatedly to achieve the desired output power ratio and number of ports required. The series of cascaded fused couplers and the respective splices are usually housed and protected in robust plastic packaging.

1.4.1.4 Monolithic Fused Couplers

Another configuration to achieve multiple output ports is accomplished by fusing more than two fibers together [39]. This method helps to minimize the number of components. In practice, only 1x3 and 1x4 fused components have found extensive use.

1.4.2 WDM Technologies

Wavelength division multiplexer (WDM) is a passive component which is designed to split/combine signals, at two different wavelengths [40, 41]. A very common wide channel spacing WDM is 980/1550nm WDM, used extensively in Erbium Doped Fiber Amplifier (EDFA), where the pump and signal at these two wavelengths are multiplexed in the amplifying (Erbium-doped) fiber [42]. An alternative pump or signal combining WDM for EDFAs is 1480/1550 nm WDM, which is a narrow channel WDM [43]. Another variety of WDM, which is extensively used for telecommunication applications is a 1310/1550 nm WDM, which is also referred to as "Classical WDM" in order to distinguish it from dense WDMs (DWDMs) [44].

In FTTH, typically, voice and data operate at 1490 nm and 1310 nm, in downstream and upstream directions. Video usually operates at 1550 nm wavelength band. The signals are then combined onto a single fiber using wavelength division multiplexing (WDM) techniques and distributed to end users via passive optical splitters. Also, the WDM technology has been considered as one of the most graceful upgrade paths beyond power-splitting PONs to support more users at higher bandwidths. For an upgrade in the outside plant, the power splitter in the remote node of a power-splitting PON is replaced with an arrayed waveguide grating (AWG). In a 1xN configuration, an AWG serves as a wavelength router or a demultiplexer because a composite WDM signal launched into the input port is separated into individual channels by the device [45–47].

1.4.2.1 Fused Fiber WDM

A fused WDM is a symmetric 2x2 FBT coupler which can take two inputs at two different wavelengths, from the two input ports, and combines them at one output port. On the other hand, if these two signals are injected into the same input port, they will separate out at the two output ports. Such a design owes its origin to the fact that for a given coupler, the coupling coefficients and the effective lengths of interaction at two different wavelengths say 1310 and 1550nm are different. Therefore the splitting ratios at these wavelengths are usually different. For a coupler to function as a WDM at these two operating wavelengths, the fabrication process has to be tailored such that the splitting ratio of the device is maximum at one wavelength and minimum at the other wavelength [48, 49]. This implies that all of the input power at one wavelength will emerge at one output port, all input power at the second wavelength will emerge at the second output port.

1.4.2.2 Filter WDM

Filter based WDMs are assembled as shown schematically in Figure 1.9. Light from fiber is collimated using a suitable collimator and is allowed to fall on a suitable filter. The filter selectively reflects a wavelength and is focused back to the fiber on the same side by the collimator. The transmitted light is focused to another fiber by a collimator. WDMs can also be realized by reflective optics as shown in Figure 1.10, as suggested by Kapany et al [50]. This configuration comprises a transparent imaging element having a curved reflective surface at one end and pre-aligned fiber insertion holes at the other end. The transparent element is characterized by an index of refraction equal to that of the fiber core, and the fibers are glued in their respective holes with index matching cement.

