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Next Generation Optical Access Network: Standardization Outline and Key Technologies for Co-existence with Legacy Systems

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SUMMARY This paper reviews next generation optical access network standardization activities, focusing on 10-Gbps class TDM PON, and introduces key technologies for their co-existence with deployed systems.

key words: *FTTH, NG-PON, 10G-EPON, XG-PON*

1. Introduction

Users are increasingly demanding broadband services, and fiber-to-the-home (FTTH) is the main technology to answer these demands. Gigabit-class passive optical network (PON) systems, IEEE802.3ah GE-PON [1] or ITU-T G.984 G-PON [2] have been widely deployed and used by many network operators. The number of FTTH users in Asia is increasing and has exceeded 30 million [3]. Especially in Japan the number of FTTH users surpassed the number of digital subscriber line (DSL) users in 2008. Recently, the number of FTTH users topped 15 million, and the ratio of FTTH services among broadband services went above 50 percent [4]. This means FTTH supports most Japanese broadband services.

With the emerging applications such as multi-channel high-density television (HDTV) distribution, broad bandwidths wider than those of the current system will be required. To respond to wider bandwidth demand, several kinds of technologies such as 10-Gbps class time division multiplexing (TDM), wavelength division multiplexing (WDM) [5], optical code-division multiple access (OCDMA) [6] and orthogonal frequency-division multiple access (OFDMA) [7], [8] have been developed and discussed as next generation PON (NG-PON) technologies.

As 10 Gb/s Ethernet [9], which was approved in 2002, has been already widely used and 10-Gbps TDM technologies have become mature, the 10-Gbps-class TDM PON system is the most attractive candidate for NG-PON systems. Therefore, standardization development organizations (SDOs) have been discussing 10-Gbps-class TDM PON standards. Recently, the IEEE802.3 committee approved the 10G-EPON standard [10] and ITU-T has been developing an XG-PON standard [11].

This paper reviews NG-PON standardization trends focusing on 10-Gbps-class TDM PON and introduces key technologies for their co-existence with current systems. First, Sect. 2 describes requirements for NG-PON systems. Second, Sect. 3 introduces a standardization outline, focusing on PHY of 10G-EPON and XG-PON. Finally, Sect. 4 introduces key technologies for co-existence with Gigabit class PON, optical filter for WDM approach, and dual-rate burst mode receiver for the TDM approach.

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2. Requirements for NG-PON System

NG-PONs are mainly expected to deliver multi-channel IP TV and other advanced video services. The bandwidth per channel of IP TV is increasing; for example the bandwidth of SDTV, HDTV and 3DTV are about 2 Mbps, 10–20 Mbps, and 50–90 Mbps, respectively. For GE-PON with 32 users, the average data bandwidth is about 30 Mbps, which seems not enough for multi-channel HDTV distribution. Moreover, more bandwidth is required for subscribers in multiple dwelling units (MDUs). For 16 MDUs with 24–48 subscribers per ONU, a total of 384–768 subscribers per PON, PON needs 10 Gbps capacity [12]. PON is expected to not only deliver IP TV but also support other applications that require wider bandwidth. Next generation mobile backhaul such as fourth generation is one candidate. Fourth generation wireless communication will require data throughput is up to Gbps class. The access point coverage will decrease and the number of access points will increase. PON with 10 Gbps capacity is applicable for its backhaul.

In addition to the high capacity demand, maximum utilization of installed optical distribution networks (ODNs) for existing PONs and smooth migration from current systems are required for NG-PON systems as shown in Fig. 1 [13].

The ODNs for existing PONs have a loss budget of about 30 dB, 20 km reach, and more than 32 split ratio. Therefore, NG-PON systems satisfy the loss budget of current ODNs. The IEEE802.3av 10G-EPON (PR30/PRX30) and the ITU-T XG-PON are currently specifying the classes that have a power budget (loss budget + power penalty) of about 30 dB [10], [11].

Realizing such a large power budget requires high-power optical transmitters and high-sensitivity optical receivers that operate under a wide input power range.

