WDM-PON for the Access Network
White Paper by Novera Optics, Inc.

Introduction

WDM-PON is a general purpose and extremely efficient future-proof optical transport technology for use in Access and Metro transport networks. It enables highly efficient use of the outside fiber plant by providing point-to-point optical connectivity to multiple remote locations through a single feeder fiber.

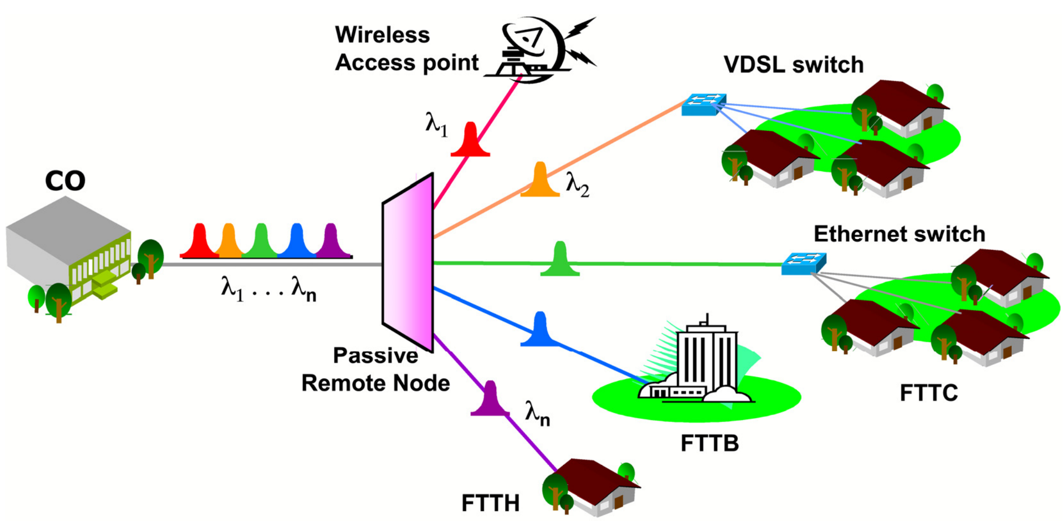

Figure 1. WDM-PON supports multiple services

Figure 1 illustrates the general architecture for a WDM-PON (Wavelength Division Multiplexed Passive Optical Network). As can be seen in the figure, this general-purpose architecture can serve multiple applications for both the business and residential customer.

This functionality is possible since each end point is connected to the central office through a dedicated bidirectional optical channel. This virtual point-to-point PON architecture enables

- large guaranteed bandwidths,
- bit rate independency,
- protocol transparency,
- graceful upgradeability,
- high QoS,

excellent security and privacy.

Novera Optics Optimizes DWDM for Transport and FTTx Networks

Although DWDM (Dense Wavelength Division Multiplexing) is commonly used in the long haul and metro markets, it has not yet made any significant inroads into the access area. One reason for this is the requirement that each remote site would need a unique transceiver (i.e. a wavelength stabilized DFB laser) that is matched to the WDM channel defined by the optical transport layer. These differently "colored" transceivers raise concerns for high operational costs (installation, management and inventory) associated with managing each remote access location.

Novera has solved this limitation by developing a breakthrough technology that eliminates the requirement for complex wavelength-specific lasers. By utilizing an optical injection locking technique, simple and identical Fabry-Perot lasers can now be used at all the remote ONU (Optical Network Unit) locations. Although all the transmitters are identical, each one operates at a different DWDM wavelength through the use of Novera's novel automatic wavelength-locking technology. The term **λ-PON™** will be used to describe a WDM-PON system that utilizes identical transceivers by means of automatic wavelength locking.

