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REVIEW ARTICLE

# Key technologies and system proposals of TWDM-PON

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**Abstract** In this paper, key technologies, system proposals and future directions of next generation passive optical networks stage 2 (NG-PON2) are reviewed. We first discuss the potential solutions for NG-PON2 standardization. Then we focus on time and wavelength division multiplexed PON (TWDM-PON), which is the primary solution selected by Full Service Access Network (FSAN). The key technologies in TWDM-PON configuration are analyzed, including how to improve the bandwidth capacity and power budget of the system, and choose upstream tunable transceiver, etc. Several system proposals are illustrated as candidates for NG-PON2 configuration.

**Keywords** next generation passive optical networks stage 2 (NG-PON2), time and wavelength division multiplexed PON (TWDM-PON), tunable transmitter, tunable receiver, power budget

## 1 Introduction

Passive optical networks (PONs) have been widely considered as the ultimate solution for future access networks. Nowadays, time division multiplexing (TDM) based Gigabit Ethernet PONs (GE-PONs) and Gigabit-capable PONs (GPONs) have been standardized and commercialized in several countries. GE-PONs are mainly deployed in Asia, whereas GPONs are the dominate PON systems in North America and Europe. Based on the ITU-T G.984 GPON standard and the IEEE 802.3ah GE–PON standard [1], GE-PONs and GPONs can deliver signal with a data rate up to 1.25/1.25 Gb/s and 2.5/1.25 Gb/s for downstream/upstream directions respectively. Since the whole bandwidth is shared by all users in the system, the bandwidth that each user could get access to is only several Mb/s. Meanwhile, a large number of newly emerging bandwidth-intensive and multimedia-rich applications, such as video-on-demand, video/photo sharing, 3-D TV, etc., are driving up the bandwidth demand of end-users, which will eventually outstrip the gigabit technologies and push forward the network upgrading progress. Therefore, interested groups, such as Full Service Access Network (FSAN), IEEE and ITU SG-15, have made efforts to draw the draft for next generation PON (NG-PON). Figure 1 shows the standardization roadmap of the PON evolution [2]. The 10 GE-PON and XG-PONs(XG-PONs represents a PON system with 10 Gb/s line rate, at least in downstream direction, X taken as Roman sign for 10) that were standardized in 2009 are the first crops of upgrade systems, which supply a line rate no more than 10 Gb/s in both directions. And they closely follows the step of NG-PON1, the FSAN proposed the conception of NG-PON stage 2 (NG-PON2). The standardization of this system is still in process and is expected to be completed by 2013. The basic requirements for the system include an aggregate capacity no less than 40 Gb/s and remain backward compatibility. Some telecommunication operators believe that NG-PON2 is more suitable for commercial deployment, so that NG-PON1 can be skipped and we can go directly into NG-PON2 [3].

In recent years, researchers had reported various evolving technology options for NG-PON2, including 40 G TDM-PON [4], wavelength division multiplex-PON (WDM-PON) [5], time wavelength division multiplexing-PON (TWDM-PON) [6] and orthogonal frequency division multiplexing-PON (OFDM-PON) [7]. However, the requirement of backward compatibility blocked off the way of WDM-PONs because they require wavelength selective optical distribution networks (ODNs). 40 G TDM-PON is also out of consideration due to the cost pressure of 40 G components in each user and the fiber chromatic dispersion would seriously limit the transmission distance. Other options are eliminated due to either technical immaturity or time-frame requirement. As a result, all attentions turned to TWDM-PON and it was selected by FSAN as the primary architecture for NG-PON2 in Apr 2012. It consists of multiple XG-PONs

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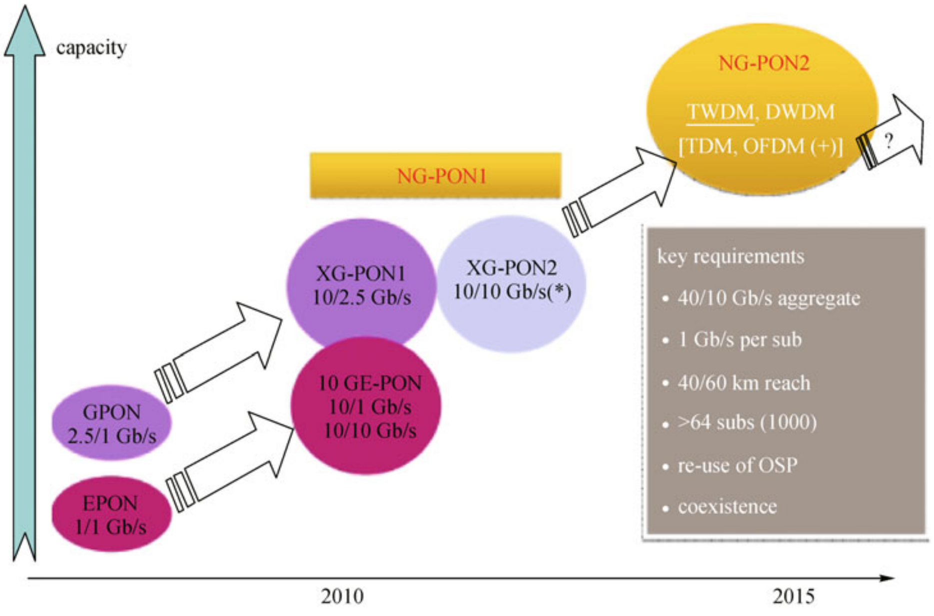

