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# Wavelength Division Multiplexing Passive Optical Network (WDM-PON) technologies for future access networks

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**Abstract**— Wavelength Division Multiplexing Passive Optical Network (WDM-PON) introduces high data rate and large bandwidth. A bidirectional WDM-PON system based on a Fabry-Perot laser diode (FP-LD) with two cascaded array waveguide gratings (AWGs) has been demnstrated. The downstream data rate equals to 10 Gbps and the upstream data rate equals to 2.5 Gbps. This network is classified to 10GPON Standard. FP-LD will be used at optical network unit (ONU) as transmitter, so it can re-modulate the downstream signal with upstream data and then re-sent upstream towards the central office (CO). The main idea for using AWGs in the system is to increase the capacity, security and privacy. AWGs will be used to multiplex and demultiplex different wavelengths in wavelength division multiplexing PON (WDM-PON). Our proposed system is an effective low cost system and the injection locked FP-LD is used as low cost colourless transmitters for high-speed optical access exploiting WDM technology.

**Index Terms**— Wavelength Division Multiplexing Passive Optical Network (WDM-PON), Fabry-Perot laser diode (FP-LD), array waveguide gratings (AWGs).

## 1- Introduction

For the last years, Passive Optical Network (PON) systems have been studied. For initial deployment, a simple and low cost Optical Network Unit (ONU) design is desirable. In addition, a variety of Wavelength Division Multiplexing-Passive Optical Network (WDM-PON) systems has been studied to increase the channel capacity in existing optical fibers.

A bidirectional Subcarrier multiplexing–WDM PON (SCM-WDM PON) is demonstrated using a reflective filter and cyclic Array Waveguide Grating (AWG) where up/downlink data could be provided using a single optical source. In the proposed scheme, the signal for downstream was modulated by a single Continues Wave (CW) laser diode and re-modulated in the ONU as an upstream, the proposed WDM–PON scheme can offer the SCM signal for broadcasting service. A 1Gbps signals both for upstream and downstream were demonstrated in 10 km bidirectional optical fiber link [1].

Designs of low cost ONU for WDM-PON are presented and evaluated. Reflective Semiconductor Optical Amplifiers (RSOAs) are proposed to be used as core of the ONU in a bidirectional single-fiber single-wavelength topology. Forward error correction (FEC) is employed to mitigate crosstalk effects [2]. Wavelength Re-use model is exploited with RSOA for WDM-PON transmission, among the various solutions to the optical subscriber network realization, the WDM-PON has been considered as an ultimate next-generation solution. The wavelength re-use model with the RSOA has recently been developed for application to the WDM-PON. The wavelength re-use scheme has a common feature that the optical signal modulated with downstream data is re-used to carry the upstream data through the RSOA in the subscriber-side equipment by a series of processes such as being flattened out, reflected at the rear facet of the RSOA, and then re-modulated with upstream data. The major advantage with the wavelength re-use scheme would be the possibility of realizing the simplest WDM-PON optical link structure, which is directly reflected on cost-effectiveness of the network both in equipment and maintenance costs. The gain saturation scheme is presented. It uses the fact that the optical gain of RSOA declines as the injection power into RSOA increases. Experimental results show that it is possible to achieve error-free bidirectional transmission with 1.25 Gbps for upstream and 2.5 Gbps for downstream data rates over 20 km transmission distance [3].

An upstream-traffic transmitter based on Fabry Perot Laser Diode (FP-LD) as modulator is proposed and demonstrated for WDM access networks. By injection-locking the FP-LD with the downstream wavelength at the ONU, the original downstream data can be largely suppressed while the upstream data can be transmitted on the same injection-locked wavelength by simultaneously directly-modulating the FP-LD [4].

A 10Gbps upstream transmission using FP-LD remotely injection-locked by coherent feed light from the CO. Experimental results show that transmission over a 10 km single mode feeder fiber incurs power penalty of 1.1 dB and up to 16 cavity modes of the FP-LD can be injection-locked [5].

