# Physical Layer Testing of Passive Optical Network (PON) Modules

## Application Note

## Introduction

A Passive Optical Network (PON1) is an access technology based on the specification developed by the Full Service Access Network (FSAN) vendor consortium. The ITU-T subsequently ratified PONs in the G.983.1 Recommendation.
Passive is the key word here: PON uses small, inexpensive optical splitters, rather than the relatively large, expensive, and power-hungry optical repeaters used in more traditional optical networks.
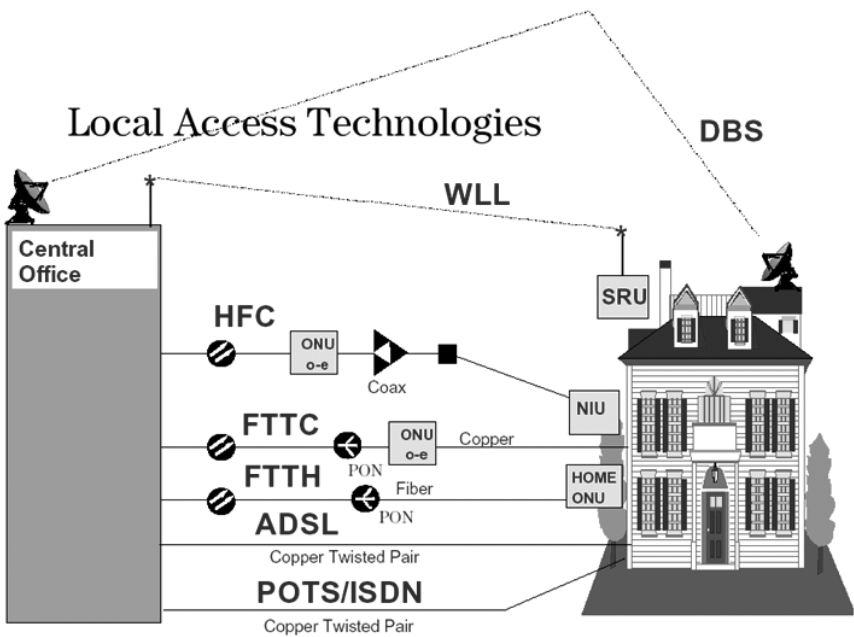
## PON Architecture

PON network components consist of Optical Line Terminals (OLTs), Optical Network Terminals (ONTs), Optical Network Units (ONUs), and passive splitters.
As shown in Figure 2 the OLT is located in the carrier's Central Office (CO) in a telco application, or at a CATV provider's head end.
The ONU or ONT terminates the circuit at the subscriber's end.
An ONT terminates the circuit on the premises in Fiber-To-The-Premises (FTTP) set-ups, where it interfaces the optical fiber to the copper wire.



Figure 1: Local Access Technologies

**Agilent Technologies**

An ONU is used in Fiber-To-The-Curb (FTTC) set-ups. In this case, the fiber stops at the curb, with the rest of the local loop provided over embedded copper-UTP in conventional telco networks and coax in CATV networks. An ONU is also used in FTTN (Fiber-To-The-Neighborhood) set-ups. In this case, it is located centrally in the neighborhood, with the rest of the local loop provided over embedded coax or UTP. While FTTN maximizes the use of embedded cable, and therefore minimizes the costs associated with cable replacement, it compromises performance to some extent.

The passive optical splitter sits in the local loop between the OLT and the ONUs or ONTs. The splitter divides the downstream signal from the OLT at the network edge into multiple, identical signals broadcast to the ONUs. Each ONU is responsible for finding the data intended for it, and ignoring all others. Upstream signals are governed by time-division multiple access (TDMA), with the transmitters in the ONUs operating in burst mode.

FSAN supports both symmetric and asymmetric modes. Current FSAN implementations are generally asymmetric, running at speeds of 622 Mbps downstream at wavelengths between 1480 nm and 1580 nm, and 155 Mbps upstream, between 1260 nm and 1360 nm. Upstream and downstream transmissions can be on separate fibers, or can share a single fiber using Wavelength Division Multiplexing (WDM).

As PON is a passive network technology, the network components do not amplify the signal. This therefore limits trunk lengths and the number of signal splits. At current speeds and with current splitter technologies, FSAN trunk lengths can be up to 20 km, and each trunk can support as many as 32 users and 64 endpoints.
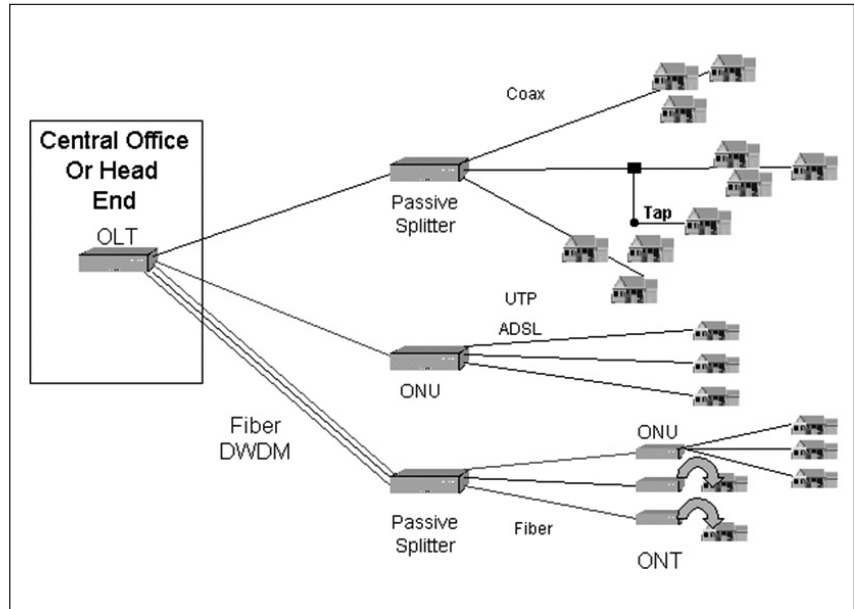


Figure 2: PON Architecture

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## PON Module Basics

The first generation of PONs used data rates from 12 Mb/s to 155 Mb/s and scalable frame sizes, such as 4012 bits.

The next generation Broadband PON (BPON, also referred to as APON) used data rates from 155 Mb/s to 622 Mb/s and used ATM cells for transmission. These provided either symmetric 155 Mb/s, or asymmetric 155 Mb upstream, 622 Mb/s downstream. The data was assigned to fixed time-slot of 56 ATM cells (= 23744 bits).

EPON systems use Ethernet framed data. For 1 Gb/s data rate, this takes 1.25 Gb/s because of 8b/10b coding. With Grant/Request handling EPON allows the negotiation of bandwidth for individual subscribers.

The latest development is GPON, running at 1.25 Gb/s and 2.5 Gb/s. Again it is based on fixed 125 µs time-slots and fixed frame size of 311040 bits per frame.

Figure 3 shows an example of PON modules, with dedicated modules for OLT and ONU/ONT.

While the downstream traffic sent by an OLT goes to each subscriber (ONU), the bigger challenge is the upstream traffic, where each subscriber can send traffic to the provider.