λ-PON™ Basics

Point-to-Point Connectivity

The basic functionality of λ–PON™ is illustrated in Figure 2. Dedicated point-to-point optical connectivity to "n" remote locations requires "n" transceivers at both the central office and at the remote ONU locations. In a conventional point-to-point architecture, this functionality is often achieved using "2n" feeder fibers as shown in figure 2. When the remote locations are located far from the central office, this extra fiber expense and the associated fiber management becomes prohibitive. In the λ–PON™ architecture these "2n" transmitters are connected by a single feeder fiber through the use of dense wavelength multiplexing and demultiplexing (Mux/DeMux). The details explaining this functionality will be described later.

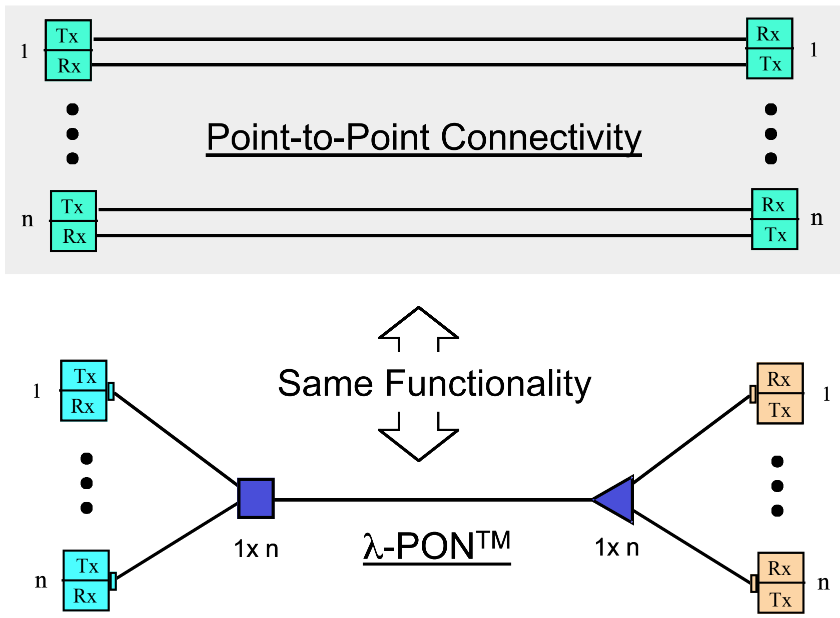

Figure 2. A λ–PON™ is equivalent to "n" bidirectional point-to-point links.

Comparison with Conventional WDM Transmission

Figure 3 illustrates the functionality of a λ–PON™ when compared to a conventional WDM transmission system. Conventional WDM systems, as illustrated at the top of figure 3, typically carry unidirectional traffic over each fiber transmission link. This allows the use of unidirectional optical amplifiers that are normally required in long-haul applications. Therefore, bidirectional traffic requires two separate data links, one for eastbound traffic and another for westbound traffic. In contrast λ–PON™ provides the same functionality using only a single bidirectional data link. This is possible by using modified wavelength Mux/DeMuxs (i.e. cyclic AWGs) that can support multiple wavelengths on each of their "n" output fibers (see figure 4 for more details). This network simplification when compared to a conventional WDM system makes a λ–PON™ solution more suitable for the access network since only a single fiber is required to connect between the two Mux/DeMux locations and only one distribution fiber is required to connect to each of the remote ONU transceivers.