In this article, we will use FP-LD in ONU as an upstream source as well as we will use cascaded AWGs in the system. The distance will be 10 Km between CO and ONUs. Downstream data rate will be 10Gbps and upstream data rate will be 2.5 Gbps. This article includes an important comparison in using RSOA and FP-LD as an upstream source in ONU.

## 2- Theory

### A. WDM PONs

Figure 1 illustrates a typical WDM PON architecture that consists a CO, two cyclic AWGs, a trunk or feeder fiber, a series of distributions fibers, and ONUs at the end users.

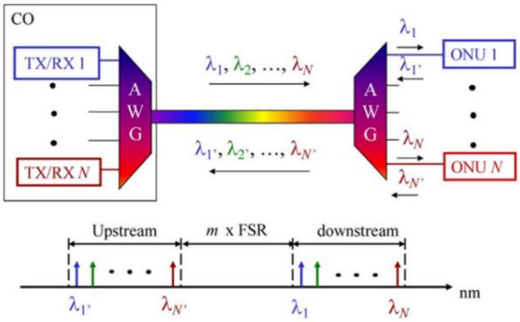



**Figure 1:** WDM-PON architecture. Inset: Allocation of upstream and downstream wavelength channels into two separate wavebands [6]

The first periodic AWG that locates at CO multiplexes downstream wavelengths to the ONUs and demultiplexes upstream wavelengths from the ONUs. The trunk fiber carries the multiplexed downstream wavelengths to a second periodic AWG that locates at RN. The second AWG demultiplexes the downstream wavelengths and guides each into a distribution fiber for transmission to the ONUs. The downstream and upstream wavelengths allocated to each ONU are separated by a multiple of the free spectral range (FSR) of the AWG, allowing both wavelengths to be directed in and out of the same AWG port that is connected to the destination ONU. In Figure 1, the downstream wavelengths assigned for $ONU_1$, $ONU_2$, and $ONU_N$ are symbolized $\lambda_1$, $\lambda_2$… and $\lambda_N$ respectively. Also, upstream wavelengths from $ONU_1$, $ONU_2$, and $ONU_N$ that are destined for the CO are symbolized $\lambda_{1'}$, $\lambda_{2'}$… and $\lambda_{N'}$ respectively. In a WDM PON, wavelength channels are spaced 100 GHz (0.8 nm) apart. In systems classified as dense WDM-PON (DWDM), a channel spacing of 50 GHz or less is used. Although a WDM PON has a physical P2MP topology in reality, logical P2P connections are facilitated between the CO and each ONU. In the example shown in Figure 1, $ONU_N$ receives downstream signals on $\lambda_N$ and transmits upstream signals on $\lambda_{N'}$. The capacity on these wavelengths is especially assigned to that ONU. The benefits of WDM PON include protocol and bit-rate transparency, security and privacy, and ease of upgradeability and network management.

### B. AWG router

The AWG router is an important element in many WDM-PON architectures. A conventional N-wavelength WDM coupler is a 1×N device as shown in Figure 2 (a).

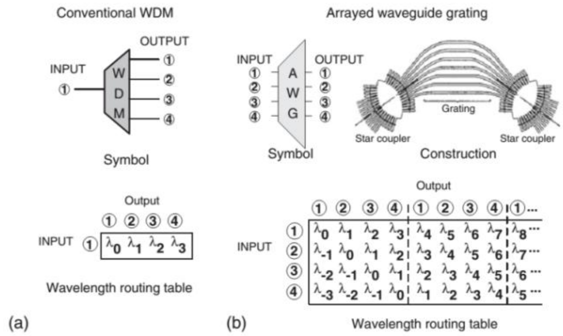



**Figure 2:** Conventional WDM coupler versus AWG.

AWGs have multiple input and multiple output as indicated in Figure 2(b) but the conventional WDM has one input and multiple output as shown in figure 2(a). A general AWG router includes two star couplers joined together with arms of waveguides of unequal lengths as shown in Figure 2(b) [7]. Each arm is related to the adjacent arm by a constant length difference. These waveguides function as an optical grating to disperse signals of different wavelengths. The optical path length difference $\Delta L$ between adjacent array waveguides is set to be