To smooth migration from existing systems, NG-PONs must be able to co-exist with installed systems such as G-PON or GE-PON and the RF-video distribution system. Co-

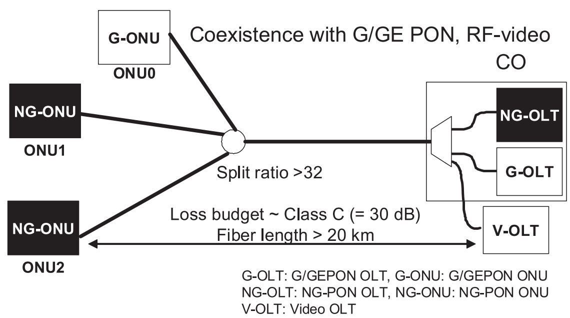


Fig. 1 Requirements for NG-PONs.

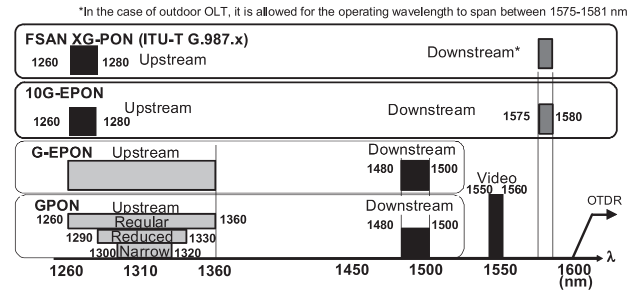


Fig. 2 Wavelength allocation of G/GE-PON and 10G-E/XG-PON.

Table 1 Optical power budget class.

	Split ratio1:16	Split ratio 1:32
Distance 10 km	PR10, PRX10	PR20, PRX20
Distance 20 km	PR20, PRX20	PR30, PRX30

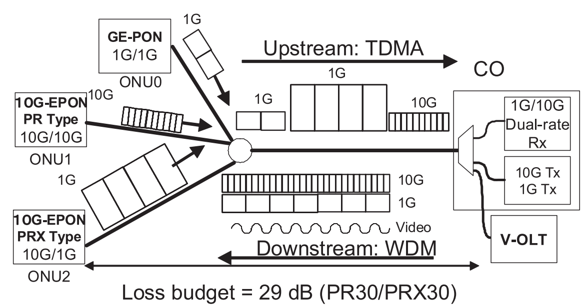


Fig. 3 10G-EPON co-existing with GE-PON and RF-video.

existence can be attained using wavelength division multiplexing (WDM) or time division multiple access (TDMA). For WDM, the wavelengths of NG-PONs must be assigned in accordance with the technical feasibility of optical filters. Since PON systems inherently use TDMA technology for upstream signal, co-exist legacy signals and next generation signals via TDMA can be applied for the upstream using a dual-rate burst-mode receiver [14] at optical line terminal (OLT). Since the dual-rate burst-mode receiver receives the legacy and the next generation signals, the receiver is required to satisfy both specifications.

3. 10 G-bps Class PON Standard Outline

This section introduces a standardization outline, focusing on PHY of 10G-EPON and XG-PON. At first, wavelength plans of both standards are introduced, and then each standard outline is described.

3.1 Wavelength Plan

Both 10G-EPON and XG-PON have almost the same wavelength allocation plan as shown in Fig. 2. The downstream uses L-band and the upstream uses wavelength range of 1260–1280 nm (O^--band) in accordance with the wavelengths of the existing systems.

The downstream wavelengths of both G-PON and GE-PON were 1480 to 1500 nm, and RF-video uses 1550 to 1560 nm. The upstream wavelength allocation of G-PON was originally 1260 to 1360 nm, the same as GE-PON, allowing use Fabry-Perot laser diodes (LDs). However, practical G-PON transmitters have used DFB-LDs and the wavelength bandwidth was able to narrow down to 40 nm (1290–1330 nm).

Since in the O^--band dispersion of single mode fiber (SMF) is a small negative value and optical pulse is slightly compressed after 20-km fiber transmission, direct modulation DFB-LDs can be used for 20 km transmission at the speed of 10 Gbps with little dispersion penalty. In addition, the wavelength range of 20 nm is large enough to use DFB-LDs without a temperature controller. The downstream wavelengths of both 10G-EPON and XG-PON are 1575 to 1580 nm. For XG-PON with outdoor OLT, it is allowed to be 1575 to 1581 nm. In L-band the dispersion of SMF is large and external modulators such as electro absorption modulator integrated DFB-LDs (EML) are used as the transmitter for the downstream.