Private frame definitions have been used since the beginning of PON technology. Today cell-based TDMA is becoming important (because ATM cells or Ethernet frames are transmitted in the payload) for upstream transmission ("back channel") from the subscriber, with each ONU using a certain time-slot to transmit data. The guard time is a critical parameter here, as this is what makes sure the packets from different subscribers fit into the correct slot to ensure proper reception at the OLT. Figure 4 shows upstream communication for a BPON/GPON network using TDMA.
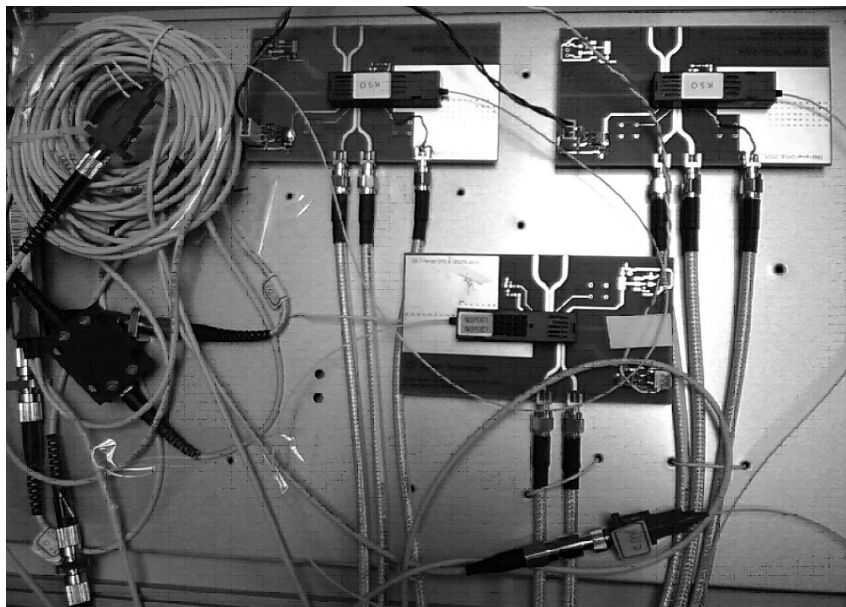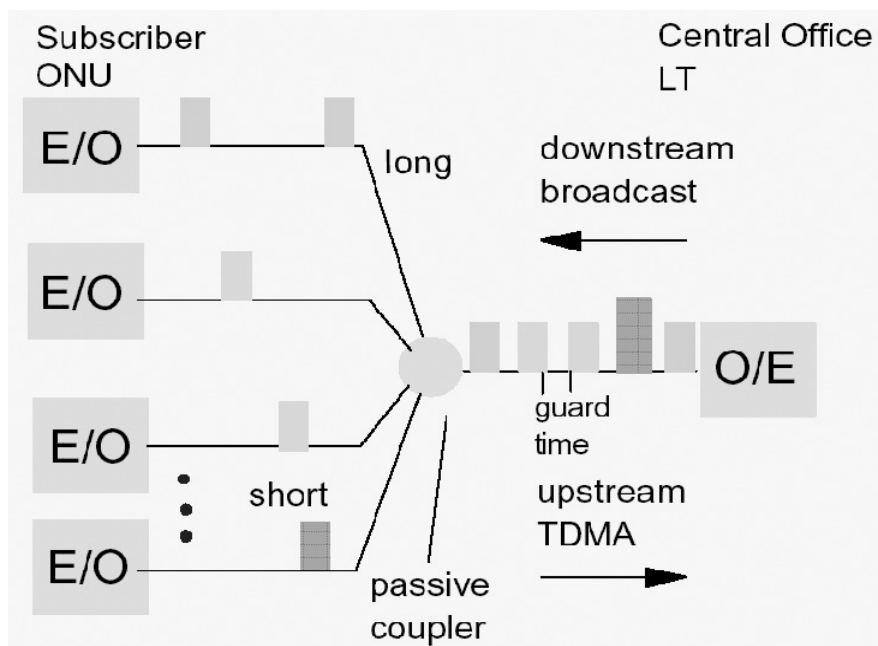


Figure 3: PON OLT and two ONU Modules



Figure 4: TDMA Principle used with BPON/GPON

## The benefits of PONs: Standardization

The International Telecommunication Union (ITU) started releasing the G.983 series recommendations and amendments in 1998. These deal with the broadband optical access systems based on PONs.

APON (ATM-based Passive Optical Network) runs the ATM protocol, favored by the ILECs for DSL and their internal backbone networks. ADSL and G.lite run well over APON in a hybrid fiber/copper network. The ITU-T standard for Wide Wavelength Division Multiplexing (WWDM) applies to APON. WWDM specifies normal transmissions in the band from 1480 nm to 1500 nm, and an enhanced band for video and other future applications between 1539 nm and 1565 nm. APONs support 16 wavelengths with 200 GHz spacing between channels and 32 wavelengths with 100 GHz spacing.

At the time of writing the IEEE is finalizing standards for EPON (Ethernet-based Passive Optical Network), which has great potential to support Gigabit Ethernet (GbE) and 10 GbE.

The ITU added the G.984. series recommendations in 2003, building on the existing and widely adopted G.983 series, but increasing capacity to gigabit levels. This should more than satisfy foreseeable customer demand. The resulting GPON keeps the same optical distribution network, wavelength plan and full-service network design principles of G.983. But, as well as allowing for increased network capacity, the new standard offers more efficient IP and Ethernet handling.

## Testing according to the IEEE 802.3ah Standard

The IEEE 802.3ah standard specifies a long list of electrical and optical parameters for PONs, including:
• Bit rate
• Frame length
• Wavelength
• Cell length
• Input levels
• Output levels
• Guard time
• Reset pulse width
• Rx input power
• Tx output power
• On time, Off time
• Receiver Setting Time
• CDR setting time
• Burst sensitivity
• Dynamic range
• BER (Bit Error Rate)
• BER against power
• BER against guard time
• Jitter/Eye Mask definition

In this document we discuss testing in two parts: First, dealing with the signal and timing issues and then dealing with the optical parameters.
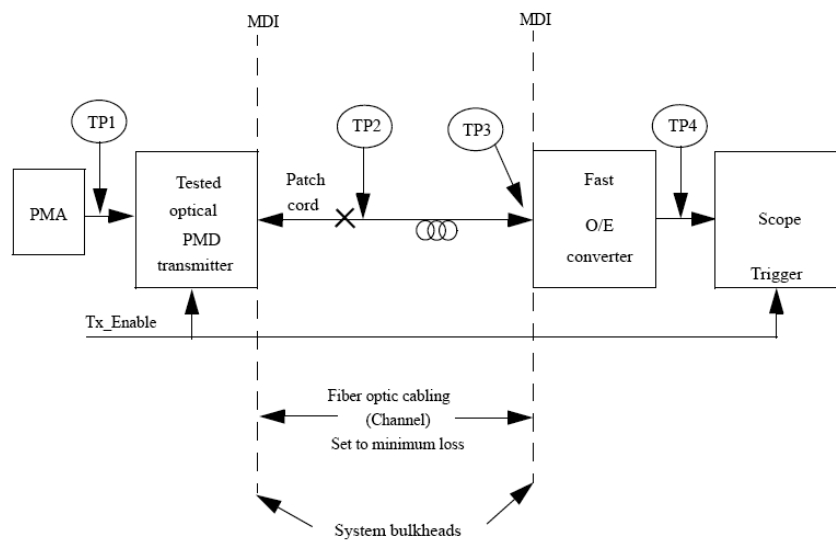