$$\Delta L = \frac{m\times\lambda_o}{n_{eff}} \tag{1}$$

Where $m$ is an integer number, $\lambda_0$ is the central wavelength, and $n_{eff}$ is the effective refractive index of each single mode waveguide [8]. An AWG has another name which is called wavelength grating router (WGR) as well as it has a very important and useful characteristic which is called cyclical wavelength routing property illustrated by the table in Fig. 2.1 (b) [9]. With a normal WDM multiplexer in Fig. 2.1 (a), if an "out-of-range" wavelength, (e.g. $\lambda_{-1}$ or $\lambda_4$, $\lambda_5$) is sent to the input port, that wavelength is simply lost or "blocked" from reaching any output port. An AWG device can be designed so that its wavelength demultiplexing property repeats over periods of optical spectral ranges called FSR. Moreover, if the multi-wavelength input is shifted to the next input port, the demultiplexed output wavelengths also shift to the next output ports accordingly. Cyclical AWGs are also called colorless AWGs.

### C. FP-LDs

The FP-LD is considered a light emitting diode (LED) with a pair of end mirrors. The mirrors are needed to create the right conditions for lasing to occur. The FP-LD is also called "a Fabry-Perot resonator" [10].

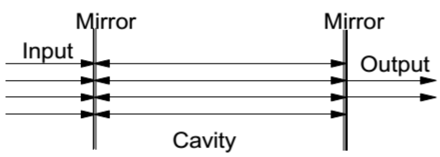



**Figure 3:** Fabry-Perot Filter structure

The input light will enter the cavity through the mirror on the left and will leave it through the mirror on the right. Some wavelengths will resonate within the cavity and it can pass through the mirror on the right but the other wavelengths will strongly attenuate as shown in figure 3. The operation of the FP-LD is similar to the operation of the Fabry-Perot filter. As the distance between the mirrors is increased, the more wavelengths will be produced within the cavity. Wavelengths produced are related to the distance between the mirrors by the following formula:

$$C_l = \frac{\lambda \times X}{2 \times n} \quad (2)$$

Where:
$\lambda$ = Wavelength
$C_l$ = Length of the cavity
$X$ = an arbitrary integer 1, 2, 3…
$n$ = Refractive index of active medium

A FP-LD is similar to an edge-emitting LED with mirrors on the ends of the cavity in its basic form. A surface of FP-LD should be easier than a surface of LED to construct. In a LED, a lot of attention is taken into account to collect and guide the light within the device towards the exit aperture. In an ideal laser, the problem of guiding the light is not taken into account. Lasing happens only between the mirrors and the light produced is exactly guided but it is not as simple as this. All types of FP-LD contain electrical contacts on the top and on the bottom to supply it by injection current. A simple double hetero-structure laser is shown in figure 4. Mirrors are formed at the ends of the cavity by the "cleaved facets" of the crystal from which it is made.

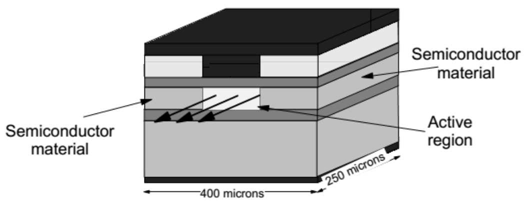



**Figure 4:** index guided FP-LD.

The operational principle of an index guided FP-LD differs from the operational principle of gain guided FP-LD. If strips of semiconductor material are put beside the active region as shown in figure 4, an index guided FP-LD are created. So, the active region is surrounded on all sides by material of a lower refractive index. Mirrored surfaces are formed and this is easy to guide the light much better than gain guidance alone. Any light strikes the edges of the cavity is captured and guided it to the cavity. Additional modes reflecting from the sides of the cavity are eliminated. This is not too much of a power loss since lasing cannot occur in these modes and only spontaneous emissions will leave the cavity by this way. It produces a spectral width of between 1 nm and 3 nm with usually between 1 and 5 lines. Linewidth is generally around .001 nm. It is better than the gain guided FP-LD.