3.2 IEEE802.3av 10G-EPON

IEEE802.3 finished standardizing 10G-EPON in September 2009. 10G-EPON provides two types of physical layer specifications:
- 10 Gbps downstream/1 Gbps upstream (PRX-xx).
- 10 Gbps downstream/10 Gbps upstream (PR-xx).

As shown in Table 1, the standard defines up to three optical power budgets that support split ratios of 1 : 16 and 1 : 32, and distances of at least 10 and at least 20 km. 10G-EPON can coexist with GE-PON and RF-video, as shown in Fig. 3. WDM is used for overlay in the downstream, and TDMA is used in the upstream.

PR30 and PRX30 have power budgets (loss budget + transmitter and dispersion penalty) as large as 30 dB as shown in Table 2. To achieve such large power budgets at 10 Gbps, high-power optical transmitters and high-sensitivity optical receivers with forward error correction (FEC) are specified. Table 3 shows the FEC parameters. 10G-EPON selected RS(255, 223) code, which has a higher coding gain than that of conventional RS(255, 239). Input signal with BER of 10^{-3} can be corrected to the BER of 10^{-12}; therefore receiver sensitivities are specified at BER =

Table 2 Optical parameters of PR/PRX30 class.

	DS	US	
	PR/X30	PR30	PRX30
Bit rate (Gbps)	10.3125	10.3125	1.25
Operating WL (nm)	1575-1580	1260-1280	1260-1360
Tx Power max (dBm)	+5	+9	+5.62
Tx Power min (dBm)	+2*	+4**	+0.62**
BER	10^{-3}	10^{-3}	10^{-12}
Rx sensitivity (dBm)	-28.5	-28	-29.78
Stressed Rx (dBm)	-27	-25	-23.38
Overload (dBm)	-10	-6	-9.38
Loss budget (dB)	29		
Extinction Ratio (dB)	6	6	6
TDP (dB)	1.5	3	1.4

*Minimum average Tx Power is valid for Extinction Ratio = 9 dB
** Minimum average Tx Power is valid for Extinction Ratio = 6 dB
Stressed Rx: Stressed Rx sensitivity
TDP: Transmitter and dispersion penalty

Table 3 FEC Code.

	Code	Overhead	Net cording gain *	Correctable BER to 10^{-12}
Conventional	RS(255, 239)	7 %	~5.5 dB	10^{-4}
High-gain	RS(255, 223)	13 %	~6.5 dB	10^{-3}

*Ideal estimation in AWGN simulation

Table 4 Burst timing.

Laser on/off time		≤ 512 nsec
Treceiver_settling (AGC)	PR-type	≤ 800 nsec
	PRX-type	≤ 400 nsec
Tcdr		≤ 400 nsec

10^{-3}.

In the PON system, burst transmission is one of the most important issues. Relaxed burst timing is needed in order to reduce optical device costs as shown in Table 4. Here, Treceiver_settling is time for data level acquisition and Tcdr is time for clock data recovery. 10G-EPON newly introduces adjustable laser on and off times [15]. Using this scheme, the ONU with fast on/off LD can reduce the on/off time, and transmission efficiency is maximized.

In addition, a data-like preamble pattern is adopted [16], [17] to reduce burst mode penalties at the OLT receiver. Since in burst transmission at 10-Gbps supports of power and jitter budget is extremely difficult, a simple preamble pattern such as "1010" may cause burst penalty due to frequency response characteristics of the receivers. Burst receivers use peak detectors for fast burst response. The difference in detected/held peak value for "1010" preamble pattern and following data area causes burst penalty. Moreover, the extracted clock timing of "1010" preamble pattern and following data area differs due to pattern dependent jitter and causes sensitivity penalty.

3.3 ITU-T/FSAN

The Full Service Access Network (FSAN) group issued the NG-PON white paper [18] in June 2009 and submitted XG-PON contributions to ITU-T SG15 Q2. As a result, ITU-T has consented to G.987.1 (Service Requirements) and G.987.2 (PMD Layer) in October 2009. Remaining issues such as the transmission conversion (TC) layer which includes FEC implementation, scrambling and frame structure are now under discussion, and consent is targeted by June 2010.

Table 5 Nominal 1 class optical parameter.