Figure 5: Point-to-Point Setup Definition, for example, for laser on/off timing and receiver sensitivity measurements
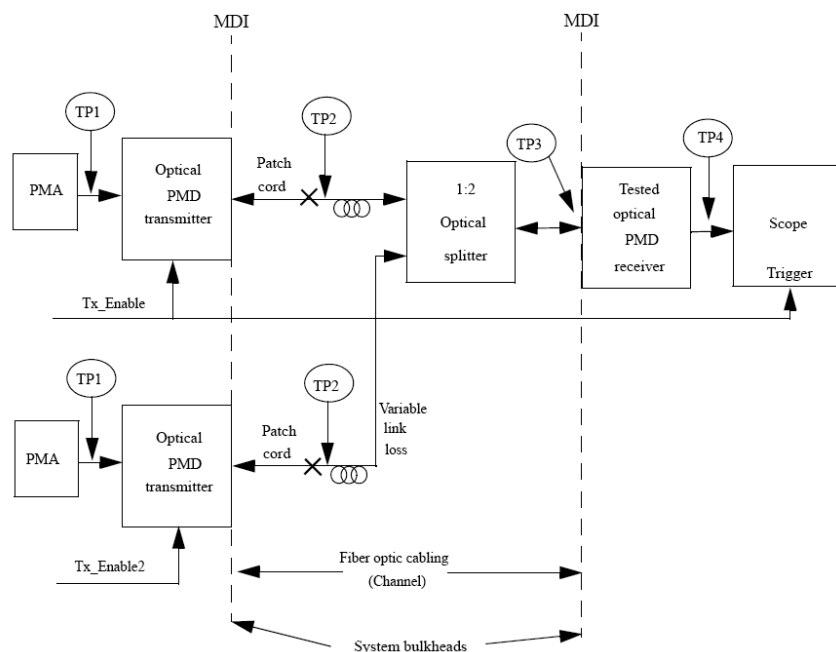


Figure 6: Multipoint Setup for example, for jitter testing

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## Signal and Timing Specifications

Signal and timing issues deal with the specifications given in chapter 60 of the of IEEE802.3ah standard.

The specifications covered here deal with:

- Tx extinction ratio
- Rx sensitivity
- Rx stressed eye
- Rx sinusoidal tolerance
- Upstream and downstream jitter
- Tx on−off ($T_{on}/T_{off}$)
- Rx settling time

These parameters need two different kinds of test setup:
- Point-to-point, as shown in figure 5, and
- Multipoint, as shown in figure 6.

The following examples are given here:
- Figure 7 specifies the Tx and the Rx timing behavior. It includes On/Off switching of the ONU, and the OLT settling

- Table 1 specifies the downstream jitter behavior.

- Figure 8 shows the transmitter output eye mask. This verifies the Tx output, and can be used as a template for the input signal to test the Rx for jitter tolerance.



Figure 7: Laser on/off timing, receiver timing

Table 1: Down-stream jitter

| | Total jitter | | Deterministic jitter | |
|---|---|---|---|---|
| Reference point | UI | ps | UI | ps |
| TP1 | 0.24 | 192 | 0.10 | 80 |
| TP1 to TP2 | 0.191 | 153 | 0.15 | 120 |
| TP2 | 0.431 | 345 | 0.25 | 200 |
| TP2 to TP3 | 0.009 | 7 | 0 | 0 |
| TP3 | 0.44 | 352 | 0.25 | 200 |
| TP3 to TP4 | 0.309 | 247 | 0.212 | 170 |
| TP4 | 0.749 | 599 | 0.462 | 370 |



Figure 8: TX Eye Mask
(x1=.22, x2=.375, Y1=.2)

## Part 1: PON Module Signal and Timing Test

The focus in this document is on the multipoint setup and upstream measurements. This is the most complex setup and most other measurements can be derived from this, by simplifying the setup.

The PON transceiver signal and timing test solution uses the following Agilent equipment:
- 81250 ParBERT
- 33250B Function Generator
- E4422B RF Signal Generator
- 86100C Infiniium DCA-J (Digital Communications Analyzer with jitter analysis) Wide Bandwidth Oscilloscope
- 86105C High Sensitivity, Broad Wavelength Multi-Rate Optical Module
- 8164B Lightwave Measurment System
- 2x 81570A Optical Attenuator
- 81635A Optical Power Sensor

The Devices under Test are the two ONUs, the Optical Coupler with the optical cables, and the OLT.

The ParBERT provides the stimulus for the OLTs and the ONU. The Function/Signal Generator can modulate the ParBERT output to introduce jitter and noise for stressed eye and tolerance testing.
The waveform measurement capabilities of the DCA-J scope and the BER measurement capability of the ParBERT are used for the analysis.

This setup corresponds to the multipoint setup shown in figure 6. It can be converted into the point-to-point setup shown in figure 5 by connecting one ONU directly to the OLT.
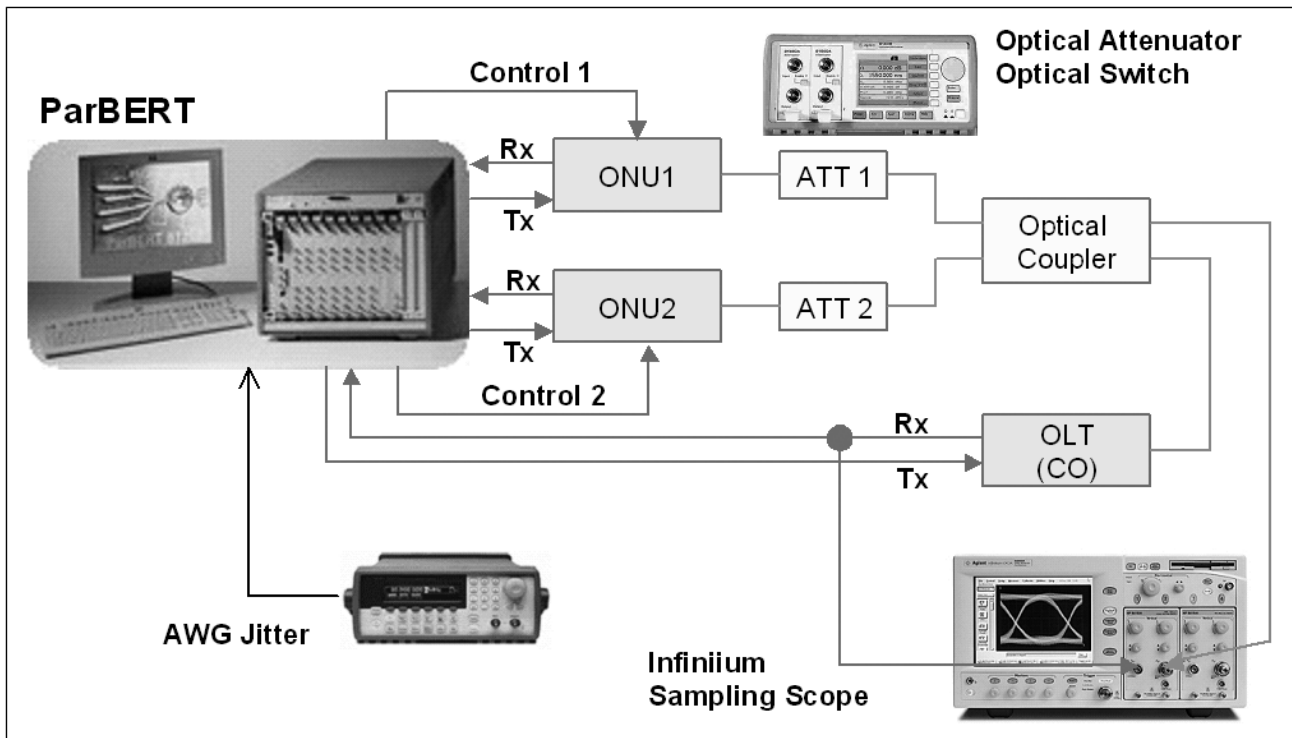


Figure 9: Agilent's Physical Layer Test Solution for Timing and Signal Measurements, including bi-directional traffic control

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**Configuring the ParBERT**

There are two cases we need to consider when providing the Tx and enable signals to the ONUs and the stimulus and analyzing signals (Tx and Rx) to the OLT.

The first case is for EPON, where we need 3 Tx, 2 Enable and 1 Rx channels. One Tx is for bidirectional stimulus of the OLT.