## 3- System Analysis

### A. System Models

In this article, the proposed system model is discussed. It contains modulator, AWG, PON link, demodulators and the FP-LD. The proposed PON architecture is shown in Figure 5. In downstream, CW laser with 193.1 THz frequency is modulated by MZM using 10 Gbps NRZ downstream data to generate the desired downstream signal. The generated signal is sent to the first AWG at CO which multiplexed it then it is sent over the bidirectional Optical Fiber. It passes through the second AWG at RN which multiplexed the input signal again. The multiplexed signal is sent to ONU. At the ONU, using optical splitter/coupler, portion of the multiplexed signal is fed to a balanced receiver. For upstream, the other portion of the downstream multiplexed signal from the splitter/coupler is re-modulated using 2.5 Gbps NRZ upstream data by FP-LD in the ONU. The re-modulated OOK signal re-pass through the AWG which demultiplexed the upstream signal then it is sent over bidirectional Optical Fiber. The upstream demultiplexed signal passes through the first AWG then it is received in CO. By using the circulator to avoid influencing the downstream signal, the upstream signal is sent to a PD is used to receive the upstream signal in the CO.

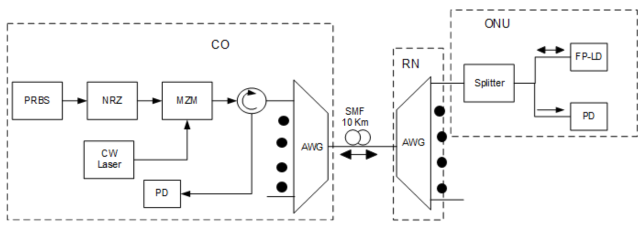



**Figure 5:** Block diagram of the proposed bidirectional PON system model

The system model is categorized into three main parts which are CO, single mode fiber channel and ONU. The parameters of the proposed system are listed in table 1.

**Table 1:** Simulation parameters are used in the proposed system.

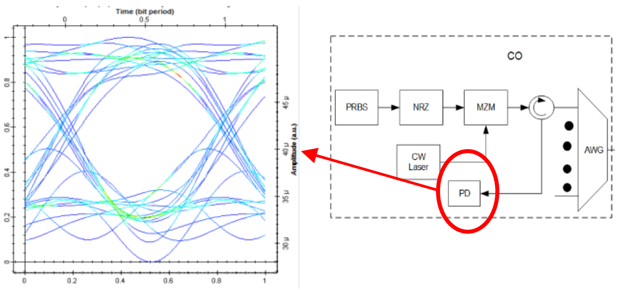
| Parameter | Value |
|---|---|
| **Layout Parameter** | |
| Bit rate (downstream) | 10 Gbps |
| Bit rate (upstream) | 2.5 Gbps |
| Sequence length | 128 bits |
| Samples per bit | 64 |
| Number of Samples | 8192 |
| **Optical Transmitter (CW laser)** | |
| Laser Power input, $P_{in}$ | 1mW (0 dBm) |
| Frequency/Wavelength | 193.1 THz / 1550 nm |
| Laser line Width | 10 MHz |
| **Optical link** | |
| Length | 10 km |
| Attenuation | 0.2 dB/km |
| Dispersion | 16.75ps/(nm×km) |

| | |
|---|---|
| **Optical Attenuator** | |
| Attenuation | 10 dB |
| **Optical Receiver (PIN PD)** | |
| Responsivity | 1 A/W |
| Dark Current | 10 nA |
| **Filter type** | |
| Low Pass Bessel Filter (LPBF) for downstream | 4 GHz |
| LPBF for upstream | 1.7 GHz |

### B. Bidirectional WDM-PON System based on FP-LD with two cascaded AWGs:

### I. CO Part:

The transceiver at CO is shown in figure 6(b). This model includes AWG after circulator as shown in the figure, it is operated as multiplexer in the downstream direction and like demultiplexer in the upstream direction. The min. BER equals to $3.6 \times 10^{-12}$. The eye diagram of upstream-received signal at CO is shown in figure 6(a).