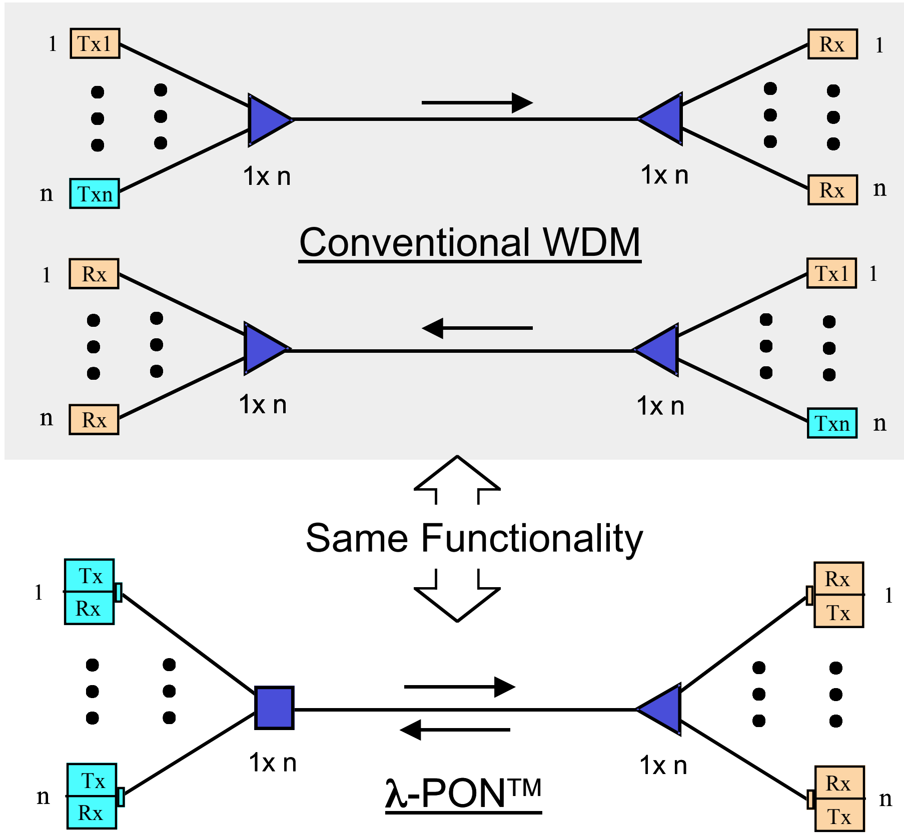

Figure 3. Functionality comparison with a conventional WDM system.

Another very important difference is the elimination of requiring "n" different laser sources (i.e. multiple wavelength-stabilized DFB lasers) at the "n" transceiver locations. By using automatically wavelength-locked FP-LDs (see figure 5 for more details), each remote transceiver in a λ–PON™ is identical and interchangeable with all the other remote transceivers. This is an important management requirement in an access network since the transceivers are typically scattered over different remote locations. Identical transceivers are critical for minimizing inventory and management costs in an access network application.

Also of importance is the recent development of athermal AWGs that enable the remote node to be completely passive. Previously AWGs required heaters to keep their WDM channels locked onto the ITU wavelength grid. This active power requirement was acceptable in conventional long-haul applications since the AWGs (together with the temperature stabilized DFB lasers) could be located in temperature-controlled environments (i.e. central offices).

In summary, a λ–PON™ system differs from a conventional WDM long-haul system by (i) enabling bidirectional transmission over each of its optical fibers, (ii) providing a point-to-multipoint architecture through a passive and environmentally hardened remote Mux/DeMux, and (iii) using identical and interchangeable automatically wavelength-locked FP-LDs.

Description of a Cyclic AWG

Figure 4 illustrates the functionality of the cyclic AWG (Arrayed Wave Guide) wavelength router used in λ–PON™. This cyclic functionality is different from the AWGs typically used in conventional WDM long-haul transmission systems (see figure 3 above). A cyclic or repeating AWG is designed to Mux/DeMux multiple wavelengths onto each output fiber as illustrated in figure 4. This enables both a downstream (ds) and an upstream (us) wavelength to be efficiently coupled to each of the remote sites over a single distribution fiber.