To achieve this we use
- 1x 81250A ParBERT with #013 Firewire and #149 Frame
- 1x E4875A Software and Measurement Suite
- 1x E4808A Highe Performance Central Clock Module
- 3x E4861B 3.35 Gb/s Data Module
- 5x E4862B 3.35 Gb/s Generator Front-End
- 1x E4863B 3.35 Gb/s Analyzer Front-End

For the second case, an ATM Base BPON, we need:
3 Tx, 2 Enable, 1 Rst, and 1 Rx channels. Again one Tx is for bi-directional stimulus of the OLT.

As well as the equipment listed above, for this we use:
- 1x E4861B 3.35 Gb/s Data Module
- 1x E4862B 3.35 Gb/s Generator Front-End

Useful Accessories:
- 2x 15432B 250 ps Transition Time converter, this shapes the input signal to ONU1
- 2x 11636B Power Divider, to add noise
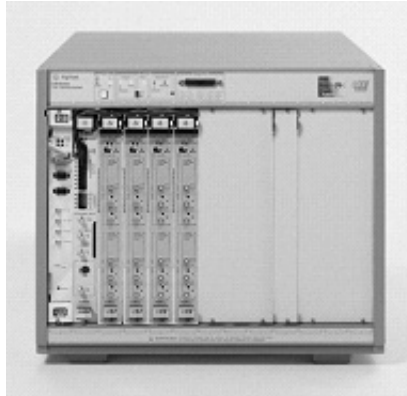


Figure 10: ParBERT configuration for the bi-directional test
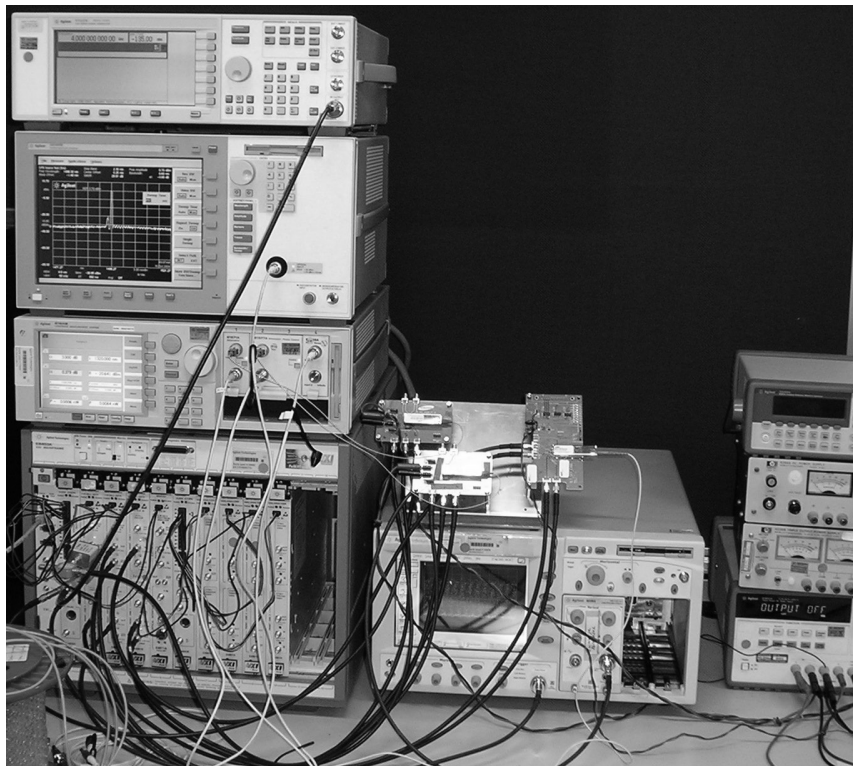


Figure 11: Complete equipment setup

**Generating the Upstream Bit Sequence**

Figure 12 shows the bit flow for upstream testing.
The left column shows the 6 signals:
- ONU1, the data to ONU1 Rx
- O1EN, the enable ONU1
- ONU2, the data to ONU2 Rx
- O2EN, the enable ONU2
- OLTRx, the data expected from ONU1 Tx, measured
- OLTTx = bidirectional traffic to OLT

The data flow is structured in 11 columns that we can later transfer into segments and blocks to enter in the ParBERT sequence editor.

The first three columns synchronize the test equipment. This synchronization automatically adjusts the timing relation by compensating for the delay in the test setup and placing the analyzer sampling point into the middle of the data eye.

From column 4 to 11 the bit flow is repeated indefinitely to measure the BER on the ParBERT, or measure waveform parameters on the DCA-J scope (or other equipment). Blocks 4 to 7 contain the burst of data for ONU1; blocks 8 to 11 contain the burst of data for ONU2. While one ONU is active, the other is supplied with data '0' to be quiet.
The burst of data contains 4 phases:
- Guard Time (blocks 4 and 8)
- Settling (blocks 5 and 9)
- ONU Data (blocks 6 and 10)
- $T_{off}$ (blocks 7 and 11)

This structure allows us to assign individual bit lengths to each segment. It is also flexible enough to allow changes while testing.

The OLTTx signal allows continuous bidirectional traffic.

| # of Sequence | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bit length | 128 | 640 | 640 | 64x10 | 128x10 | 2048 | 64x10 | 64x10 | 64x10 | 4096 | 64x10 |
| | | | | | | | | | | | |
| ONU1 | 0 | ONU1 DATA | 0 | 0 | PRE | ONU1 DATA | 0 | 0 | 0 | 0 | 0 |
| O1 EN | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| ONU2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | PRE | ONU2 DATA | 0 |
| O2 EN | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| OLTRx | - | ONU1 DATA | - | - | - | ONU1 DATA | - | - | - | - | - |
| OLTTx | OLTTx | | | | | | | | | | |
| | ->Sync | | | Trigger | | | | | | | |
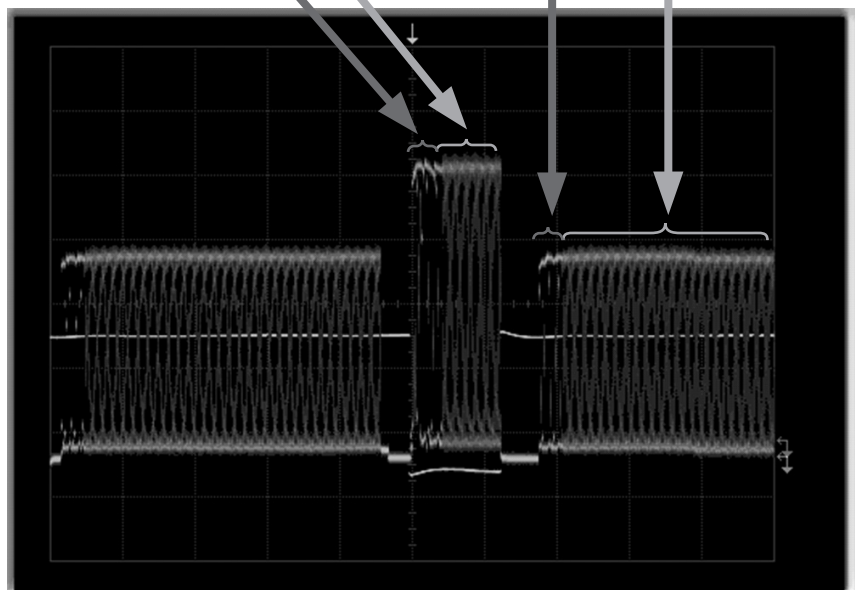


Figure 12: Test Sequence (bit flow) for up-stream testing including bi-directional data flow

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**Setting Up the ParBERT for Bidirectional Upstream Test**

We use 5 Generators to stimulate the 2 ONUs with data and enable the OLT input. One Analyzer looks at the OLT output while checking the BER with regard to the data supplied to ONU1.