(A) (B)

**Figure 6:** (a) Eye diagram for upstream signal at CO in WDM-PON with AWG at RN, (b) The transceiver at CO

### II. Bidirectional channel Part

The channel includes bidirectional optical fiber and AWG. A bidirectional single mode fiber of 10 km is used to forward the signal and to backward it with an optical delay of 1 unit in order to separate the upstream and downstream signals. Table 2 shows the main parameters of a bidirectional optical fiber.

**Table 2**: Bidirectional optical fiber parameters in GPON

| Parameter | Value |
|---|---|
| Reference wavelength | 1550 nm |
| Length | 10 km |
| Attenuation | 0.2 dB/km |
| Dispersion | 16.75 ps/(nm×km) |
| Dispersion slope | 0.075 ps/(nm$^2$×km) |

The downstream optical signal will pass through AWG which is used as demultiplexer in the downstream direction and as multiplexer in the upstream direction. The main parameters of AWG are listed in table 3.

**Table 3:** AWG parameters at RN

| Parameter | Value |
|---|---|
| Size | 2 (two input port and two output port) |
| Frequency | 193.1 THz |
| Bandwidth | 25 GHz |
| Frequency spacing | 100 GHz |
| Insertion loss | 0 dB |
| Return loss | 65 dB |
| Depth | 100 dB |
| Filter type | Gaussian |
| Filter order | 2 |

### III. ONU Part

The transceiver at ONU includes two parts, first part is used to receive the signal from CO and second part is used to send signal to CO. Figure 7 illustrated ONU part.

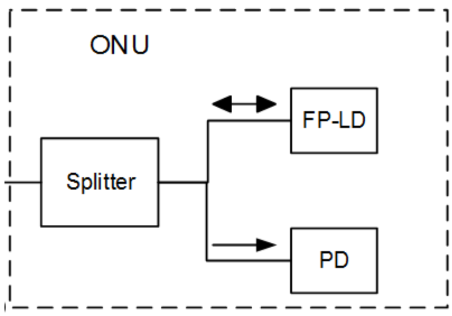



**Figure 7:** ONU part in WDM-PON with two cascaded AWGs

ONU includes many components for receiving downstream signal and for transmitting upstream signal. Received signal components include splitter, optical attenuator, PIN PD, LPBF, 3R regenerator and BER analyzer, transmitted signal components include FP-LD, NRZ generator and PRBS generator. Splitter is used to split the downstream signal into two partitions, one of them is received by PIN PD and the other portion is passed to FP-LD. BER analyzer is used to measure the BER of downstream signal so the value of min. BER equals to $1 \times 10^{-13}$. The eye diagram of downstream signal is shown in figure 8.

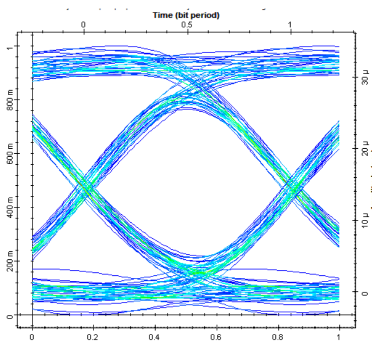



**Figure 8:** Eye diagram of downstream signal at ONU in WDM-PON with two cascaded AWGs

### IV. BER versus Received power for the proposed system with two cascaded AWGs:

In this section, we will show the influence of the received power variation on the BER in both upstream signal and downstream signal, According to the previous section, our system includes three main parts such as CO part, Bidirectional SMF and ONU part. The BER versus downstream-received power Pd curves for the downstream and upstream signals are shown in Figure 9.

