HETEROGENEOUS INTEGRATION ROADMAP

2019 Edition

Chapter 17: Test Technology

Section 02: Test of Photonic Devices

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Section 2: Test of Photonic Devices

Executive Summary

This section addresses overall lifetime test issues resulting from the inclusion of photonic capabilities into devices and products. The emphasis is on silicon wafers and die with photonic functionality, and assemblies and products that include these devices. Systems in Package (SiP) assemblies and systems are addressed to the extent viable given the diversity of test needs that are specific to applications. The test issues for wafers, die, SiPs and systems will be addressed at the Design, Qualification, Validation, Production and In-Use stages of life cycles. Current and anticipated optical parameters to be tested and their value or level are considered along with the test access issue at each stage of the product life cycle.

Telecommunications test equipment, components and methods were and are being adopted for optical testing of products used for non-long-haul applications. The traditional methods are being extended and new methods developed to address test needs for photonic wafers, photonic integrated circuits, System in Package (SiP) that utilize optics, and complete systems. Utilizing these extended methods requires optical probing of both wafers and die combined with electrical probing, resulting in a series of mechanical issues. The inclusion of optical probing, especially single mode probing, requires gratings or other access points on wafers. For individual die, dual mode (electrical and optical) probing is especially difficult due to the small size of die and difficulty of holding and locating probes accurately. At the SiP level, the problems are easier because the device is larger, not as fragile, and is often designed to facilitate dual-media probing. The wafer, die and SiP probe fixtures tend to be expensive due to the complexity and accuracy required. System-level test access is usually easier because at that level, electrical interfaces and optical connectors are included as part of the DUT.

In addition to probe access, optical test methods to simultaneous characterize and compare multiple optical lanes and/or ports at the same time are needed. One need is comparative simultaneous testing of multiple signals from arrays of ribbon fibers, waveguides or chip sources or detectors for optical skew, jitter, etc. A related need is simultaneously evaluating optical signals multiplexed on one fiber or waveguide. Applications with arrays of up to 256 ports (fibers, waveguides chips) or ~256 multiplexed wavelengths are forecast in the next 10 years.

In addition to the standard telecom optical parameters (power, wavelength, attenuation, jitter, SNR, etc.), emerging applications utilize virtually every parameter that light can have, potentially requiring the extension of test capability in multiple dimensions such as polarization, phase noise, spatial modes, multiple fiber cores, etc. While these emerging needs are potentially very broad, the near-term emerging needs seem most likely to be extensions of data communications needs.

Optical communication applications are likely to utilize 650 nm to 1700 nm wavelengths, multiplexed wavelength spacing down of 25 GHz, detector efficiency of ~1Amp/Watt, receiver sensitivity as great as -45 dBm, power levels of 1 watt or less, symbol rates of 100 Gbaud per lane, modulation schemes utilizing up to 10 bits per symbol, polarization multiplexing, BERs of 10-12, etc. Over time these parameters will improve, so test capabilities will need to stay ahead of them. Data rates as high as 500 Tbps per fiber are likely to emerge in the next 10 to 15 years.

Design for test by including optical test access points, Built In Self Test (BIST), redundancy for self repair and prognostics to report changes and deterioration during operation over the life cycle of optical products are desirable and of value in an increasing number of applications. These should be considered for inclusion not only in designs but in software design tools as well.

This section on photonics test contains our best estimates of key trends influencing this industry over the next 15 years. This roadmap includes trends in semiconductor device technologies and their impact on test, as well as roadmaps for key test enablers (Device Handlers, Test Interfaces, and Test Methods). The resulting Cost of Test is also analyzed and discussed.

INTRODUCTION

This section focuses on unique attributes of testing optical devices. No attempt has been made to duplicate required and typical electrical or mechanical testing.

The chapter is open ended on optical applications testing with much of the material broadly applicable. It does, however, concentrate primarily on testing data communications products.

The section addresses photonic testing for:

a. photonic integrated circuits (PICs) on wafer
b. individual PIC die
c. photonic System in Package (SiP) devices
d. system level optical functionality, such as a complete transceiver or Active Optical Cable (AOC).

Another dimension addressed is testing needs over a product life cycle:

a. during development to prove functionality and de-bug devices
b. qualification testing
c. pre-production validation
d. in-process production testing to assure product quality and improve yield.