Figure 13 shows the general generator and analyzer setup. The frequency is set to 1.25 Gb/s, the analyzer start delay to 40 ns. This delay setting is important, as it reflects the propagation delay of the cabling. It needs to be accurate to within ± 10 ns for proper synchronization of the ParBERT. The system is already started and running, and the BER window displays the current BER of '0'.

Figure 14 shows the sequencing setup. The 6 columns represent the 6 ports. Synchronization happens in block 2 as Auto Delay. Repetitive data can be setup using multiple nested loops; finally there is an infinite loop for indefinite looping on the ONU1 and ONU2 frames. The ParBERT Sequence Editor is a powerful tool for taking the data flow from figure 12, and entering and modifying it as needed.
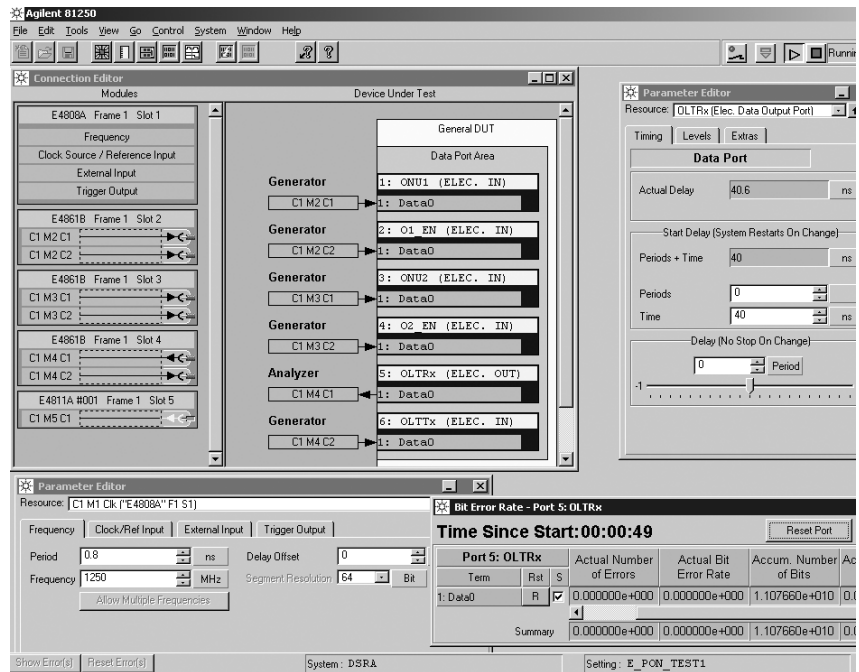


Figure 13: ParBERT system setup
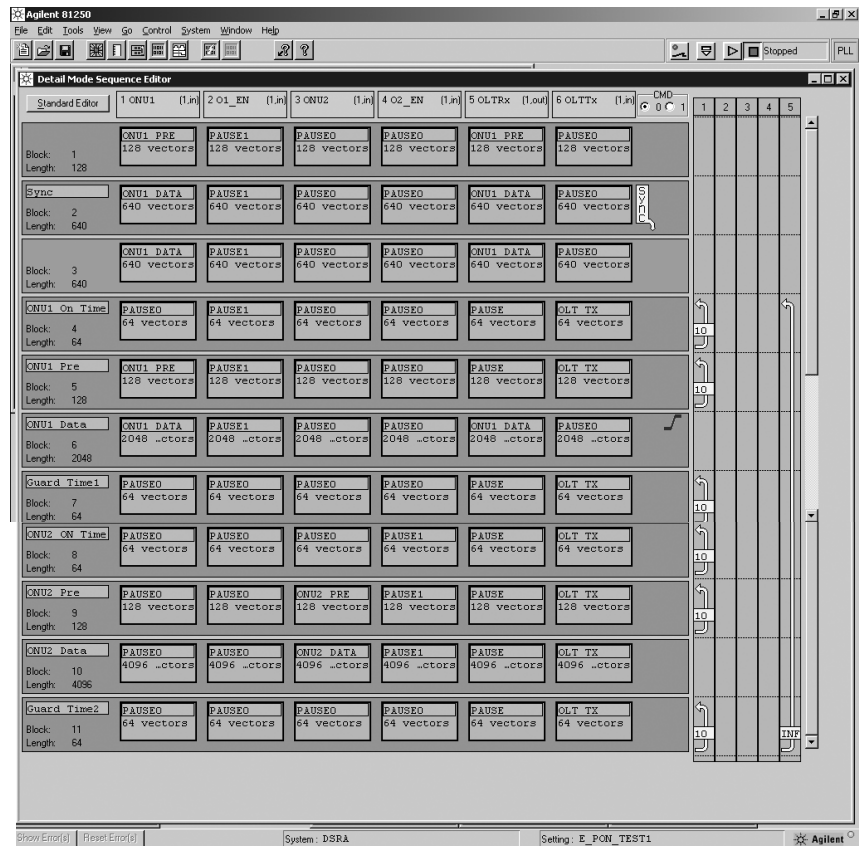


Figure 14: ParBERT Sequence Editor for bidirectional upstream test sequence

**Measurements of the On-time, Off-Time, Dynamic Range and Guard Time**

Here we look at the ONU1 output when running the data sequence shown before.
Examining the first bits, we can verify the Laser On-time switching. The last bits tell us about Off-time switching.

Changing the attenuator settings lets us adjust the ratio of ONU1 power level to ONU2 power level. This lets us characterize the dynamic range behavior (see figure 24).

Sequence Block 7 and 11 define the Guard Times. Changing the length of block 7 affects the Guard Time between ONU1 and ONU2, changing length of block 11 affects it between ONU2 and ONU1. This gives us much flexibility for checking the Guard Time behavior.

First bit (0)

bit 64

bit 128

bit 256

bit 1024

bit 2046

bit 3064
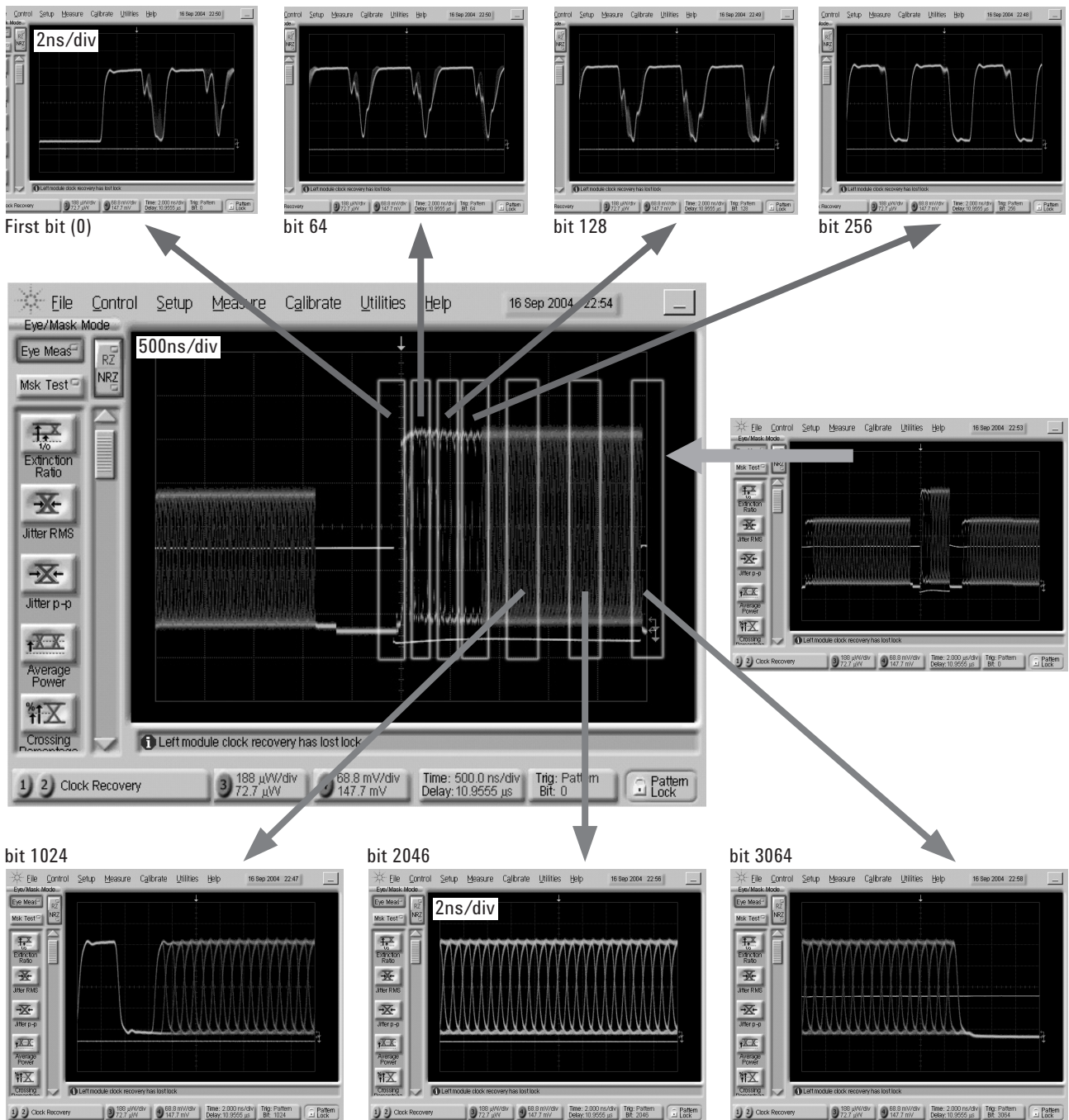
Figure 15: Zoom into the ONU 1 signal with the DCA, parallel to continuous BER measurement