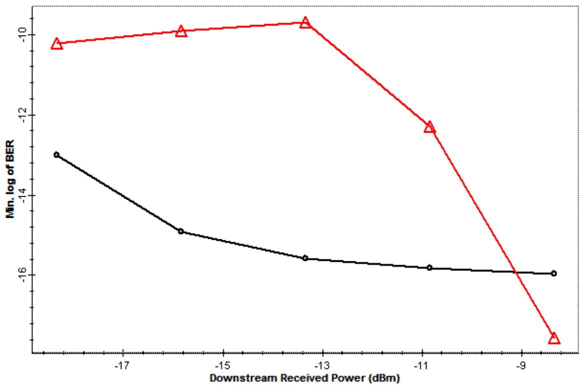



**Figure 9:** Min. log of BER versus Downstream received power at ONU for downstream and upstream in WDM-PON with two cascaded AWGs

It is noted from the figure 9 that the BER versus the downstream received power $P_d$ (injected power) at ONU for the upstream signal goes down with increasing $P_d$ from -18 dBm to -8 dBm. When $P_d$ = -18 dBm, the BER = $6\times10^{-11}$. When $P_d$ = -8 dBm, the BER =$2.7\times10^{-18}$. For the downstream signal, the BER curve goes down with $P_d$ from -18 dBm to -8 dBm. When $P_d$ = -18 dBm, the BER = $1\times 10^{-13}$. When $P_d$ = -8 dBm, the BER = $1\times10^{-16}$. Figure 10 is illustrated BER versus upstream received power $P_u$ at CO.

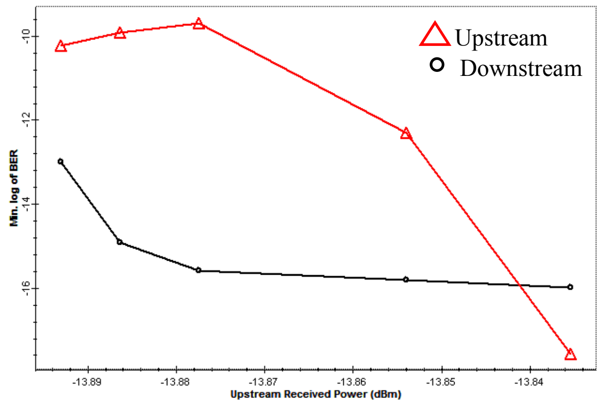



**Figure 10:** Min. log of BER versus upstream received power at CO for downstream and upstream signals in WDM-PON with two cascaded AWGs

It is noted from the figure 10 that the BER versus the upstream received power $P_u$ at CO for the upstream signal goes down with increasing $P_u$ from -13.89 dBm to -13.835 dBm. When $P_u$ = -13.89 dBm, the BER =$6\times10^{-11}$. When $P_u$ = -13.835 dBm, the BER =$2.7\times10^{-18}$. For the downstream signal, the BER curve goes down with $P_u$ from -13.89 dBm to -13.835 dBm. When $P_u$ = -13.89 dBm, the BER = $1\times 10^{-13}$. When $P_u$ = -13.835 dBm, the BER = $1\times10^{-16}$.

### V. Upstream BER versus FP-LD bias current for the proposed system with two cascaded AWGs:

In this section, we will explain the effect of FP-LD bias current on upstream BER at CO for the proposed model. Input power of CW laser is fixed at CO and it equals to 0 dBm. Figure 11 shows upstream BER versus the bias current of FP-LD.

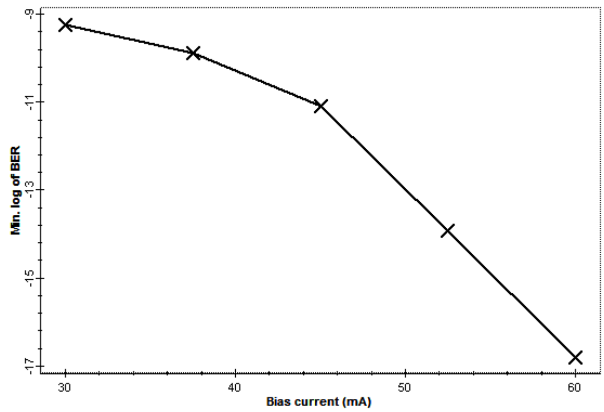



**Figure 11:** Upstream BER versus bias current of FP-LD

**Table 4:** Upstream BER versus bias current ($I_b$)

| $I_b$(mA) / BER | 30 | 37.5 | 45 | 52.5 | 60 |
|---|---|---|---|---|---|
| Upstream BER | $5.7\times10^{-10}$ | $1\times10^{-10}$ | $8\times10^{-12}$ | $1\times10^{-14}$ | $1.5\times10^{-17}$ |

We can conclude from table 4, upstream BER is decreased and it became better as bias current of FP-LD is increased.