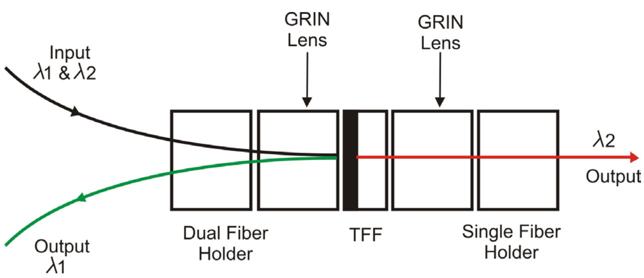

Figure 1.9: Thin Film Filter based WDM

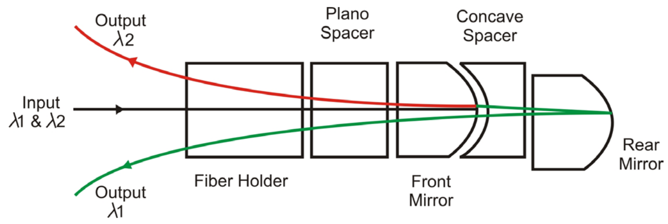

Figure 1.10: Reflective Optics based WDM

1.4.3 Mode Conditioning in Multimode Networks

Local Area Networks (LANs) often employ multimode fibers tuned for use with Light Emitting Diodes (LEDs) that is having limited modulation capability. In order to support high speeds as per Gigabit Ethernet requirements, the systems need laser sources such as Fabry-Perot (FP) lasers or Vertical Cavity Surface Emitting Lasers (VCSEL). The larger core diameter of the multimode fiber results in the laser signal disintegrating into an uneven distribution among all the modes and this degraded optical power profile, often translates into bit errors. The smaller spot sizes concentrate energy near the centers of the multimode fibers and hence are particularly sensitive to any central irregularity in the refractive index profile. Thus the launch dependent modal power distribution of multimode fiber combined with Differential Mode Delay (DMD) can cause serious problems in Gigabit Ethernet LANs. To address these needs, and hence to achieve useful link distances at Gigabit speeds, the signal from the single mode must be adapted to the multimode fiber. This adaption is conventionally done using an optical mode conditioning patch cable (MCP), which is an optical mode conditioner for efficiently conditioning a single mode optical signal propagating in a single mode optical fiber for propagation within a multimode optical fiber [51]. A lateral launching technique is well known for obtaining a better bandwidth– distance product by launching a small light spot with a radial offset from the multimode fiber core center [52]. Long period gratings, which acts as a spectrally sensitive loss element, by coupling light from lower order modes to higher order modes [53] can be effectively used to achieve modal power distribution in multimode Gigabit Ethernet networks.

1.4.4 Possible Evolution Scenarios of PON System

Besides the high capacity, a cost effective PON system requires a high split factor (large number of subscribers) and *a* long reach, to achieve an increased sharing of the fiber plant and the centralized equipment, a flexible and cost-effective deployment, and a high bandwidth usage. High split factor and long physical reach are two conflicting requirements when the optical power budget is limited. Eventually, higher line rates normally result in lower receiver sensitivity, which will decrease the optical power budget. A possible evolution scenario for the PON system to increase the physical reach and the split factor is to deploy optical amplification in the PON system. Experimental systems, such as Super PON have shown that it is possible to increase the split factor to 1:2048 or extend the physical reach to 135 km by the use of optical amplifiers [54]. This kind of system however requires a new standard and may only be economical on a longer term. Although a pure WDM-PON is not a cost-effective option, the combination of WDM and TDM-PON can be very attractive to increase the data capacity over a shared PON fiber plant.

1.4.5 All-Fiber Technology

All-fiber components are formed by transforming the properties of optical fiber itself, either by heating, tapering or by changing the refractive index. All-fiber approach is preferred for realizing a variety of components for passive optical networks, owing to its capability of keeping the integrity of signal transmission with low forward and return losses and high power handling [24]. Fused fiber technology and Long Period Gratings are two prominent technologies that contribute to all-fiber platform. In these methods, the signal never leaves the fiber and hence the integrity of the signal is preserved. In fused fiber method, the basic fabrication process involves stretching a pair of single mode fibers together, which are held in intimate contact across a short unjacketed length, in a high temperature flame. This process of heating and stretching results in narrowing of the two fibers into a single biconical tapered junction. Such components are also some times called fused biconical tapered (FBT) couplers.

In planar lightwave circuit splitters, epoxy comes in the optical path and hence may not be ideal for power splitting applications such as high power analog video transmission. Also, planar lightwave circuit splitters are not cost competitive for low port counts, less than eight. On the other hand wideband fused couplers are limited in port count by two. Cascading of 1x2 couplers affects the uniformity of the 1xN splitters as well as its reliability. 1x4 splitters are vital components in passive optical networks, where distributed splitting is preferred [55]. Monolithic 1x4 couplers are attractive solution that can offer the advantages of PLC splitter (high port count) and fused couplers (epoxy free optical path). However, methods to achieve wideband performance of monolithic couplers are not established well, which is one of the main focuses of this research.