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## Measuring Extinction Ratio, Receiver Sensitivity and Tx Eye Mask

Figure 16 and 17 show the Extinction Ratio measurement, which is a predefined measurement on the DCA-J scope.
The pictures show the ONU output.

Figure 18 shows the upstream ONU signal with respect to a GbE Mask with 10% Margin. This type of mask is also predefined on the DCA-J scope.

Figure 19 shows the OLT's Receiver Sensitivity as an upstream measurement in point-to-point mode. The attenuation or the optical power is varied while monitoring the BER. The graphical presentation is made using a spreadsheet.
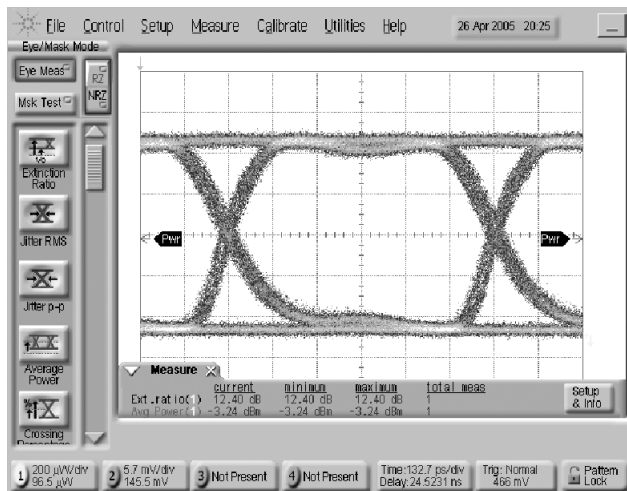
Figure 16: Static Extinction Ratio
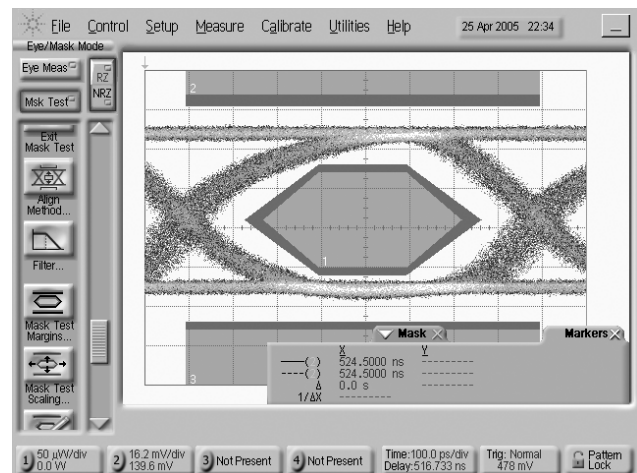
Figure 18: Output signal and Eye Mask
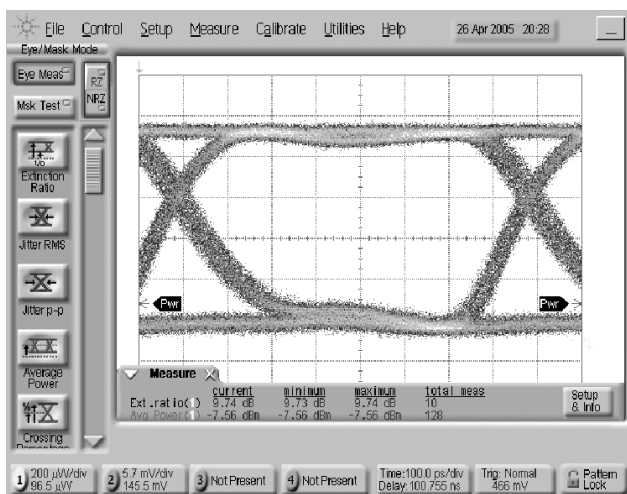
Figure 17: Dynamic Extinction Ratio
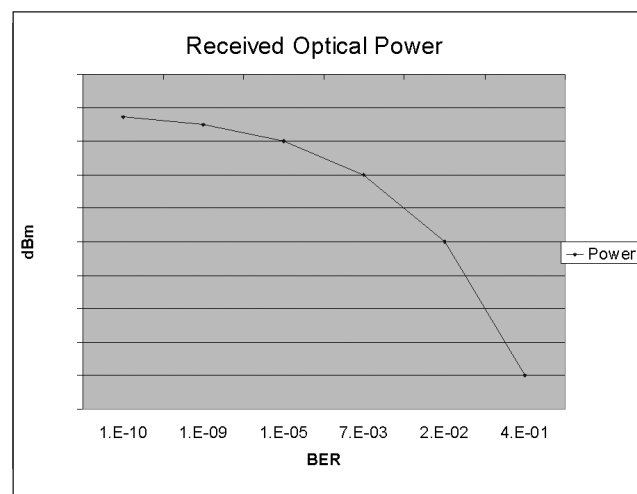
Figure 19: Receiver sensitivity

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**Measuring Upstream Jitter**

Figure 20 shows the setup of a electrical signal with jitter applied to ONU1. The jitter modulation is according to the eye mask in figure 8. A sinusoidal signal from the function generator is applied to the Delay Control of a ParBERT generator to close the eye by 0.56 UI (an opening of 448 ps). This can be controlled using the markers on the DCA-J scope.

Figure 21 shows the output of ONU1device when the signal from figure 20 is applied.
The eye opening is further reduced by the intrinsic jitter of ONU1.

The standard requires measurements of both upstream and downstream $T_j$ and $D_j$. Upstream it is required with and without jitter applied to the ONU.
The Output Timing measurement provided by the ParBERT measurement suite give direct readings of the $T_j$ and $D_j$ measurements.