Ref.: FSAN/ITU-T G.984 G.987 G.ngpon2
IEEE 802.3ah 802.3av (*) not a standard (+) no longer considered

**Fig. 1** Standardization roadmap of PON evolution (Ref. [2])

stacked onto a common ODN using different wavelengths, which combines the benefits of TDM-PON and WDM-PON. If four wavelengths are used, the bandwidth would be four times of the XG-PON. TWDM-PON features plenty of inherent advantages, such as statistical sharing of bandwidth, i.e., customers can flexibly get access to a bandwidth ranging from several Mb/s to a peak of 10 Gb/s; backward compatibility, i.e., the splitter based ODN can be fully reused for TWDM-PON system, which reduces the cost and complexity in construction. However, despite that the technologies of XG-PONs are quite mature and can be directly used in TWDM-PON constructing to cut the implementation period, there are still some technology challenges to be addressed, which will be presented and discussed in detail in the following sections. The contents of this paper is organized as below: we first provide an insight into the key technologies including tunable transmitters, i.e., colorless upstream laser source and the choice of tunable receiver; and the methods for optimizing parameters including loss budget, power efficiency are also briefly presented, then we give an overview of the current research status of TWDM-PON. Conclusions are finally drawn.

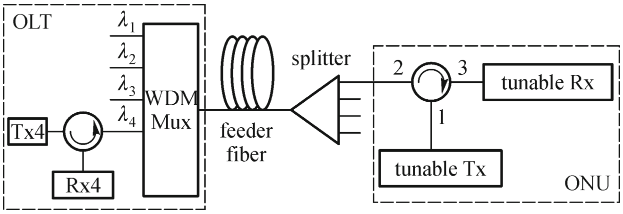

**Fig. 2** System configuration for TWDM-PON

## 2 Key enabling technologies

The system configuration of TWDM-PON is shown in Fig. 2, taking 4 pairs of wavelength as example. It is a tree topology with the optical line terminal (OLT) at the root of the tree and the optical network unit (ONUs) at the leaves. They are connected by the feeder fiber and power splitter as in TDM-PONs. In the OLT, a set of distributed feedback laser diodes (DFB-LDs) operating at different wavelengths serve as downstream laser sources, followed by a WDM for multiplexing. As the splitter is used in the ODN to distribute power, every ONU would receive signals of all wavelengths, so that each ONU must contain a device that could correctly select the downstream wavelength. Similarly, for the upstream deployment, ONU that will work on any wavelength, i.e., colorless ONU is intensively preferred by operators for easier network laying and maintaining [8].

### 2.1 Tunable transmitter

A tunable laser for use in an ONU needs to be compact, low cost, and have a tuning range sufficient for the TWDM-PON, in which it is going to be applied. Several techniques have already been developed as candidates of upstream laser source for WDM-PON, including spectral slicing of broad band sources, remote reflective modulators, and injection-locking etc. Some of the ideas can be borrowed in constructing TWDM-PON. In WDM-PON proposals, directly modulated Fabry-Perot laser diode (FP-LD) and reflection semiconductor amplifier (RSOA) are the most popular choices for upstream laser source. Both of them can be injection locked by the seeding light from the central office or self-seeded by using a filter and reflector to get a single wavelength output. Therefore, by varying the wavelength of the seeding light, the output wavelength is tuned and a colorless laser source is obtained. Some classic ONU proposals employing FP-LD and RSOA are presented as below.

### 2.1.1 FP-LD

Injection locking of FP lasers using an injected wavelength was shown half a decade before PON was born for applications in coherent transmission systems [9]. FP-LD shows a multi-mode output and the power of a particular mode fluctuates randomly with time. As the mode power is proportional to the spontaneous emission coupled to the lasing mode, we can achieve a single mode oscillation from an FP-LD by injecting a single mode seeding light. In this case, the mode that the nearest to the seeding light can be locked while other modes are suppressed [10]. The principle of injection locking can be used to turn a FP-LD into a wavelength agnostic source in the ONU. The seeding light could be originated from the OLT [11] or the downstream signal which can be erased by the FP-LD and re-modulate signal on it [12]. Figure 3 is the network configuration of downstream wavelength reuse. One of the key advantages of the OLT seeding approach is the simplicity of the ONU as the light sources are at the central office, which made it easier to manage, and upgrade the network. However, Rayleigh scattering inducing crosstalk would seriously distort the signal in the single fiber transmission system. which limit the transmission distance. Besides, as the emission spectral of FP-LD is sensitive to temperature variation, temperature control is required to ensure that the seeding light is locked to the intended cavity mode of the FP-LD.

In self-seeding schemes, the FP-LD is self-seeded by its own spectrally filtered light, in which the transmitting wavelength is solely determined by the characters of the spectral selecting filter. In this case, the need for a seeding light in the OLT is removed and the Rayleigh back-scattering (RBS) caused signal distortion is also eliminated. Zhu et al. have demonstrated a upstream multi-