Long period gratings (LPG) are formed by making periodic index perturbations along the length of the fiber. LPGs help to couple power from core modes to the cladding modes of the fiber. The most prominent reason for the successful incorporation of LPGs in communication systems is the fact that they provide a mechanism for producing wavelength dependent attenuation in the transmission. Fused coupler technology can also be used to realize wavelength division multiplexers, but the isolation is limited. Combining the LPG with fused WDMs can offer all-fiber WDMs with isolation greater than 30 dB.

1.5 Conclusions

Among the different optical access architectures, Passive Optical Network provides unique advantages because of its passive nature and reduced operational costs. The advantages of PON architecture as well as main optical technologies and components for passive optical networks are discussed in detail. All-fiber technology based on fused coupler and long period grating offers a versatile platform for realizing a variety of components for passive optical network applications. The present work focuses on developing fused monolithic 1x4 coupler and high isolation fused WDMs. Details of the work are given in subsequent chapters of the thesis.

References

1. J. R. Stern, J. W. Ballance, D. W. Faulkner, S. Hornung and D. B. Payne, "Passive Optical Local Networks for Telephony Applications and Beyond", Electronics Letters, Vol. 23, pp. 1255-1257, 1987.
2. Donald. E.A. Clarke and Tetsuya Kanada, "Broadband: The Last Mile", IEEE Communications Magazine, Vol.31, pp. 94-100, 1993.
3. Yih-Kang Maurice Lin, Dan R. Spears, and Mih Yin, 'Fiber-Based Local Access Network Architectures", IEEE Communications Magazine, Vol. 27, pp. 64-73, 1989.
4. Cedric F. Lam, Passive Optical Networks Principles and Practice, Ch. 1, pp. 1-17, 2007

5. James F. Mollenauer, "Functional Requirements for Broadband Wireless Access Network'", IEEE 802 Broadband Wireless, Access Study Group, March 5, 1999.
6. Fiona Vanier, World Broadband Statistics Report – Q1 2008, www.point-topic.com, 2008
7. Timo Smura, "Techno-economical analysis of IEEE 802.16a-based fixed wireless access networks”, PhD thesis, Helsinki University of Technology, 2004.
8. G. P. Agrawal, "Fiber-Optic Communications Systems", 3rd edition, Wiley 2002.
9. N. J. Frigo, ‘‘A survey of fiber optics in local access architectures,’’ in Optical Fiber Telecommunications, III A, edited by I. Kaminow and T.L. Koch, pp. 461–522, Academic Press, 1997.
10. E. Harstead and P. H. van Heyningen, ‘‘Optical Access Networks,’’ in Optical Fiber Teclecommunications, IV B, edited by I. Kaminow and T. Li, pp. 438–513, Academic Press, 2002.
11. S. S. Wagner, H. Kobrinski, T.J. Robe, H.L. Lemberg, and L.S. Smmot, ‘‘Experimental demonstration of a passive optical subscriber loop architecture,’’ Elect. Lett., Vol.24, pp. 344–346, 1988.
12. S. S. Wagner and H. L. Lemberg, ‘‘Technology and system issues for a WDM-based fiber loop architecture,’’ IEEE J. Lightwave Tech., Vol.7, pp.1759–1768, 1989.
13. H. Shinohara, ‘‘Broadband access in Japan: rapidly growing FTTH market,’’ IEEE Commun. Mag., pp.72–78, Sept. 2005.
14. X. Z. Qiu. J. Vandewege. F. Fredricx, P. Vetter, "Burst mode transmission in PON access systems", The 7th European Conference on Networks and Optical Communications, NOC'2002, Darmstadt, Germany, pp. 127-132, 2002.
15. ITU-T Recommendation G983.4, "A broadband optical access system with increased service capability using dynamic bandwidth assignment”, Nov. 2001.
16. Ryosuke Nishino, Yoshihiro Ashi, “Development of Dynamic Bandwidth Assignment Technique for Broadband Passive Optical Networks", FTTH Conference 2004.
17. Ton Koonen, "Fiber-optic techniques for broadband access networks", Telektronikk, Vol. 101, pp. 49-65, 2005.
18. John E. George, "Optical System Design Considerations for FTTP Networks". FTTH Conference 2004.
19. Eyal Shraga. "GPON and EPON (GE-PON) Economical Comparison", FlexLight, White Papers, 2005.
20. ITU-T Recommendation G983.1, "Broadband Optical Access System Based on Passive Optical Networks", Nov. 2001.