Figure 22 shows the measurements obtained with and without jitter modulation. The graph visualizes the BER over time, the table below allows a direct read-out of remaining Eye Opening (Phase Margin), and the values of $D_j$ and $T_j$. The $T_j$ value is extrapolated for a BER of 1e-12 as specified by the standard.
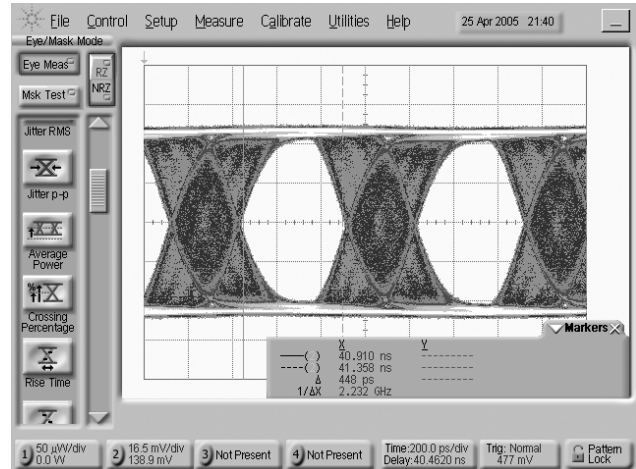


Figure 20: Jitter input signal
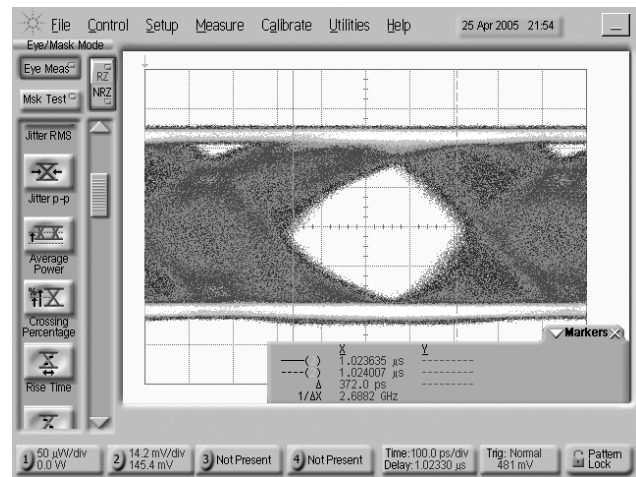


Figure 21: Output signal with jitter applied
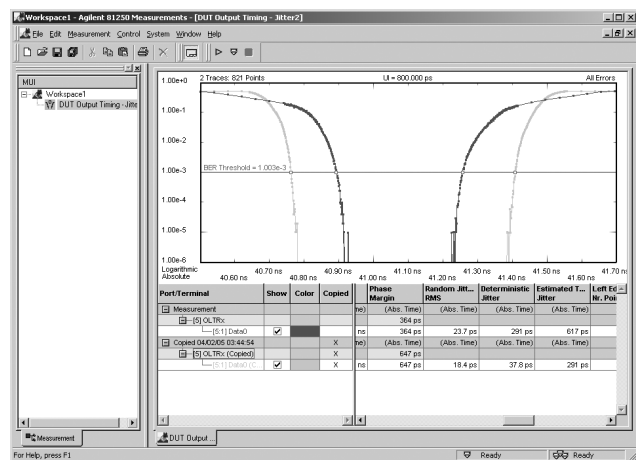


Figure 22: $T_j$ and $D_j$ at OLT output

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## RX Stressed Eye, Dynamic Range & RX Sinusoidal Tolerance

Figure 23 shows the stressed eye supplied to ONU1 for the vertical eye closure penalty test. By using power dividers, a sinusoidal signal at 4 GHz is added to one of the differential inputs to ONU1. The noise is incremented until the BER shows errors. At this point the ONU1 input signal is measured giving:

Vertical eye closure Penalty: 6.64 dB
An = 800 mV
Ao = 173 mV

Figure 24 shows the Dynamic Behavior against BER. The setup used is same as in Figure 15.

Figure 25 shows the Sinusoidal Jitter Tolerance.
Jitter is added to the data sent to ONU1 by applying a sinusoidal signal to the delay control input of the ParBERT. The amplitude of the sinusoidal signal sets the amount of jitter. It is increased until the BER shows errors. The current jitter modulation ($P_j$) is measured with the DCA-J scope. This is repeated for different frequencies of the sinusoidal signal. The graphical presentation is made using a spreadsheet. It shows the maximum $P_j$ (in UI) tolerated as a function of jitter frequency.
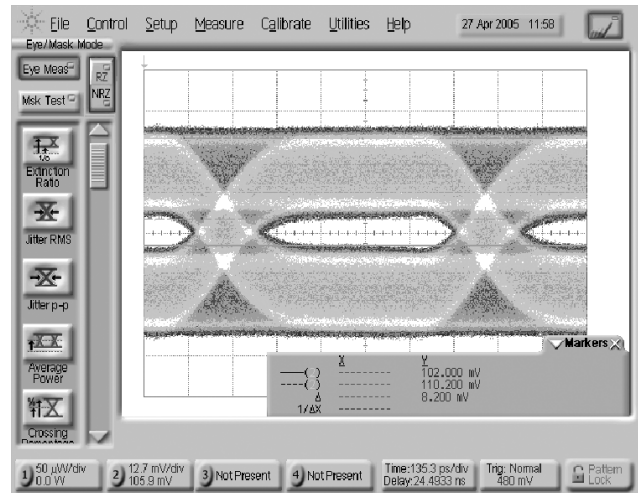


Figure 23: Stressed Eye applied to ONU 1
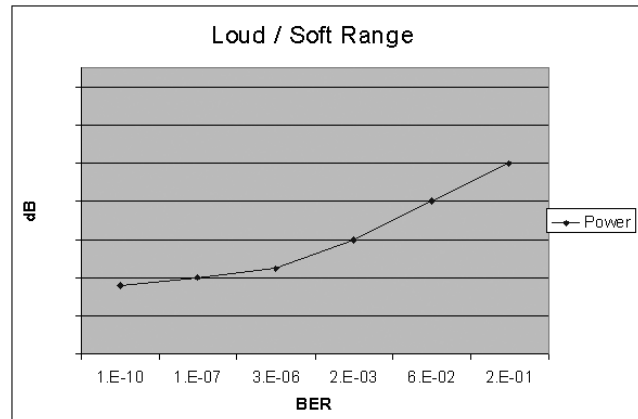


Figure 24: Loud/Soft Range
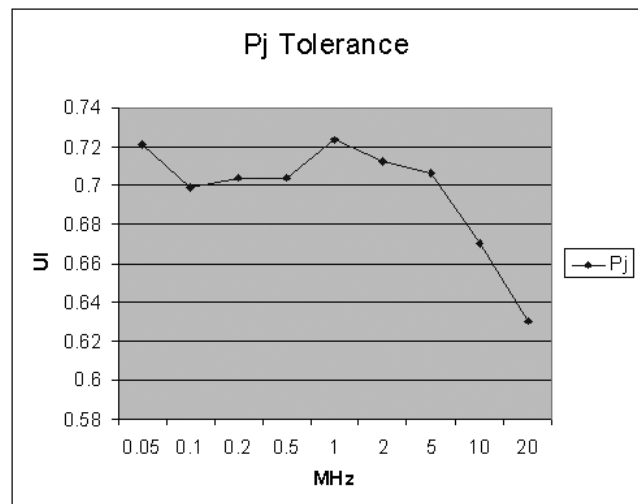


Figure 25: Jitter Tolerance

## Part 2: Optical Measurements

Both the ONU and OLT modules, and their subcomponents, such as diplexers and triplexers, are characterized in the optical wavelength and amplitude domains according to international standards. This assures practical and optimized network use in the PON. The specified wavelength range used for upstream and downstream transmission differs for various PON architectures. Generally, signal transmission is in the ranges 1260-1360 nm (O-band) and 1480-1560 nm (S- and C-band). These are important for transmitter and receiver characterization[2,3].