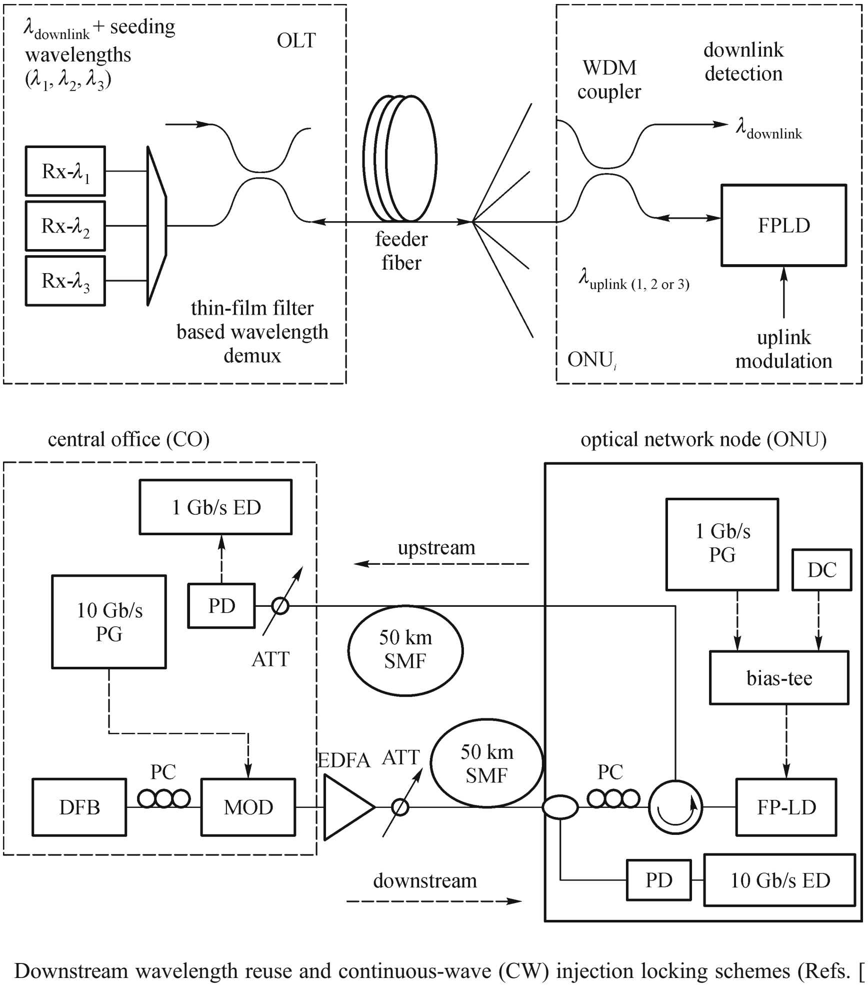

**Fig. 3** Downstream wavelength reuse and continuous-wave (CW) injection locking schemes (Refs. [11,12])

wavelength shared TDM-PON by using self-seeded FP-LD as upstream laser source. The different ONU structures and the output spectra of the laser module are shown in Fig. 4 [13]. The tuning flexibility is limited by the discontinuous emission modes, only existing in several specific wavelengths spaced by ~1 nm, and it also requires temperature control to meet the requirement of different channels in TWDM-PON system. Besides, the modulation bandwidth of FP laser is limited to 1.25 GHz, which is a significant aspect to restrict its application for higher bandwidth requirement condition.

### 2.1.2 RSOA

RSOA is another promising candidate for colorless laser source, which is considered as the most practical solution. RSOA is a semiconductor optical amplifier (SOA) with a single fiber pigtail that serves both the input and the output. In a common SOA, the pigtailed facet of the SOA chip is prepared for ultralow reflection. While in the RSOA, the opposite facet is made highly reflective as if it were the facet of a FP laser. The incoming light is amplified as it travels through the chip, reflected at the opposite facet, and amplified again as it travels back toward the fiber. Without the incoming light, the RSOA would simply be a broadband light source and we can change this by sourcing a wavelength at the central office. Similar with FP-LD, RSOA can be injection locked by a bank of lasers in the OLT [14] or by itself [15]. The injection locking method also suffers from RBS inducing crosstalk, resulting in a short reach limitation [16]. Self-seeding RSOA was investigated to overcome the crosstalk problem [17].