Links vs Channels

An optical link utilizes one wavelength traveling from one point to another in one fiber or waveguide. Information may be imposed on the beam utilizing any methods such as On-Off-Keying, PAM XX, dual polarization or any method that affects only that wavelength.

A Channel may consist of a single lane but often, even usually, has multiple lanes. The lanes may be on multiple parallel fibers or waveguides, or on the same fiber or waveguide utilizing wavelength division multiplexing. Many datacom standards utilize multiple lanes to achieve their data rates.

Evaluating technical capability is most easily done utilizing lanes because channels that combine many lanes make it difficult to understand the underlying technology. System designers, however, find the channel view more useful as the technology details are not important at their level.

SITUATION (INFRASTRUCTURE) ANALYSIS

Generic Photonic Device Testing

Figure 1 illustrates the general test requirement; the need for both electrical and optical test inputs, and then analysis of the electrical and optical outputs from the device under test (DUT). In addition, environmental parameters, such as temperature, humidity, vibration, etc. may be test inputs. Finally, in addition to the optical and electrical test responses, physical factors such as temperature rise may be outputs that are monitored during testing.

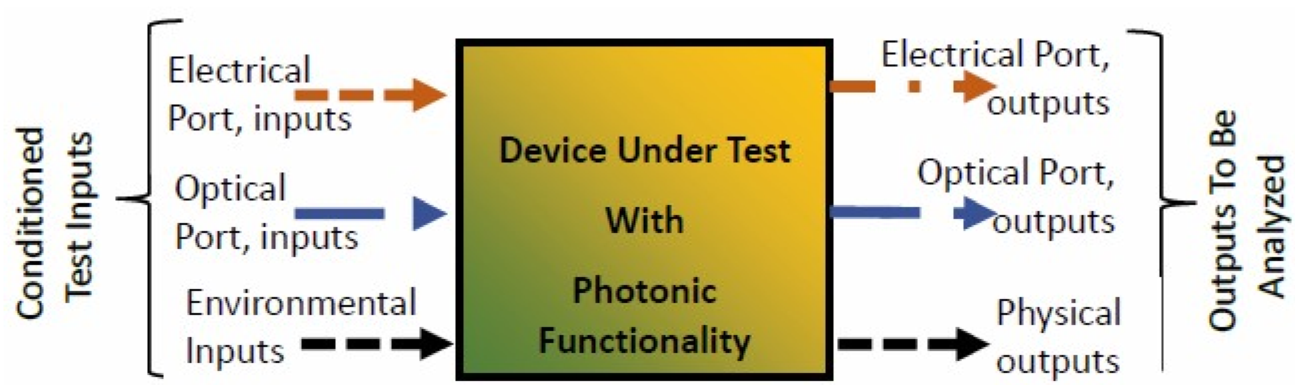

Figure 1. Generic Photonic Product Test Environment

The electrical ports are electrical contacts, or arrays of contacts, for power, control, monitoring of functionality and of course data inputs and/or outputs.

Optical input ports may provide optical beam/s to be modulated or data streams, often in arrays, to be analyzed. The optical "connections" may be a butt coupling, an air gap with a beam bridging into the device or an evanescent coupling resulting from proximity of waveguides. Making these test connections, especially the optical connections, is frequently a major project.

The photonic input and output signals may have multiple parameters. Specifically, optical signals may have:

- Intensity
- Polarization

- Direction
- Mode profile
- Wavelength
- Variation over time:
  - modulation (fast)
  - drift (slow)
- Skew between beams
- Signal-to-Noise Ratio (SNR, RIN, Crosstalk)
- Bit error rate (BER)

One or more of these parameters must be imposed on a suitable optical beam or beams and injected into devices on the optical ports to provide a drive signal. The device under test will perform a function determined not only by the input optical signals, but by the electrical inputs as well. The resulting electrical and optical signals are on the corresponding output ports.

Environmental inputs may include all of the usual variables: temperature, humidity, temperature cycling, Highly Accelerated Stress Test (HAST), vibration, shock, etc.

Physical outputs include temperature rise, mechanical changes such as delamination, cracking, swelling, wire breaks or optical chain interruptions, etc.

Photonic test requirements vary by the test level (wafer, die, photonic SiP, system) and test need (access, sources, detectors, functions). Table 1, Photonic Test Requirements, gives a generic view of the testing needs for items containing photonic elements at the various levels.