	DS			US	
	N1	N2 op. 1	N2 op.2	N1	N2
Bit rate (Gbps)	9.953280			2.488320	
Operating WL (nm)	1575-1580*			1260-1280	
Tx Power max (dBm)	+6.0	+8.0	+12.5	+7.0	+7.0
Tx Power min. (dBm)	+2.0	+4.0	+10.5	+2.0	+2.0
BER	10^{-3}			10^{-4}	
Rx sensitivity (dBm)	-28.0	-28.0	-21.5	-27.5	-29.5
Overload (dBm)	-8.0	-8.0	-3.5	-7.0	-9.0
ODN Loss (dB)	14-29	16-31		14-29	16-31
Path Penalty (dB)	1.0			0.5	
Extinction Ratio (dB)	8.2			8.2	

*In the case of outdoor OLT it is allowed for 1575 to 1581 nm

XG-PON (XG-PON1) specifies asymmetrical physical layers of 10 Gbps downstream/2.5 Gbps upstream. 10-Gbps downstream/10-Gbps upstream (XG-PON2) will be specified in the future.

Two loss budget classes of Nominal-1 (N1: 29 dB) and Nominal-2 class (N2: 31 dB) were defined as shown in Table 5. In addition, extended class that has a loss budget of more than 31 dB has been discussed. Just like 10G-EPON, to realize such a large loss budget, FEC needs to be implemented and used in the downstream as well as implemented and optionally used in the upstream. For downstream the FEC code of RS(248, 216), which has gain as large as that of RS(255, 223), and for upstream RS(248, 232), which has gain as large as that of RS(255, 239), will be consented in June 2010.

4. Key Technologies for Co-existence

As described before, WDM and TDMA technologies are indispensable for smooth migration. This section introduces WDM filters in central office and ONU for co-existence by WDM approach and dual-rate burst receiver for the TDMA approach.

4.1 WDM Filter in Central Office and Wavelength Blocking Filter in ONU

To overlay NG-PON on G-PON using WDM, WDM filters are required, as shown in Fig. 4. The WDM filter, called WDM1r, combines and isolates the wavelengths of NG-PON (DS: 1575–1580 nm, US: 1260–1280 nm) and G-PON (DS: 1470–1500 nm, US: 1290–1330 nm) signals in the central office. The filter that is implemented in ONU and isolates G-PON signals and RF-video signal is called the ONU wavelength blocking filter (WBF). Unlike a conventional WDM transmission system, both wide pass band and narrow guard band are required.

Figure 5 and Table 6 show two kinds of WDM1r con-

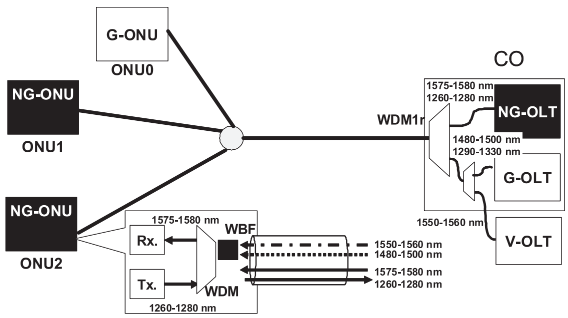


Fig. 4 Co-existence of deployed system with NG-PON via WDM.

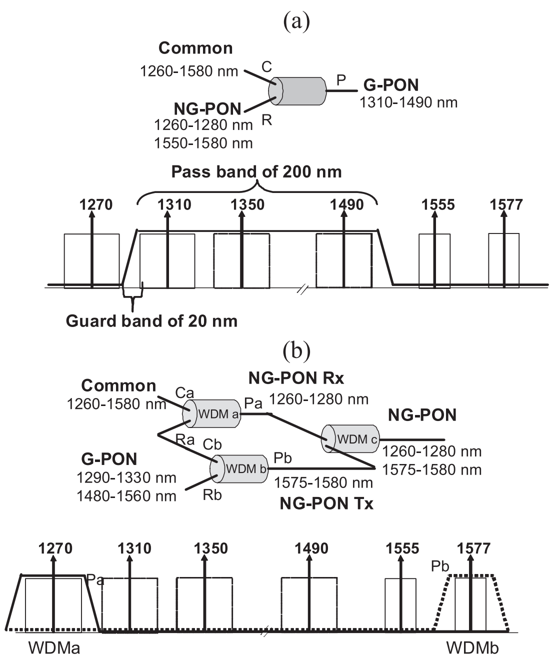


Fig. 5 Examples of WDM filter for co-existence G-PON and NG-PON: (a) Single pass band type, and (b) Combination of two kinds of band pass filter.