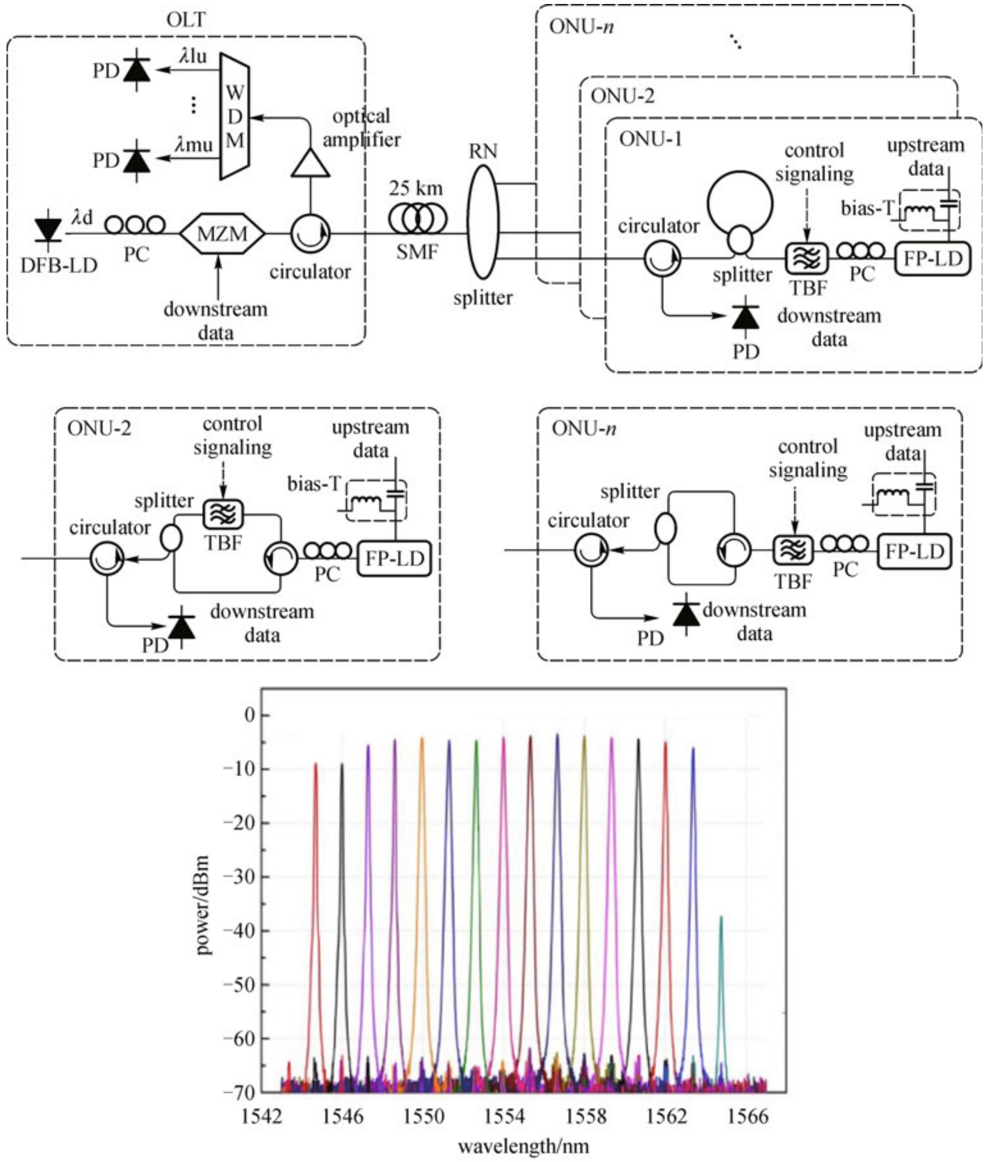

**Fig. 4** Self-seeding FP-LD (Ref. [13])

Compared with FP-LD, the wavelength tunability of RSOA is more flexible, which relax the requirement on the seeding light.

As there is no laser feedback as in a directly modulated laser, which could speeds up the removal of carriers from the active layer, the modulation bandwidth of RSOA is wholly dependent on the carrier lifetime, which is generally limited to ~2 GHz as shown is Fig. 5. A longer RSOA is faster, and it can be barely pushed to 10 Gb/s operation [18], but if it beyond that, other help is needed. Therefore, regular RSOA is considered to be non-ideal candidates for a high speed access network. However, recent work has overturned that view. By introducing electric equalization and forward error correction (FEC), Cho et al. demonstrated a 25 Gb/s operation using a relatively standard RSOA [19]. Figure 6 shows the experimental setup used to evaluate the 25.78 Gb/s signal obtained from a directly modulated butterfly-packaged RSOA. Inset (a) and (b) in Fig. 6 are the eye diagrams of the directly modulated signal before and after the electronic equalization, and we can find that without the equalization, there was no eye opening at the decision point (a), but after electronic equalization, a clear eye opening is obtained (b). Advanced modulation formats have been also demonstrated by taking advantage of halved modulation bandwidth of 4-ary pulse amplitude modulation [20] and duobinary [21]. These techniques, however, require high-speed electronics either at the transmitter or at the receiver.

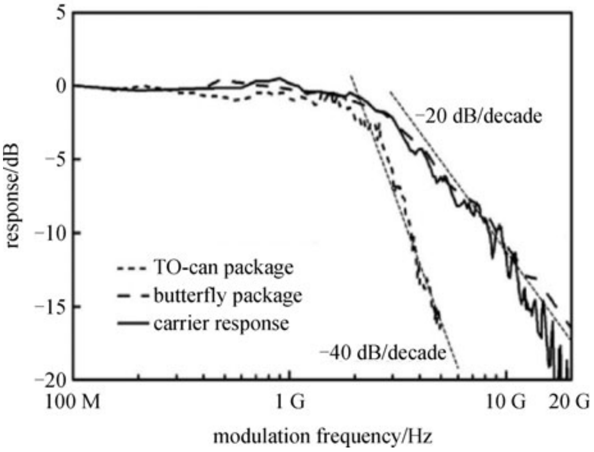

**Fig. 5** Measured frequency responses of TO-can packaged (dotted) and butterfly-packaged (dashed) RSOAs (Ref. [19])

Optical equalization method is also presented. In Ref. [22], a delay-interferometer (DI) performed as an optical equalizer as well as a vestigial side-band filter, which improved the eye opening and the dispersion tolerance of 10 Gb/s signals generated by a 1.5 GHz-bandwidth RSOA. Figure 7 shows the optical spectra of the signals and the transmittance of the 16.1 GHz DI. The DI filtered out the lower-frequency sideband of the RSOA output and remained the upper-frequency sideband. Figure 8 shows the eye diagrams of signals spectrally filtered by the DI in comparison with unfiltered case. The improvement of the eye opening is obvious.