A similar table can be developed for specific applications to provide some insight into the related requirements for each application.

Several types of product testing of devices, including those with photonic capability, are usually required:

- Test during development to ensure the design “works”.
- Qualification testing, typically done before a product is committed to wide use.
- In-process testing to monitor manufacturing process quality.
- Final testing before each individual product is shipped to a customer.

Every application, including photonic products, has a specific set of these tests that is applicable to that product. Data communication is an application of immediate interest, one of the most important at the moment, and an application about which much is known; hence we will concentrate on it.

Table 1. Photonic Test Requirements

	Test Need			
Test Level	**Optical Access**	**Sources**	**Detectors**	**Functions**
Wafer	45o mirrors, vertical grating couplers, cleaved fiber, tapered fiber, lensed fiber, focused free-space beam, evanescent coupling	External sources injected via fiber or free-space access Integrated sources	External photo-detectors, potentially in arrays; Imaging sensors (eg. CCD/CMOS FPAs); Optics to collect and/or image light to be detected. Integrated photodetectors	Wide variety of device characterization and functional tests; media loss/cm, insertion loss, modulation depth/ bandwidth, polarization control, wafer uniformity, detector sensitivity/responsivity, temperature sensitivity, die-to-die variation, skew between outputs
Chip	Wafer options plus edge coupling to embedded or surface waveguides.	Wafer options	Wafer options	Wafer options plus edge coupling impacts on loss, spectral bandwidth and polarization
Photonic SiP	Butt coupling or expanded beam connector, evanescent coupling, fiber splice, ribbon fiber splice	External or on-chip laser source to simulate application related requirements.	External detector or detectors, potentially in an array, gathering light from an edge emitting waveguide or vertical emitting 45° mirror, or vertical emitting grating	Wafer and chip options, plus characterize package connections, and application specific tests such as eye diagrams, BER, environmental sensitivity
System	Conventional optical connector, fiber splice	External or internal laser source or sources to simulate inputs.	As needed to measure and evaluate system outputs.	Intensity, skew between lanes, polarization, eye diagram, SNR
In Use, Over Lifetime	Limited, if any. Primarily wireless or electronic	Both self and remotely initiated data reporting	Primarily wireless or electronic	Monitor & report performance changes. Initiate self-repair.

Data Communications Device Testing

Some specific points and issues important in testing data communications photonic products, especially transceivers, are these:

i) Test time is being increased by IEEE Standards that "stretch" the required reach. That reduces SNR and rapidly raises the BER. Thus, "wisely" managing the required reach reduces test cost.

ii) For some data communication applications, a simple, "worst case" Eye Diagram Test is sufficient. This point illustrates that choosing the right criteria that properly balances the test need and potential faults can reduce test cost.

iii) Some Optical Components, especially lasers, are nonlinear, so testing is harder to do and more demanding, but also more important.

The need for specific, high-tolerance physical location of optical components during testing makes changing optical test configurations difficult and time consuming. Gradually reducing input signal strength and measuring the decrease in performance can sometimes provide a way to determine margin and robustness of Optical Systems. This approach, of course, is widely used as one criteria/methodology for electronic products.

Developing new test software, fixtures, sources, detectors, etc. often takes a long time and depends on the materials and devices to be tested. Optical engineers are innovative and continually developing new design and test methods. Fortunately, low volume test capability is improving to support researchers. (These capabilities may eventually impact high volume needs.)

Test Equipment

Optical device test equipment is available from multiple suppliers. Historically, the telecommunications industry was the major consumer, but in recent years the use of optical communications for short distances, such as LANS, FTTX, and AOC and in Data Centers, as well as a variety of sensors, has broadened the demand. Much of the demand emerging for these new optical applications is filled by utilizing equipment developed for and derived from that used by the Telecom sector. As these applications grow in importance, specialized equipment is emerging and becoming available.

Test Processes

Bit Error Rate (BER) Testing is the most time-consuming and therefore more expensive than other testing.

Eye diagram evaluation is of great value and one of the most common test methods for data communications devices.

A related test methodology is "constellation measurement" used for characterizing complex modulation schemes such as QAMXX. Several versions of this method are in use depending on the modulation scheme to be evaluated.