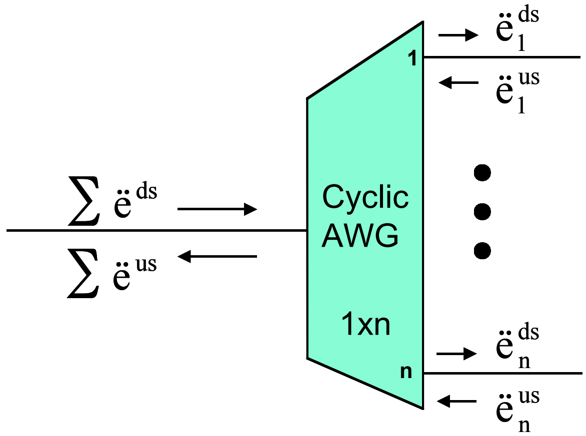

Figure 4. Basic operation of a cyclic AWG

One way to understand the operation of a cyclic AWG is to realize it uses the same principles as a classical bulk-optics diffraction grating that operates at a high diffraction order. This allows both a downstream and upstream wavelength to be diffracted into the same output fiber by using the different diffraction orders within the AWG. Another way to understand this operation is to assign a free-spectral-range to the AWG, as in the case of a classical etalon. This results in multiple wavelengths being coupled into each output fiber that are spaced by the free-spectral-range of the cyclic AWG.

Automatic Wavelength Locking in a WDM-PON

Figure 5 illustrates the operation of automatic wavelength locking in a λ-PON™ system. An un-modulated BLS (Broadband Light Source) located at the OLT (Optical Line Terminal) in the central office is used to generate seeding signals for "locking" the wavelengths of the remotely located identical FP-LDs (Fabry-Perot Laser Diodes). The BLS seeding signal is transmitted downstream through the single feeder fiber into the passive remote node containing the athermal and cyclic AWG. At this location the BLS wavelength spectrum is divided or "sliced" into "n" narrowband DWDM (dense WDM) channels by the demultiplexing function of the AWG. Each spectral slice is then transmitted through a single distribution fiber and injected into a remotely located FP-LD. When the FP-LD is current modulated with the electrical data signal, the injected seed signal forces the laser to operate in a narrow wavelength range defined by the optical passband of the DWDM transmission link. This wavelength locking process can be easily understood when one realizes that the FP-LD basically acts as an optical amplifier that modulates, amplifies and reflects the injected BLS seeding signal. The FP-LD is not capable of free-lasing due to the gain saturation caused by the amplified seeding signal. This results in a stable narrow-band output data signal, free from any of the noise associated with mode-hopping found in standard free-running FP-LDs.

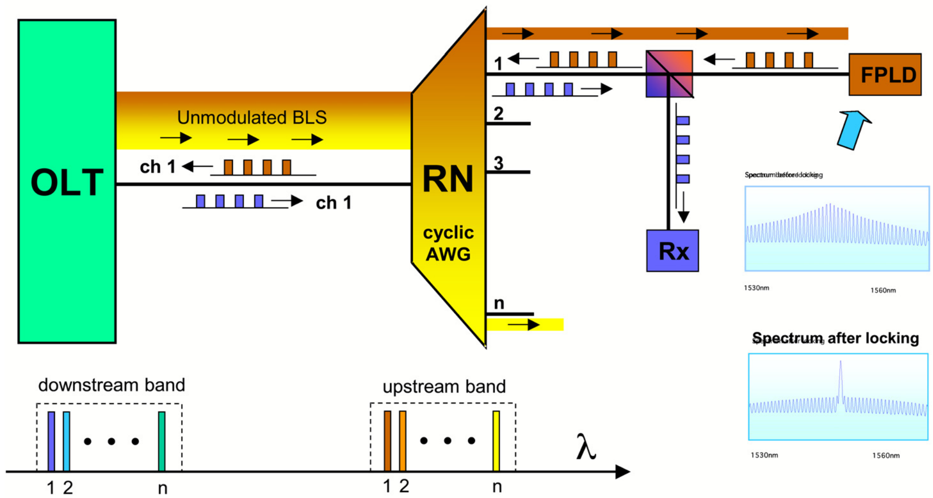

Figure 5. Basic description of automatic wavelength locking

The lower right hand side of figure 5 shows the FP-LD wavelength spectrum before and after applying the seeding or "locking" signal. Without the application of the locking signal, the FP-LD lases in multiple wavelength modes (see top insert on the right). This spectrum is unsuitable for data transmission through the DWDM transmission link due to the generation of mode partition noise caused by the wavelength filtering of the AWG. After injection of the locking signal the multimode spectrum is transformed into a quasi single-mode signal (see bottom insert) similar to that of a DFB laser. This "DFB-like" signal is automatically aligned to the DWDM channel defined by the optical transport layer. This wavelength locking process results in a "plug and play" functionality where all the remote FP-LDs are identical and interchangeable but can operate at different wavelengths without the need of any complex control or locking circuitry.