### 2.1.3 Integrated devices

Integrated devices are more suitable for practical application due to their compact size. One candidate is electro-modulation laser (EML), which is integrated with a tunable LD, an electro-absorption modulation (EAM) and a SOA onto one device, or reflectice EAM (REAM). In comparison with FP-LD and RSOA, EML and REAM can be operated with much higher modulation rates and much lower chirp, allowing long range transmission. However, as the modulation is based on electro-absorption, EML and REAM have relatively low output power and are usually

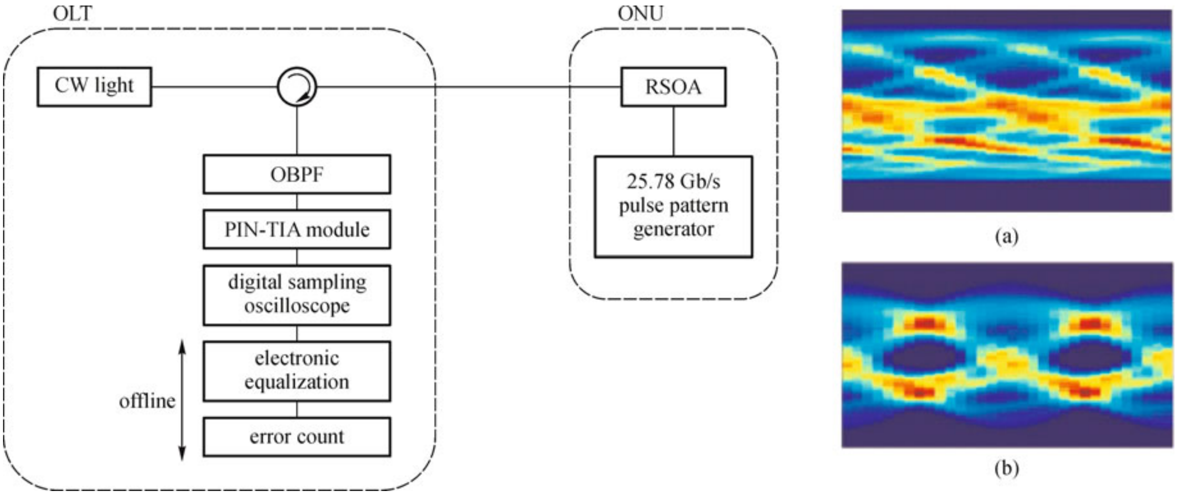

**Fig. 6** Experimental setup used to evaluate 25.78 Gb/s directly modulated RSOA (Ref. [19])

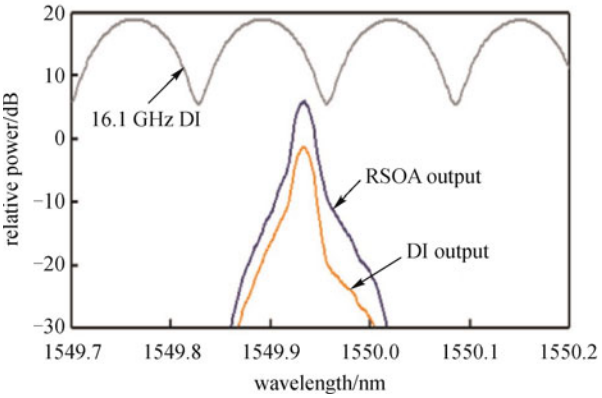

**Fig. 7** Optical spectra of signals and transmittance of DI (Ref. [22])

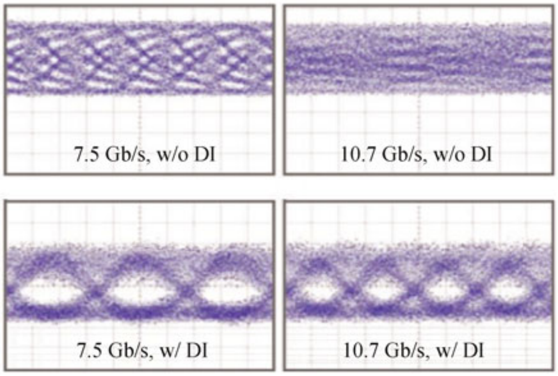

**Fig. 8** Eye diagrams (Ref. [22])

integrated with a SOA to compensate for losses on-chipand fiber-coupling, which increases the cost and limits its application in cost-sensitive PON [23].

To meet the twin constraints of low-cost and high performance for the access network, direct modulation laser (DML) seems the most convenient way only if the propagation penalties that distort the signal are diminished. DML transmitters offer many advantages including small footprint, high output power, low driving voltage, and low power consumption. The output wavelength can be thermally tuned in a small range of ~3 nm by varying its working temperature, which is not suitable for WDM systems that require a wide wavelength tuning range. But in TWDM-PON, as the wavelengths are much less than in WDM-PON, a 3 nm tuning range is sufficient only if the wavelength plan is set reasonably.

However, the modulation of carrier density via drive current produces inherent and highly component-specific frequency chirp. This chirp will result in broad spectrum that severely limits the transmission distance in standard single mode fiber (SSMF)without dispersion compensation because of its interaction with fiber dispersion along the transmission link. To support high dispersion tolerance, a suitable optical filter is used to control the phase between adjacent bits. With an optical spectrum reshaping filter is placed at the laser output to perform frequency to amplitude modulation conversion to increase extinction-ratio (ER) and convert the slowly varying adiabatically chirped pulses to flat-topped chirp pulses with abrupt phase transitions, the signal shows higher tolerance to fiber dispersion [24].

#### 2.1.4 Others

Other implementation technologies include tunable lasers, such as multi-section distributed Bragg reflector (DBR) laser (electrical control) without cooling [25], external cavity laser (ECL) with mechanical control without cooling [26], ECL with thermo/electro/piezo/magneto-optic control without cooling [27,28].