Test Access, Fixtures and Methods

PIC Layout for Test:

- Layout photonic chips and substrates to facilitate testing and packaging by enabling optical access for simultaneous multi-channel optical probes as well as DC, RF and microwave electrical probes.
- Route all optical I/O to the same device edge, organized in a standard linear array; e. g., 127 um or 250 um pitch. All optical ports can be accessed simultaneously by alignment of a single fiber array probe.
- DC and RF pads should similarly be routed to a single, although different, device edge to allow simultaneous probing with multi-conductor probe cards. Ideally only four independent probe heads need to be aligned, to the North, South, East and West edges of the device. Anticipate interference of probe structure mounts when designing compact devices.
- Include on-wafer/chip test structures for calibrating probes.
- Include on-wafer/chip test devices for characterizing individual components, in isolation from a complex, integrated system.
- Incorporate Built In Self Test (BIST) whenever possible.
- Enable debug of faulty circuits by designing test points (grating couplers or photodiodes) to tap off signals. Might make use of the CLIPP (Contactless Integrated Photonic Probe).

Wafer DUT Interface:

- Optical probes must interface by surface grating couplers which impose limits of narrower spectral bandwidth and polarization dependency. Alternative vertical coupling technologies could include etched turn mirrors. Possible for grating couplers to be diced off during singulation, so the final chip is edge-coupled.
- Optical probes can be: single-channel, multi-channel, SMF, PMF, flat facet (cleave, UPC), APC.
- facet, lensed, tapered.
- Optical probe alignment should ideally have 6 degrees of freedom, with 0.1 micron translational precision, and 0.3 arcminute rotational precision.[1]
- Test on an opto-electronic probe station (manual or automated) with a temperature-controlled wafer chuck. A commercially available system from PI is shown in figure 2. A video of it in action is at the following link: https://www.youtube.com/embed/_TG3lUu-k0k?rel=0

[1] The 0.3 arc minute requirement is pointing accuracy required for free space beam such as encountered in Lidar and other free space applications. The requirement in most datacom applications is significantly less, such as 1° which is required for simultaneous alignment of multiple fiber probes in a linear array.

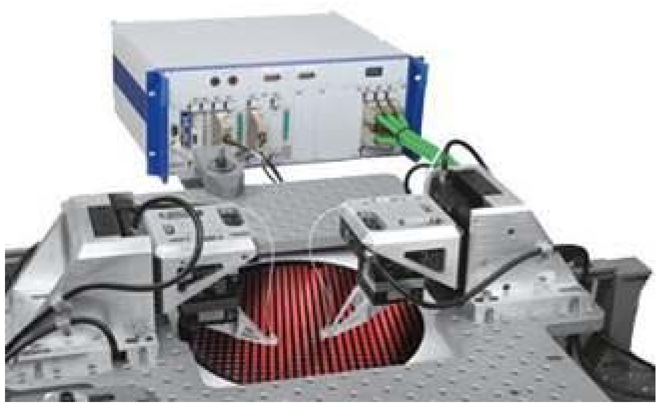

Figure 2. A PI Wafer Probe Station for photonic integrated circuits.

Chip DUT Interface:

Figure 3. PI Probe Station Concept for Individual PICs.

Probing individual chips as suggested in Figure 3 and earlier in Table 1 is viable under some conditions but is generally to be avoided, with wafer-level testing preferred. Individual PIC testing has not only the usual optical and electrical probe interface issues but the added issues of handling and aligning an individual die. Handling is particularly difficult for thin die, meaning 100 microns, that are commonly used.

Whenever necessary, however, test capability for chips is available commercially, even for PICs.

Packaged device DUT interface:

Testing during development on a lab bench: Temperature control is possible through the use of a thermal-stream forced air system. Connections are made through standard connectors (optical and electrical). No probes are required.

One version of a test fixture suitable for products with both electrical and photonic inputs and outputs is illustrated below in Figure 4. This is a highly custom fixture designed specifically for the device to be tested. The configuration is viable because the device configuration, meaning locations of optical and electrical access points, is chosen with the fixture needed to make connection in mind. The electrical connections through pogo pins is well known but does put stress on the DUT, causing it to deform to varying degrees depending on dimensions, temperature, etc. These physical changes make interfacing the optical ports more complex as they must move not only laterally, but somehow be keyed to align in the other 2 dimensions as well as 2 angular dimensions. This might be accomplished with pins, for example, commonly used with the US Conec optical connectors. That, of course, will make the fixture more complex than suggested by Figure 4.