21. ITU-T Recommendation G983.3, "A broadband optical access system with increased service capability by wavelength allocation", 2001
22. FlexLight Networks and BroadLight, "Comparing Gigabit PON Technologies: ITU-T G.984 GPON vs. IEEE 802.3ah EPON". White Paper, May 2004.
23. "Passive Splitters for FTTH-PON Applications", White paper available at www.ftthcouncil.org, June 2004.
24. F. Gonthier, "Fused couplers increase system design options", Laser Focus World Magazine, pp. 83-88, June, 1998
25. D. Salazar, M. A. Felix, J. A. Valenzuela, H. Marquez, "A simple technique to obtain fused fiber optic couplers", Instrumentation and Development, Vol.5, pp. 170-174, 2001
26. S. Varghese, Biji Thomas, M. Iqbal, Abraham Thomas, Suresh Nair, "Highly reliable planar splitters designed for FTTH application" Proceedings of Eighth International Conference on Optoelectronics, Fiber Optics and Photonics (Photonics-2006), Hyderabad, pp.32, 2006
27. I. B. Sohn, M. S. Lee, J. Y. Chung, ''Fabrication of optical splitter and passive alignment technique with a femtosecond laser,'' IEEE Photonics Technology Letters, Vol.17, pp. 2349–2351, 2005.
28. R.A. Betts, "Fabrication techniques for integrated optics devices", Physics in Technology, Vol. 14, pp. 194-198, 1983
29. Katsunari Okamoto, "Recent progress of integrated optics planar lightwave circuits", Optical and Quantum Electronics, Vol. 31, pp.107-129,1999
30. M. Kawachi, "Silica waveguides on silicon and their application to integrated components," Opt. Quantum Electron., Vol. 22, pp. 391- 416, 1990.
31. S. Suzuki, M. Yanagisawa, Y. Hibino, and K. Oda, "High-density integrated planar lightwave circuits using SiO_2–GeO_2 waveguides with a high refractive index difference," J. Lightwave Technol., Vol. 12, pp. 790–796, 1994.
32. Navarro, Anthony G., "Silica Waveguide Design and Fabrication using Integrated Optics: A Link to Optical VLSI Photonics Integration for Semiconductor Technology", 22nd Annual Microelectronic Engineering Conference, pp.68, May 2004
33. A. Himeno, K. Kato, and T. Miya, "Silica-based planar lightwave circuits," J. Select. Top. Quantum Electron., Vol. 4, pp. 913–924, 1998.
34. K. Okamoto, ''Planar Lightwave Circuits for FTTH and GMPLS,'' in Proc. of APOC 2006, paper 6351–28, Kwangju, Korea. Sept. 3–7, 2006.
35. E. Edmon, K.G. McCammon, R. Estes, J. Lorentzen, ''Chapter 2: Today's broadband fiber access technologies and deployment considerations at SBC,''

Broadband optical access and FTTH, ed. Chin-Lon Lin, Chap. 3, p17, John Wiley & Sons, 2006.