### 2.2 Tunable receiver

In TWDM-PON, a tunable wavelength selection device is required in the ONU, because each ONU should be able to get access to all wavelengths for dynamic bandwidth allocation. The wavelength selective filter is required to be compact in size, have a tuning range that covers the whole operation waveband, and low cost. Microring-resonator, thin film filter, Bragg gratings, Bragg reflectors, liquid crystal tunable filter, thermally tuned and angle tuned FP filters are the research focus. In the following contents several techniques will be introduced as example.

#### 2.2.1 Microring resonator

Thermally tunable Si microring resonator (MRR) filter with flat-top passband is a promising candidate for WDM signal processing, because it is compact and easy to be integrated with other Si devices, including electro-optic modulators, optical routers and reconfigurable optical add-drop multiplexers (ROADMs), etc. A thermally tunable Si 3rd order MRR filter has been proposed, which shows a box-like response with low intra-band ripple (~0.65 dB), low insertion loss (less than 0.9 dB) and out-of-band rejection higher than 40 dB. By applying power to TiN heaters, the filter can be thermally tuned over the whole feedback shift register (FSR) of ~3 nm with the tuning efficiency of 48.4 mV/nm [29].

#### 2.2.2 Silicon Fabry–Perot filter (FPF)

FPF, also called as etalon, is realized by a silicon wafer with both sizes carefully polished. The incoming light experiences a multiple-beam interference. As a result, the wavelengths that match the resonant conditions are selected at the filter output as indicated in Eq. (1).

$$\lambda_m = (2nL_c\cos\theta)/m, \tag{1}$$

where $n$ is the etalon reflective index, $L_c$ is its length. By varying the reflective index or the length of the FP resonator, we can tune the output wavelength of the FP filter. For the reflective index tuning, we can use thermo-optic effect, which is the refractive index variation induced by a temperature change. The thermo-optic effect is very strong and the thermally induced expansion of a silicon wafer is very poor, resulting in a large pre valence of the thermo-optic effect. A thermal tuning coefficient of 0.083 nm/K is obtained at 1550 nm [30].

The device can also be tuned by changing the optical path length in the cavity, which may be achieved mechanically, thermally, or electro-optically. Hence, the FP filter is a versatile and flexible component and a prime candidate for a wavelength selective filter in TWDM-PON systems.

### 2.2.3 Thin film filter

As a group, micro electro mechanical systems (MEMS) Fabry-Perot devices tend to possess wide tuning range, but have an serious limitation. They are structurally restricted to the simplest type of single-cavity etalon design. Plasma enhanced chemical vapor deposition (PECVD) is the preferred process for dense, compliant, homogeneous optical coatings of thin film silicon [31]. It is known that thin film narrowband filters may be tuned by mechanical rotation of the angle of incidence [32] and linear variable filters are also commercially available based on spatially graded deposition, tunable by linear translation.

### 2.2.4 Fiber Bragg grating (FBG)

FBG is also one of candidates because of its sharp spectral filtering characteristics and low insertion loss. Conventionally, the Bragg wavelength of FBGs can be shifted by imparting either the strain or temperature effect on a uniform FBG. Temperature change linearly shifts the Bragg wavelength mainly through the refractive index variation of the grating induced by the thermo-optic effect. The temperature sensitivity of the Bragg wavelength is 10 pm/°C [33]; therefore, temperature change in the order of 100°C is required to shift the Bragg wavelength in a nanometer regime. Mechanically induced strain physically extends or compresses the grating period, which leads to a linear shift of the Bragg wavelength in conjunction with the refractive index change in the grating through the strain-optic effect. The excellent tolerance of silica-glass fibers to mechanical strain makes strain tuning preferable for achieving a wide tuning range.

## 3 Power budget

Power budget is also a key parameter in evaluating a network performance. On one hand, the coverage of a PON is characterized by the maximum transmission distance between the OLT and the furthest away ONU, and by the split ratio, i.e.. The number of subscribers served by a single OLT on the other hand. Both are limited by the power budget of the upstream and downstream directions. In general, GPON has a reach of up to 20 km and a 1:32 splits. Only if the power budget allow, there would be room for growth. Such an extension of PON reach and split is an attractive option for network operators, because it allows them to concentrate OLTs in fewer central offices, and serve a larger geographic area from each OLT. Meanwhile, the cost of the OLT can be spread over a larger number of subscribers and therefore actually save cost on a lower-tier service.

Power budget is determined by the transmitting power and the sensitivity of received signal in both upstream and downstream directions. To avoid fiber nonlinearity such as stimulated Brillouin scattering, four wave mixing etc, the power launching into the transmitting fiber cannot be too high. Furthermore, no amplifier can be added in the transmission link between OLT and ONU to keep the system passive. So the promotion of power budget relies on the higher signal sensitivity. Pre-amplification and avalanche photo diode (APD) are employed in the receiver end to obtain a higher reception sensitivity.

## 4 System proposals

### 4.1 40/10 Gb/s TWDM-PON

Many institutions are working on constructing TWDM-PON system. The most outstanding one is Huawei, who has claimed that “A 40 Gb/s PON system is demonstrated, which is totally compatible with the existing ODN” in 2011. Figure 9 shows the network configuration. 40/10 Gb/s transmission is demonstrated by stacking four XG-PONs with a capacity of 10/2.5 Gb/s in downstream/upstream direction. The ONU tunable transmitter is based on thermally tuned DFB laser with more than 400 GHz wavelength tuning range. The ONU tunable receiver is based on thin film tunable filter in front of a 10 Gb/s APD ROSA whose wavelength tuning range is more than 800 GHz. A power budget of 40 dB in the downstream and 38 dB in the upstream have been achieved, which could support a total split ratio of 1:512 and a distance of 20 km [6].