Figure 5 also illustrates the bidirectional functionality of a WDM-PON. Simultaneously along with the downstream BLS signal, "n" independent downstream data wavelengths are transmitted in a different wavelength band (shown at bottom left of figure 5). Due to the cyclic nature of the AWG (see figure 4), both a spectral slice of the BLS and one downstream data wavelength are demultiplexed and sent to each remote ONU. Each ONU transceiver uses an identical dichroic band-splitting filter which separates the two bands, directing the downstream BLS seeding wavelength into the FP-LD and the downstream data wavelength into a standard optical receiver. The modulated upstream data signal generated by the wavelength-locked FP-LD returns along the same optical path as the downstream BLS seeding signal.

λ-PON™ System Description

Figure 6 shows a typical configuration for a λ-PON™ system. Wavelength-locked FP-LDs are used at both the central office and the remote ONUs. All the ONU transceivers are identical and interchangeable. The central office OLT houses the BLS, a Mux/DeMux and the "n" downstream wavelength-locked laser sources.

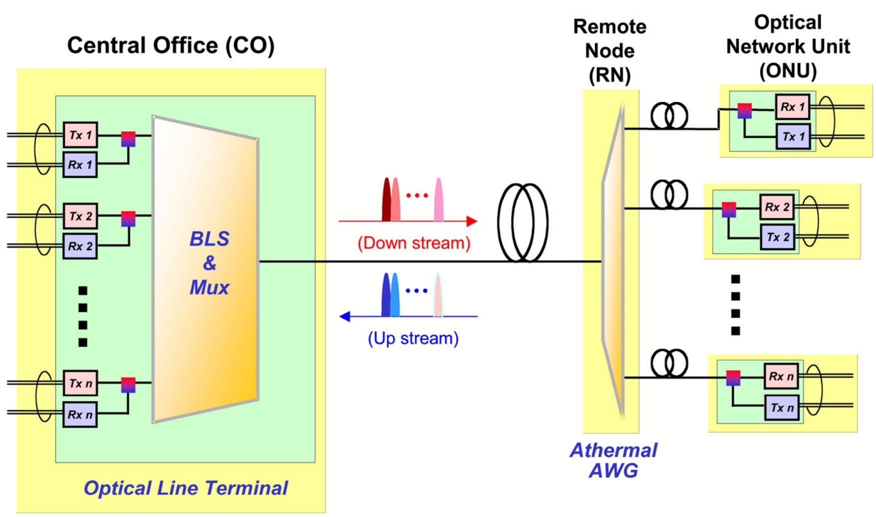

Figure 6. λ-PON™ system configuration

A single feeder fiber is used to connect the OLT to the environmentally hardened passive remote node. From the remote node, "n" distribution fibers are used to connect to "n" remote ONUs. In summary, over a single feeder fiber a λ-PON™ architecture provides a dedicated and bidirectional optical point-to-point connection between "n" transceivers in the central office and "n" remotely located ONUs. There are no special requirements for addressing or managing the multiple remote ONUs.