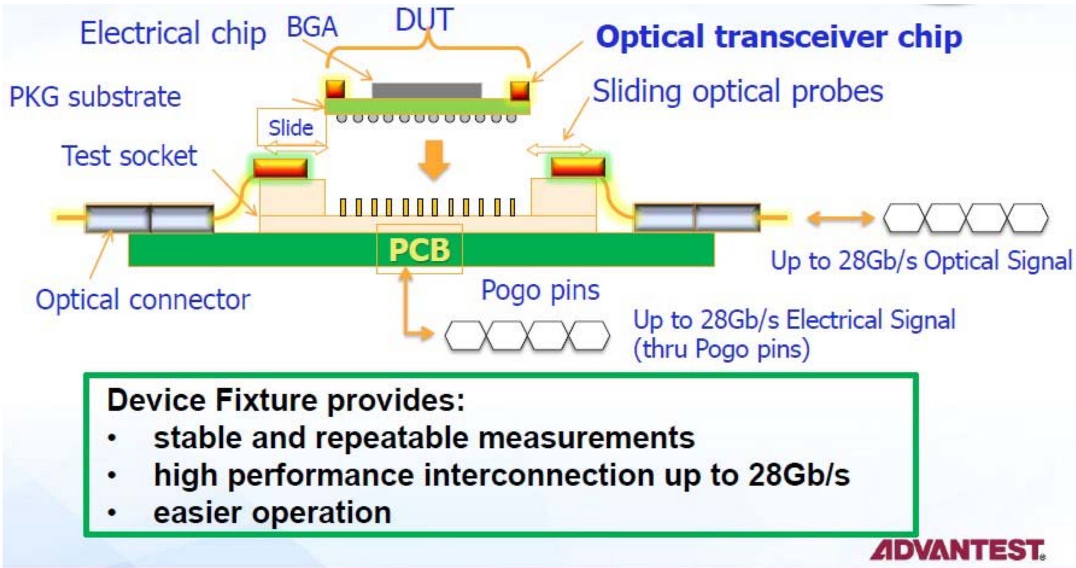

Figure 4. A Test Fixture with both Optical and Electrical probes.

Design Tools and Design for Test

Design tools for PICs are starting to emerge. Including consideration of test will contribute to minimizing the cost and difficulty of optical element test and raise the reliability of the end devices. PICs with many optical elements and/or optical functions may benefit from on/in-chip optical ports to inject optical test signals or ports to probe optical signals. Optical IO test ports can be included as gratings or splitters that allow injection or tapping of signals. These could be in addition to vertical and horizontal ports that communicate on-to and off-of chip for regular IO functions.

Test Standards

The most complete set of optical data communications standards are published by Telcordia. The standards for Optical Fiber and Equipment can be found at: http://telecom-info.telcordia.com/site-cgi/ido/docs2.pl?ID=187033671&page=docs_doc_center. These standards related to telecommunications, of course, and are applicable to system-level test requirements and to high reliability systems. Less demanding standards are needed for primarily commercial and industrial applications.

Standard Physical Platforms, meaning photonic wafer fabrication methods and a related process design kit (PDK) that Applications can be built on, have not emerged. Fortunately developing and making available such a platform is one of the objectives of AIM-IP. The photonic industry will be able to support a minimal number of innovations, so the sooner standardized packaging emerges, the better.

The PDK that AIM-IP is offering will limit innovation, so it is important that AIM-IP choose its PDK wisely and that the PDK evolves in response to user needs and demands. The AIM MPW capability will be important to Universities and Innovation.

The kinds of testing required vary over the life cycle of a product. Figure 5 below lists typical optical device test activities and requirements over the life of a device from conception through the in-use and end of life phases.