### 4.2 $N \times 10/1.25$ Gb/s TWDM-PON

We have demonstrated a TWDM-PON by using a single

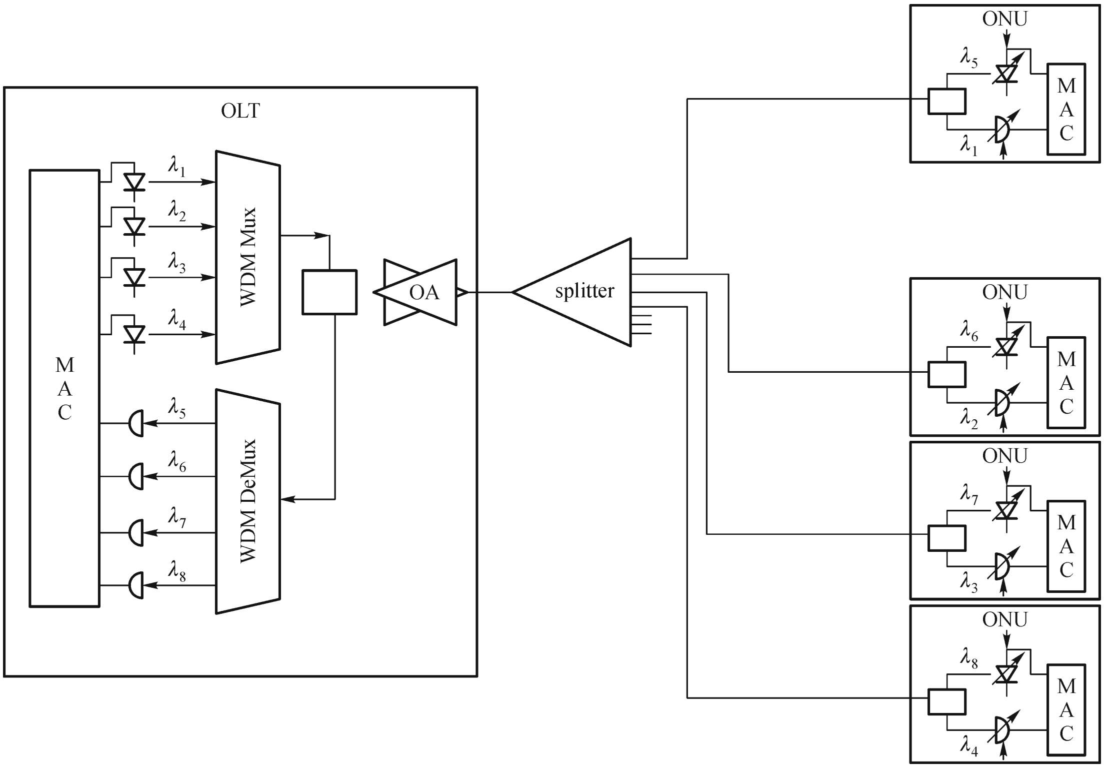

**Fig. 9** 40/10 Gb/s TWDM-PON (Ref. [6])

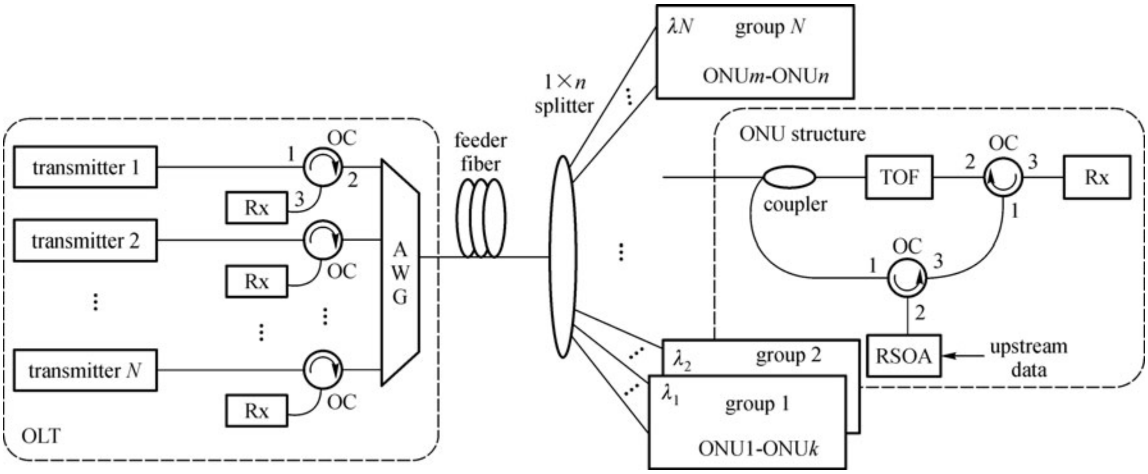

**Fig. 10** Network scheme (Ref. [34])

tunable optical filter (TOF) for both upstream wavelength selection and upstream wavelength generation in ONU [34,35]. The network configuration is shown in Fig. 10. A RSOA and TOF based fiber ring laser serves as the upstream laser source. The RSOA is self-seeded by the filter, and a colorless laser source is obtained with a tuning range from 1535 to 1565 nm, which is limited by the tunability of the filter. The proposed laser source can be directly modulated at a data rate of 1.25 Gb/s. Furthermore, although the upstream and downstream wavelengths are in the same waveband and pass through the same filter, the back reflection and RBS inducing crosstalk can be mitigated due to the self-phase modulation (SPM) inducing spectral red shift in a gain saturated RSOA. Figure 11 shows the optical spectra of upstream lasers in comparison with the passband of filter, from which we can obtain that the laser generated in the fiber ring is always located at the long wavelength side within the passband of the TOF. Therefore, by tuning the central wavelength of the TOF to align with the downstream wavelength for minimal loss,