36. R. Gritters, H. Taguchi, and A. Geraci, ‘‘Low Insertion Loss PLC Splitters for Improved PON Performance,’’ White paper from Seikoh Gaiken USA, Fiber optic product news http://www.fpnmag.com
37. K.A. McGreer, H. Zu, C. Ho, N. Kheraj, Q. Zhu, M. Stiller, and J. Lam, ‘‘Planar lightwave circuits for PON applications’’ Proc. of OFC, paper NWD4, Mar., 2006.
38. Shigehito Yodo, Akio Hasemi and Masanobu Shimizu, “Single mode 1x8 Fused Couplers”, Proceedings of 5th Conference on Optical/Hybrid Access Networks, Canada, pp. 4.05/01 - 4.05/06, September, 1993
39. J. W. Akrwright and D. B. Mortimore, “Monolithic MxN single-mode fused fiber couplers using capillary tube technology”, E-FOC 91 Proceedings, pp. 246-251, June 1991
40. H. A. Roberts, “Single-mode fused wavelength division multiplexer”, SPIE Proceedings – fiber optic couplers, connectors and splice technology II, 574, pp. 100-104, 1985.
41. J. M. Senior and S. D. Cusworth, “Devices for wavelength Multiplexing and Demulitiplexing “, IEE Proceedings, Pt.J, 136, pp. 183-185, 1989.
42. F. Gonthier, D. Ricard, S. Lacroix, and J. Bures, “2x2 multiplexing couplers for all-fiber 1.55μm amplifiers and lasers”, Electronic Letters, Vol.27, pp.42-44, 1991.
43. J. D. Minelly and M. Suyama, “Wavelength combining fused-taper couplers with low sensitivity to polarisation for use with 1480 nm-pumped erbium doped fiber amplifiers”, Electronic Letters, Vol. 26, pp. 523-524, 1990.
44. S. S. Orlov, A. Yariv and S. V. Essen, “Coupled mode analysis of fiber optic add-drop filters for dense wavelength-division multiplexing”, Optics Letters, Vol. 22, pp. 688-690, 1997.
45. M.K. Smit, ‘‘Progress in AWG design and technology’’ Proc. of 2005 IEEE IEEE/LEOS Workshop on Fibers and Optical Passive Components, pp.26–31, 2005.
46. M.K. Smit, ‘‘New focusing and dispersive planr component based on an optical phased array,’’ Elect. Letters, Vol.24, pp385–386, 1988.
47. H. Takahashi, S. Suzuki, K. Kato, and I. Nishi,‘‘Arrayed-waveguide grating for wavelength division multi/demultiplexer with nanometer resolution,’’ Elect. Letters, Vol.26, pp87–88, 1990.

48. C. M. Lawson, P. M. Kopera, T. Y. Hsu, and V. J. Tekippe, "In-line single-mode wavelength division multiplexer/demultiplexer", Electronic Letters, Vol. 20, pp. 963 -966, 1984.
49. P. Roy Chaudhuri, B. P. Pal, and M. R. Shenoy, "Modeling fused 2x2 all-fiber coupler components", Proceedings of National Symposium on Advances in Microwaves and Lightwave, New Delhi, pp. 57-62, 2000.
50. Narinder S. Kapany, Fred C. Unterleitner, "Fiber Optics Communications Module", US Patent 4329017, 1982
51. IEEE 802.3z, "Information Technology - Telecommunication & Information Exchange Between Systems - LAN/MAN - Specific Requirements - Part 3: Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications", 2002.
52. L. Raddatz, I.H. White, D.G. Cunningham, and M.C. Nowell, "An experimental and theoretical study of the offset launch technique for the enhancement of the bandwidth of multimode fiber links", J Lightwave Technology, Vol. 16, pp. 324–331, 1998
53. W. T. Chen and L. A. Wang, "Optical coupling between singlemode fibers by utilizing long period fiber gratings", Electronics Letters, Vol.35, pp. 421 – 423, 1999
54. R. P. Davey, P. Healey, I. Hope, P. Watkinson, D. B. Payne, Oren Marmur, Jorg Ruhmann, Yvonne Zuiderveld, "DWDM reach extension of a GPON to 135km", Journal of Lightwave Technology, Vol. 24, pp. 29-31, 2006.
55. Samuel Varghese, Suresh Nair, "FTTH compliant truly fused 1x4 couplers for passive optical network applications", White paper available from SFO Technologies, www.nestgroup.net , 2008