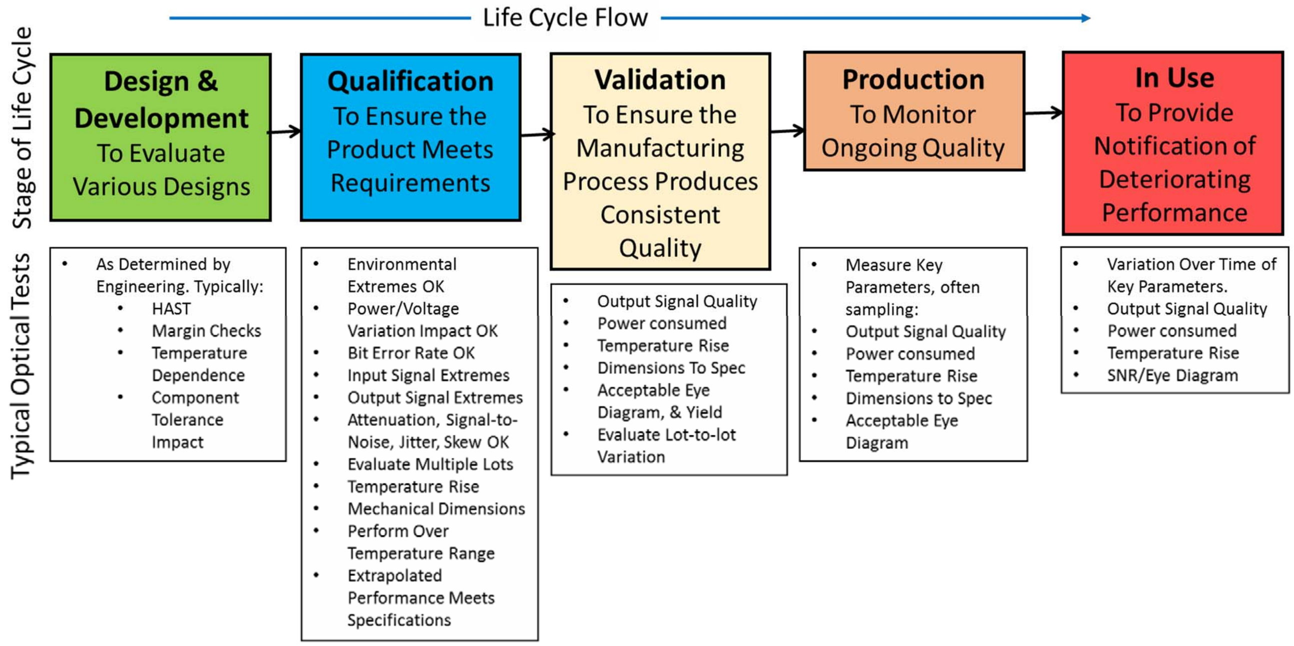

Figure 5. Test Needs over An Optical Product Life Cycle

Environmental Technology

Optical Test has minimal environmental issues other than a few safety requirements associated with laser intensity or UV hazards.

Separately, the environment in which optical devices must perform, and the related proof of performance test evaluations they must be subjected to, have a wide range. A very demanding requirement is the classic Telecordia telecommunications standards to ensure 40-year life. These are still required for some products, such as sub-sea amplifiers. At the other extreme are consumer disposable that have minimal requirements. Between these extremes are a variety of environments in which development and qualification tests must ensure performance.

Generic Test, Inspection and Measurement (TIM)

Types of measurements, O/O, O/E, E/O, E/E: Wafer characterization:

- Wafer mapping: inking for good die identification, yield calculations, process improvement.
- Wafer metrology: layer thicknesses, surface roughness, haze, feature definition, step heights, sheet resistance, doping profiles, mature industry.

Device characterization:

Waveguides: Modal structure, group velocity, dispersion, loss, power handling, polarization dependence, Rayleigh scatter, nonlinear limits (i.e., characterize second and third order susceptibility coefficients, SHG, SFG, DFG, Raman, Brillouin, SPM, XPM, FWM)

Photodiode: Responsivity vs wavelength, polarization dependent loss, dark IV Curves (extract dark current, diode ideality factor, series resistance), bandwidth vs bias, linearity, power handling/compression, over-temperature sensitivity, input capacitance and resistance

Laser diode: LIV curves (extract threshold, slope efficiency, power saturation), RIN, SMSR, center wavelength, linewidth, frequency noise, ASE, tuning coefficients, tuning range/rate, direct modulation bandwidth, over-temperature sensitivity, tolerance to optical feedback

SOAs: spectral gain, efficiency, bandwidth, saturation power, noise figure, amplified spontaneous emission, input power dynamic range

Modulators: extinction ratio vs input signal swing, input capacitance and resistance, electrical to optical bandwidth, spectral bandwidth, insertion loss, polarization dependent loss, resonance frequency and free spectral range and reflected power if applicable, dependence of extinction and optical bandwidth on biasing point

Splitters/Combiners: split ratio, insertion loss, wavelength dependence, polarization dependence, reflected power