figuration using thin film optical filters. There are two implementations for the WDM1r: single pass band filter (type (a)) and band pass filter combination (type (b)). Type (a) is required in both flat pass bands over 200 nm and narrow guard bands of 20 nm between O$^-$-band characteristics. It is difficult to make such wide pass bands without ripples less than 0.5 dB, which is not suitable for mass production. On the other hand, for type (b), no filter is required for such a large pass band, and so is suitable for mass production. The insertion loss for deployed G-PON is less than that of type (a). In addition, dual fiber transceiver can be used without WDM c. Therefore, we developed a type (b) filter.

Figure 6(a) shows optical transmission characteristics of the filter NG-PON ports and (b) shows characteristics of the filter G-PON port. As you can see, low insertion loss less than 1 dB is realized for G/NG-PON ports, and high isolation as large as 35 dB is realized for NG-PON ports.

WBF in ONU is also required for NG-PON and G-PON to co-exist because it isolates the wavelengths of NG-PON wavelengths of 1575–1580 nm from G-PON signals and RF-video signals. Figure 7 shows the isolation characteristics of WBFs provided by NEC Electronics. As you can see, 35-dB isolation is achieved at 1560 nm, which allows co-existence with RF-video.

Table 6 WDM1r architecture comparison.

	Max Insertion Loss (dB)		Cost	Remark
	G-PON 1290-1320nm 1480-1560 nm	NG-PON 1260- 1280 nm 1575-1580 nm		
(a)	1.5	0.8	High	Pass band 200 nm Guard band 20 nm Ripple ~1.0 dB
(b)	0.8	1.6	Low	Mass productivity Small impact on legacy G-PON

Excluding connector's loss, Temperature range:0-40 deg.C,
All state of Polarization

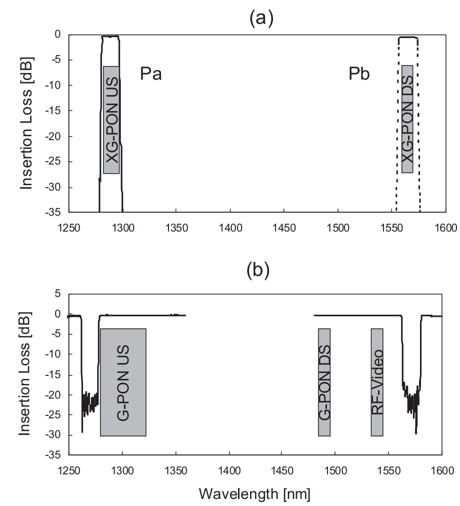


Fig. 6 Transmission characteristics of the WDM1r; (a) NG-PON ports, Solid line shows port Pa and dashed line shows port Pb, (b) G-PON port.

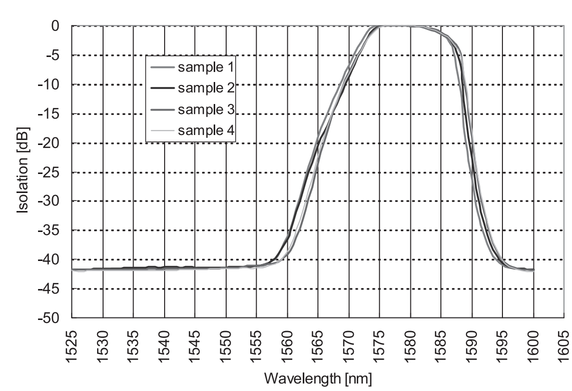
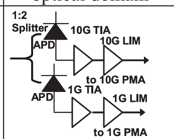
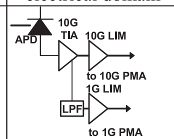
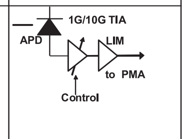


Fig. 7 Isolation characteristics of the WBF for ONU.

4.2 Dual-Rate Burst Mode Receiver

A burst mode receiver needs to operate wider dynamic range

Table 7 Dual-rate receiver configuration.

	(a) Parallel (Static)		(b)Serial (Dynamic)
	(a-1) Split in the optical domain	(a-2) Split in the electrical domain	
			
Pos.	Simple	Fewer optical components.	High sensitivity. Fewer optical components.
Cons.	Receiver sensitivity degrades due to optical splitter. More optical components.	Receiver sensitivity degrades at 1 Gbps signal.	Dynamic control is required.