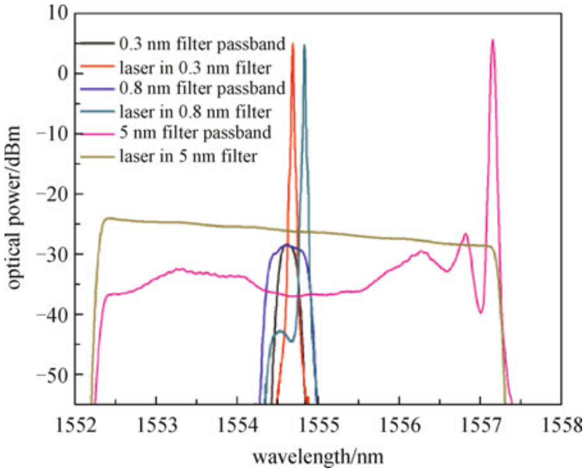

**Fig. 11** Spectra of upstream laser (Ref. [36])

the upstream wavelength will be shifted from the downstream one, then the back-reflection and RBS inducing crosstalk can be sufficiently suppressed [36]. With 25 km fiber transmission, the power budget is ~17 dB, therefore the proposed PON could support a 1:32 splitting ratio with a 2 dB power margin and a capacity of $N \times 10/1.25$ Gb/s in downstream/upstream direction ($N$ is the number of wavelengths). The application for burst mode transmission is also successfully demonstrated [37].

### 4.3 Symmetric 40 Gb/s TWDM-PON

We have demonstrated a symmetric 40 Gb/s TWDM-PON system as shown in Fig. 12. A thermally tuned 10 Gb/s directly modulated laser is used as the upstream colorless source. In ONU, a tunable optical filter is employed for both downstream signal selection and upstream signal chirp management. An erbium doped fiber amplifier (EDFA) followed by a PIN are used for upstream signal reception, achieving a sensitivity of −32 dBm at 1e–3. For downstream signal receiving, a RSOA is placed before the PIN as pre-amplifier, which increased the downstream signal sensitivity by 9 dB from −20.5 to −29.5 dBm at 1e–3. The power budget of the symmetric 40 Gb/s TWDM-PON is 31 dB, which could support a 25 km fiber transmission and 1:256 splitting ratio [38].

## 5 Conclusions

NG-PON2 systems are currently entering a very exciting period and plenty of schemes are being proposed as standardization solutions. As the most promising candidate, TWDM-PON targets at a bandwidth capacity higher than 40 Gb/s, good backward compatibility, the ability of supporting future customer applications and low upgrade cost, which provides a smooth evolution from TDM-PON. Even though the 10 GPON technology is mature and can be applied in TWDM-PON, the system configuration faces unique technical challenges, including the colorless

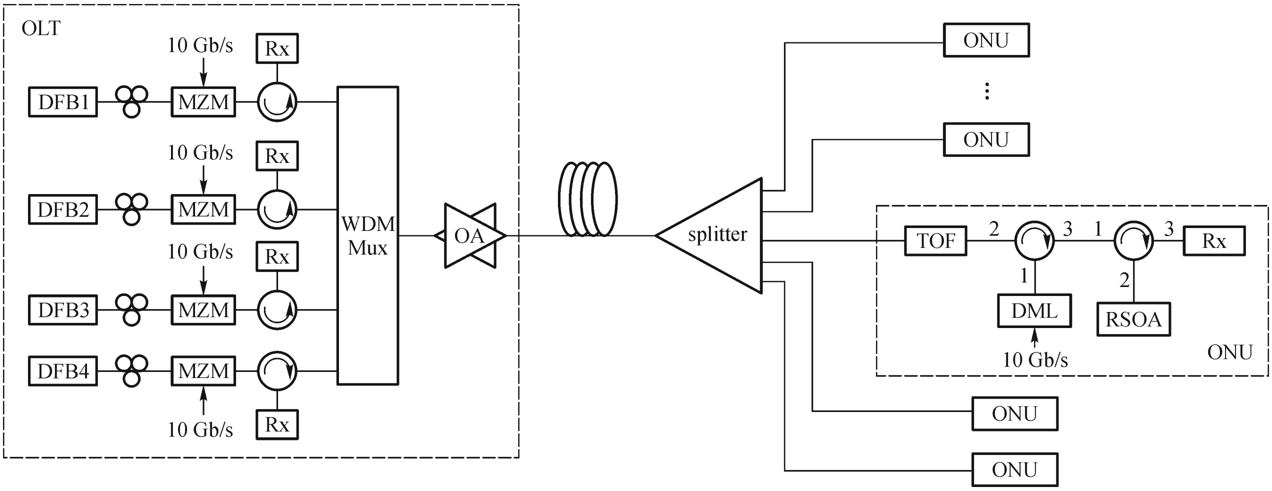

**Fig. 12** Symmetric 40 Gb/s TWDM-PON (Ref. [38])

upstream laser source, the choice of wavelength selective filter, power budget enhancement to support more users, etc., which attract continuous attentions.

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