Filters: band pass/band reject, attenuation/loss, center wavelength, bandwidth, 'Q' and free spectral range and reflected power if applicable, dependence of extinction and optical bandwidth on biasing point, polarization dependence, tunability: speed, efficiency, performance impact

Attenuators: center wavelength, bandwidth, attenuation, polarization dependence, reflected power vs wavelength and polarization

Polarizers: degree of rejection, insertion loss, reflected power vs wavelength and polarization

Fiber Couplers: optical bandwidth, insertion loss, polarization dependent loss, reflected power

Switches: crosstalk, extinction ratio vs input signal swing, input capacitance and resistance, electrical to optical bandwidth, optical bandwidth, insertion loss, polarization dependent loss, resonance frequency and free spectral range and reflected power if applicable

Optical Connector Characterization:

The incorporation of optical connectors to build systems is increasingly important as a means to eliminate fiber pigtails to reduce handling and the size of systems. Connectors, however, introduce another variable that must be controlled and measured/tested.

Specific component and system characterizations to be performed related to connectors include:

- Connector loss.
- Wavelength dependence of connector loss.
- Connector return loss.
- Connector polarization-dependent loss.
- Connector re-mating loss variation.
- Dust contamination induced connector loss (test TBD).
- Telcordia GR-1435 Uncontrolled Environment Thermal Aging, Humidity Aging, Thermal Cycling, and Humidity/Condensation Cycling testing.
- Signal Bit Error Rate vs. connector number and loss (25 Gbps/channel).
- Estimated system implementation cost.

Functional tests

The most demanding test requirements are found in single mode applications so those are addressed below. Multimode signal testing is usually less demanding.

The Telecom Industry utilizes single mode technology over hundreds of kilometers and has led the development of optical test equipment and capability. Much of that equipment can be adopted for use with products being developed for the emerging needs for shorter distances.

Data communications test needs differ from Telecom in that they tend to utilize more parallel signal transmission through parallel media, either ribbon fiber or waveguide arrays, transmit light shorter distances are impaired by modal dispersion and sometimes utilize more complex modulation schemes.

The general optical signal technical properties and test parameters follow in Table 2 below.

Table 2. Optical Test Parameters, Values, Media and Ranges

Parameter	**Range**	**Comment**
	Optical Signal Characteristics	
Wavelength	750 to 1,650 nm	These are the primary wavelengths used for optical communications. Longer, and sometimes shorter, wavelengths are used in sensors and analytic applications.
Optical power	<1 watt (30 dBm). usually < 0.1 watt (20 dBm)	This value applies to most communications, sensor and analytic applications. Much higher power levels are used for industrial processes. Laser safety must be considered.
Wavelength spacing	Down to 25 GHz or ~0.2 nm at 1.5 microns	Applies in dense wavelength division communications multiplexing (DWDM) applications. More demanding in some sensors.
Optical Modulation Rate	~50 GHz near term, 100 GHz long term	This is the single lane modulation rate.
Laser Sources	40 Gbps/link and higher	Reliable laser sources for 40 Gbps/link and higher rates utilizing higher order modulation are needed.
Optical Amplitude Modulation	Up to 64 levels (6 bit) per single phase near term, 1024 levels (10 bit) long term	For QAM modulation, other formats will also be supported, such as OOK, PAM and PSK
Polarizations	2	X and Y for SMF. More complex SDM being explored for FMF (few-moded fiber).
Detectors	Responsivity	~1Amp/Watt (These values assume conventional photodiodes. Avalanche photodiodes provide higher sensitivity but introduce added noise.)
Detector bandwidth	~50GHz near term, 100 GHz long term	Waveguided photodetectors, higher BWs may require UTC structures
	Probing	
# of simultaneous optical test signals needed	1 to 12 near term, up to 200 long term	Some number of optical test signals may need to be injected/received simultaneously using ribbon fiber or parallel optical waveguides with a combination of the following characteristics; one or more wavelengths modulated with controlled polarization, phase and/or amplitude with known and controlled skew between fibers.
Physical connections; Input of test signals and output of device signals	1. Conventional optical fiber connectors 2. Specialized for- test-only gratings built into substrates and products 3. Focused beams 4. Spliced fibers	A variety of probes (methods to get light into and out of optical ports, such as fibers, waveguides or elements such as lenses, mirrors, etc.) are likely to be required. For SM applications, alignment of the probes to the DUT (device under test) of < 0.1 microns will be required. MM applications require <5 micron alignment. Cleaning and inspection are required for each connector end contact face before mating with another connector to perform a test.
Test Receivers	Up to -80 dBm sensitivity, 650 nm to 1,700 nm, up to 50 GHz BW	Need to measure power level, wavelength, polarization, latency and eye diagrams with up to 1024 signal levels (32 x 32 constellation). Also phase and skew between parallel signals.
Bit Error Rate (BER)	< 10-9 to < 10-12	BER is highly dependent on signal-to-noise ratio, signal conditioning, the application and the degree of error correction coding used, if any.
	Optical Communication Signal Media Properties	
Single Mode Fiber	Typically 6 micron diameter high index glass core, step-index 125 micron diameter lower index outer glass cladding, overall diameter of 250 microns with 125 micron polymer buffer.	
MultiMode Fiber	50 to 62.5 micron diameter high index glass core, graded-index 125 micron diameter lower index outer glass cladding, overall diameter of 250 microns with 125 micron polymer buffer.	
MultiCore Fiber	Recently developed for SM applications. Initially 7 SM cores in a 125 micron diameter with other combinations under consideration.	
Ribbon Fiber	Either SM or MM fibers built as a linear array, usually on 250 micron centers.	
Waveguides	Single mode from 0.2 microns to 6 microns, with strip or rib geometry. Both SM and MM waveguides are built in silicon, InP, glass and polymers. Waveguides typically have higher loss than fiber.	