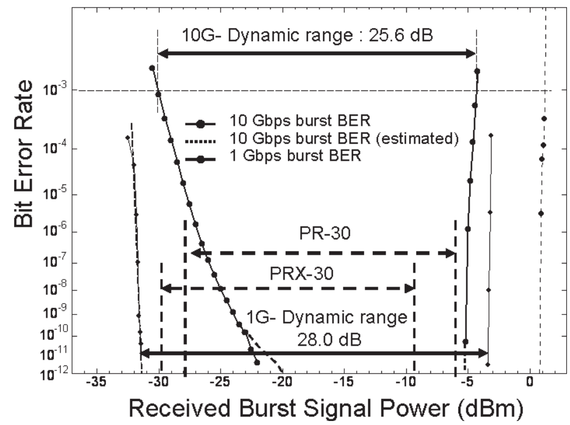


Fig. 8 BER characteristics of the dual-rate burst mode receiver.

for dual-rate operation compared with single-rate operation. As shown in Table 2, 10G-EPON requires sensitivity of −29.78 dBm at 1.25 Gbps and −28 dBm at 10 Gbps and overload of −9.38 dBm at 1.25 Gbps and −6 dBm at 10 Gbps. Therefore, dual-rate receiver is required to operate from −29.78 dBm to −6 dBm. Table 7 details dual-rate burst mode receiver architectures. The dual-rate receiver architecture is classified into parallel and serial types. The parallel architecture splits received signal in to each receiver circuit. The parallel configuration that splits in the optical domain (a-1) is the most simple. However, receiver sensitivity degrades due to optical splitter and so requires more optical components. The parallel configuration that splits in the electrical domain (a-2) uses fewer optical components. However, since in this configuration the bandwidth of a trans-impedance amplifier (TIA) is as wide as 10 GHz, receiver sensitivity degrades at 1 Gbps signal. On the other hand, serial configuration is expected to realize high receiver sensitivity at both speeds, and it uses fewer optical components. However, since it requires dynamic switching mechanism on gain and bandwidth, the technical hurdle is higher than that of the parallel.

Therefore, we adopted the configuration (a-2) as a proto-system. The receiver consists of a Mesa-structur APD [17], a TIA that has a bandwidth of more than 7 GHz, limiting amplifiers (LIMs), and a 4-th Bessel-Thomson low pass filter (LPF). A 10- and 1-Gbps signal can be correctly input into 10 and 1-G bps physical medium attachments (PMA) respectively. To achieve −30 dBm sensitivity at 1 Gbps, an LPF was inserted to suppress high-frequency noise. The receiver used an AC-coupled circuit, and its time constant was designed to satisfy the settling time of 400 ns. We evaluated the dual-rate burst receiver characteristics. In the experiment, 1300-nm high-power direct modulated AlGaInAs-multiple quantum well DFB-LD (MQW DFB-LD) [18], which has launch power of more than +4 dBm, was used as high-power burst transmitters. 10-Gbps burst frame containing of a preamble of 400 nsec and 64B66B coded payload of 1 msec was used and 1-Gbps frame containing of a preamble of 400 nsec and PRBS 2^7-1 coded payload of 1 msec was used. The guard time including the laser on/off time was 100–140 nsec. These frame structures are short enough for evaluating the burst response as shown in Tables 4. The burst receiver alternately received the 10-Gbps and the 1-Gbps burst frame. We evaluated the bit error rate (BER) of the payloads and burst responses less than 400 ns were confirmed. Figure 8 shows BER performance of the receiver. A wide dynamic range was observed of 25.6 dB for 10 Gbps at a BER of 10^{-3} (empty circle) and 28.0 dB one for 1 Gbps at a BER of 10^{-12} (solid circle). Both the burst-mode sensitivities and the burst-mode dynamic ranges are good enough for 10-G/1-G co-existing PON systems.

5. Conclusion

This paper reviewed standardization trends of optical access networks, focusing on 10-Gbps class time division multiplexing passive optical network (TDM PON), and introduced key technologies for their coexistence with Gigabit class PON. Optical filters are introduced for a wavelength division multiplexing (WDM) approach and dual-rate burst mode receiver for TDM approach, and feasibility is demonstrated of co-existence with these technologies.

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