### VI. WDM-PON based on FP-LD versus WDM-PON based on RSOA with two cascaded AWGs:

We will study the effect of CW laser power on the BER at CO for the two systems when the input power is fixed and it equals to 0 dBm. Figure 12 shows the architecture of these colorless systems.

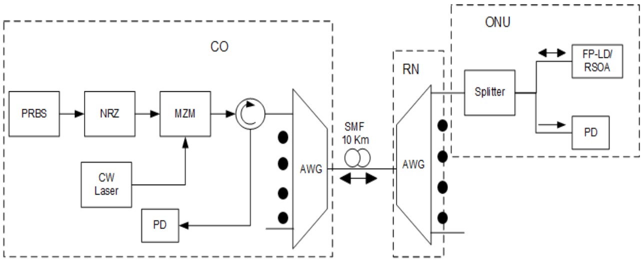



**Figure 12:** Architecture of WDM-PON showing colorless sources based on RSOA or FP-LD with two cascaded AWGs.

FP-LD and RSOA are used at ONU to remodulate the down-stream signal with upstream data (2.5 Gbps) which is sent to CO. We will show the effect of using FP-LD on the up-stream signal at CO, min. BER of upstream signal equals to $6\times10^{-11}$ while min. BER for upstream signal when using RSOA equals to $1\times10^{-6}$. Upstream received power when using FP-LD equals to -13.89 dBm and upstream received power when using RSOA equals to -3 dBm. Now we will conclude the difference between RSOA and FP-LD in table 5.

**Table 5:** Comparison between using FP-LD and RSOA on WDM-PON

| PON type | WDM-PON based on FP-LD | WDM-PON based on RSOA |
|---|---|---|
| Min. BER for upstream signal at CO | $6\times10^{-11}$ | $1\times10^{-6}$ |
| Received power at CO for upstream signal | -13.89 dBm | -3 dBm |
| Cost | low | high |
| Amplify the in-coming signal | No | Yes |

Figure 13 is shown the comparison between upstream BER for both WDM-PON based on RSOA and FP-LD when input power CW laser is increased from 0 dBm to 10 dBm.

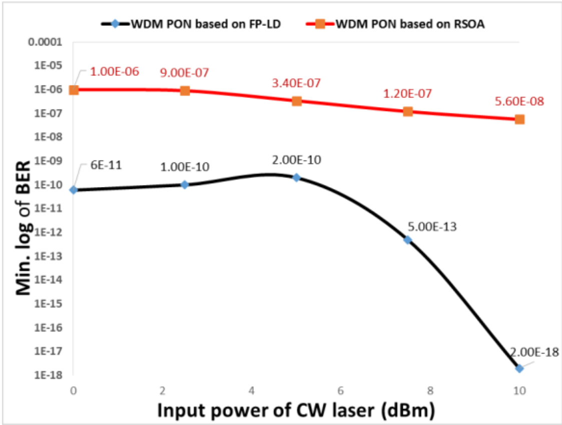



**Figure 13:** WDM PON based on RSOA versus WDM PON based on FP-LD in the results of upstream BER when input power of CW laser is increased.

WDM PON based on FP-LD is better than WDM PON based on RSOA in the results because the upstream BER values are good in our proposed system as illustrated in fig-ure 16.

## 4. Conclusion

The proposed model includes two cascaded AWGs and FP-LD. This model contains two AWGs to in-crease the number of ONU, the multiplexing and demultiplexing channels and support more securi-ty and privacy. FP-LD is very effective device in this model due to its low cost optical source. All results in this model are shown, it compare with a model that is used RSOA at ONU and we note FP-LD is better than RSOA because the upstream BER with FP-LD is lower than the upstream BER with RSOA.

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