### Testing RMS Spectral Width

Spectral characterization of the transmitter laser assures operation in the specified wavelength range and within the specified spectral width. Transmitters for the access network mostly take advantage of cost-effective laser sources, for which spectral width could be a concern. Typically, the ONU uses Fabry-Perot lasers, which are economical and well suited to O-band wavelengths. The limits for spectral width become tighter for both module types when the center wavelength of the laser is not at the center of the band, since this increases dispersion penalty and the bit error ratio.

Thanks to the generous wavelength ranges and moderate data rates, the spectral specifications for PON transmitters do not need the most expensive laser technology. These can be tested with an optical spectrum analyzer (OSA). Its optimized sweep time and portability provides the best fit for both development and manufacturing when minimum measurement time and adequate accuracy and sensitivity are taken into consideration.

Figure 26 shows spectra from an inexpensive DFB laser source in an OLT (left) and a Fabry-Perot laser source in an ONU (right), both measured with the Agilent 86143B OSA.

Special characterization needs to be done for WDM-PON, because the service provider and subscribers are connected virtually point-to-point using individually dedicated wavelengths. The advantages of this are network expandability and lack of signal collision[4]. Mature WDM measurement technology provides the ability to test such components with single-box test solutions that include a tunable laser source (TLS) with sub-picometer resolution and one or more power meters to measure the spectra accurately.

### Average Launch Power for the Transmitter

Absolute power measurement for ONU and OLT transmitters can be made using an optical power meter. The uncertainty of the meter determines the accuracy of the test. The responsivity curve of InGaAs photodiodes used in the Agilent 81634B Optical Power Sensor is optimized for O- to L-band detection and calibrated for ±2.5% uncertainty*. An uncertainty of ±1.5% is possible using the Agilent 81624B Optical Head. When measuring high port counts, the dual channel Agilent 81635A Optical Power Sensor increases throughput, and minimizes the cost of ownership and investment.

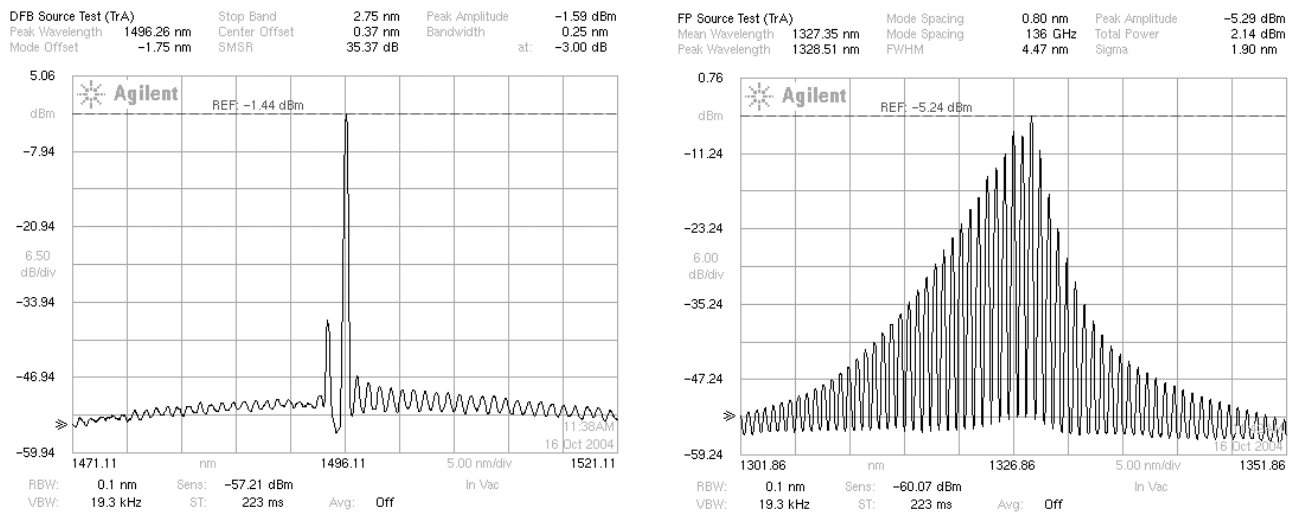*all uncertainties traceable to NIST and PTB standards laboratories.



Figure 26: Spectra from an inexpensive DFB laser source (left) and Fabry-Perot laser source (right)

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### Receiver Sensitivity and Reflectance

The receiver characteristics of primary interest are sensitivity and reflectance. The performance reliability of the signal conditioning unit in a test setup greatly influences any electrical and optical test parameters. Signal conditioning includes optical attenuators for controlling the signal power level to determine sensitivity, and optical switches for automating the setup for operational efficiency. The challenge is to minimize measurement uncertainty in the test setup. The result of ONU extinction ratio in the eye diagram using the Agilent DCA-J scope is observed to compare the influence of using an optical attenuator on the test result. An experimental result shows the difference between the extinction ratio without any attenuator in the test setup and with Agilent 81577A Optical Attenuator is only 0.09dB.

Figure 27 compares the influence of optical attenuators in the test setup. (left: no attenuator, center: result using Agilent 81577A, right: result using other attenuator)

Optical attenuators, couplers, and power meters are combined in the test setup but the lack of specification for such multiple equipment setups can make performance unpredictable. Minimizing the complexity, and therefore such measurement uncertainty, can be achieved using an optical attenuator with integrated power control, such as the Agilent 81576A or 81577A Optical Attenuator. All the performance including accuracy, insertion loss, and return loss are specified for the instrument, so the measurement uncertainty can be quantified and calculated.

## Considerations for Network Maintenance

After deployment it is suggested to maintain the access network using an optical signal, for example at 1650 nm[5], for active line monitoring. This is critical for regular network maintenance, or in TDMA when it is necessary to perform an installation test for new subscribers without incurring service down-time. The characterization of components for this is typically done with an OSA (often in combination with a TLS) that can measure to 1650 nm and above. Optical time-domain reflectometry (OTDR) is commonly used for monitoring the deployed network.
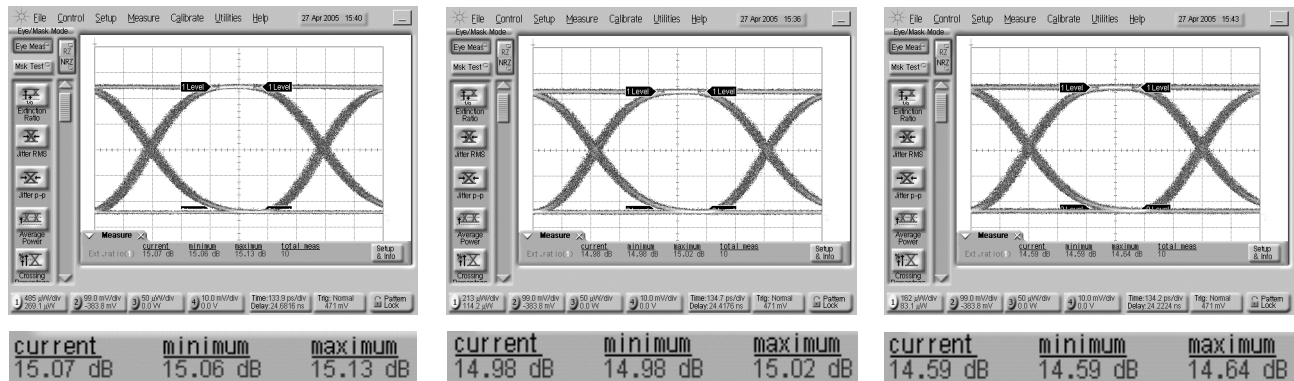


Figure 27: Comparison of the influence of optical attenuators

## References

[1] The PON Forum:
www.ponforum.org

[2] IEEE Draft P802.3ah™/D3.3
(Amendment to
IEEE Std 802.3™-2002)

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