Comparison with a TDM-PON

Figure 7 illustrates the major functional differences between a TDM-PON (Time Domain Multiplexed) and a WDM-PON. TDM-PONs have a long development history with examples such as APON, BPON, EPON and GPON. The main concept behind the TDM approach is to use a single high-performance shared transceiver at the central office (see top of figure 7) to communicate with the "n" remote ONU transceivers. This approach requires the use of a 1xn power splitter to divide the optical power equally between the multiple ONUs. Since each remote ONU uses the same upstream wavelength, they must all take turns using dedicated and variable time slots where only a single ONU is allowed to transmit. A relatively complex processor located at the OLT controls the management and assignment of these individual transmission time slots. In the downstream direction a single data wavelength is used to broadcast to all the users. The ONUs identify their specific data packets by address information located in the header bit streams.

Although a TDM-PON minimizes the number of required optical components, it does this at a performance penalty. First, there exists an approximate $1/n^2$ penalty in the optical power budget. This occurs due to two effects, a 1/n power loss through the optical power splitter combined with an additional 1/n penalty due to the receiver noise bandwidth that must be "n" times the average data rate to each ONU. Secondly, potential QoS (Quality of Service) issues may arise since "n" different users share the same data stream and a relatively complex algorithm is required for granting time slots to each of the users. This interaction or "coupling" of the "n" users into a single PON data channel can also raise some difficult management problems, for example, if too many users in a PON decide to sign-up for premium services relating to either data rate or QoS. In addition to algorithm complexity, the opto-electronic hardware also needs to become significantly more complex due to its required burst-mode nature. For example, the OLT receiver must quickly adjust both its gain sensitivity and clock synchronization for each ONU transmission since each will have a different time delay and link loss.

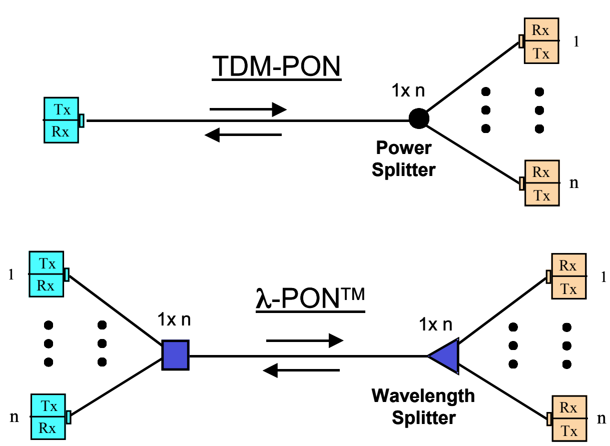

Figure 7. Functionality comparison between a TDM-PON and a λ-PON™ access network.

The above problems are not present in a WDM-PON. Since a wavelength splitter is used in place of the power splitter, the splitting loss can be very small (in theory this loss can be zero but in practice losses occur due to fiber coupling and waveguide imperfections). In addition, since WDM provides a point-to-point optical connection, the above receiver noise penalty does not exist since the bandwidth of each receiver is matched to its data rate. Also, due to the direct point-to-point connectivity between end points, there are no QoS issues since each user is uncoupled from the others who share the PON. These features can be of high value if both business and residential customers share the same PON.

Another relatively important advantage is the ability to completely characterize all the optical fiber paths in a WDM-PON by use of a WDM-OTDR (Optical Time Domain Reflectometer) located at the central office. This is possible since at each wavelength a single optical path exists between the central office and remote ONU. In a TDM-PON, the remote-node power splitter prevents an OTDR from separating and identifying the multiple Rayleigh backscatter signals from each of its “n” distribution fibers.

Summary

λ-PON™ is an efficient and future-proof WDM transport architecture optimized for the access network. It provides a point-to-point optical connection over a shared fiber plant by allocating a pair of dedicated wavelengths for each ONU. To reduce both capital and operating costs, λ-PON™ utilizes a newly developed technology that enables automatic wavelength locking of identical Fabry-Perot laser diodes. Features supported by λ-PON™ technology are:

- Identical wavelength-independent DWDM ONT/ONUs
- Simple point-to-point dedicated connectivity
- Bit-rate and protocol independency
- High security and privacy
- Complete fiber characterization through use of a WDM-OTDR

Simple future data-rate upgradeability