Education and Training

Test is essentially a manufacturing activity and thus requires education and training in a series of disciplines and skills. Tables 3 and 4 below provide some guidance on these needs.

Table 3. Academic Education Requirements

Knowledge Required	Content
AC/and DC electricity & electronics	Voltage, current, frequency, power, electronics, transformers, capacitors, inductors, transistors, ions, conductors, semiconductors, non-conductors electrical to optical and optical to electronic conversion.
Basics of Optics	Ray tracing, lenses, mirrors, prisms, wavelength, phase, polarization, intensity, beam divergence, beam focus, optical modes, E and H fields as related to the Poynting Vector, light in fibers, both single and multimode, etc.
Characteristics of Signals	Power, transmitting information, signal to noise ratio, modulation methods including OOK, orthogonal signals, multiplexing, demultiplexing, Shannon Limit, etc.
Basics of Statistics	Gathering data, maintaining integrity, managing data bases, standard deviation, mean, median, Parato charts, statistical process control, control limits, Cp, Cpk, etc.
Measurements	Basics of mechanical, electrical, optical metrology. Repeatability, gage studies, etc.
Financial basics	Basic business financial concepts; revenue, costs, elements of cost, product cost elements, overhead, cash, AR, AP, depreciation, equity, etc. “The $ in must be greater than the $ out”. “We make investments in order to make more money back utilizing the result of the investment,” etc.

Table 4. Training Requirements

Skill Required	Areas of Training*
Personal Behavior	Show up on time. Be prepared to perform your job. (Be present mentally and not preoccupied with a non-job related issue, rested, healthy, properly dressed, etc.)
Safety	Rules, behavior, precautions, etc., related to safety for machinery, chemicals, slips and falls, people related, spills, MSDSs.
Quality	Follow the rules. Ensure procedures are followed. Go beyond the formal requirements and propose improvements. Follow the Japanese “5S” rules. Follow “Deming’s 14 Rules For Management”. Use statistics to improve yield and minimize variation.
Cost	Why cost is important, sources of cost, minimizing cost, proposing cost reductions, minimizing waste, maximizing reuse and recycling.
Equipment operation	Safe operation, instrument setup, calibration, standard operations, maintaining records, impact of each process on cost, use of the operating manual, machine maintenance.
Metrology	Use of calipers, electronic and optical measurement methods, storage of data and analysis, ensuring accuracy.
Interpreting Instructions	Read what it says, ask question, make sure you understand, do not “assume”, eliminate and resolve ambiguities,
Completing Jobs On Time	Ensure you understand what is required; ensure all of the instructions, materials equipment and other resources are available. Start as soon as possible. Look for potential barriers ahead and ensue they are eliminated. Be prepared to revise your approach. Ask for help. When you error, admit you made a mistake, learn from it, ensure you do not make it again. Do not hide your errors.

*While training is often highly specific to each job, basics apply to all jobs.

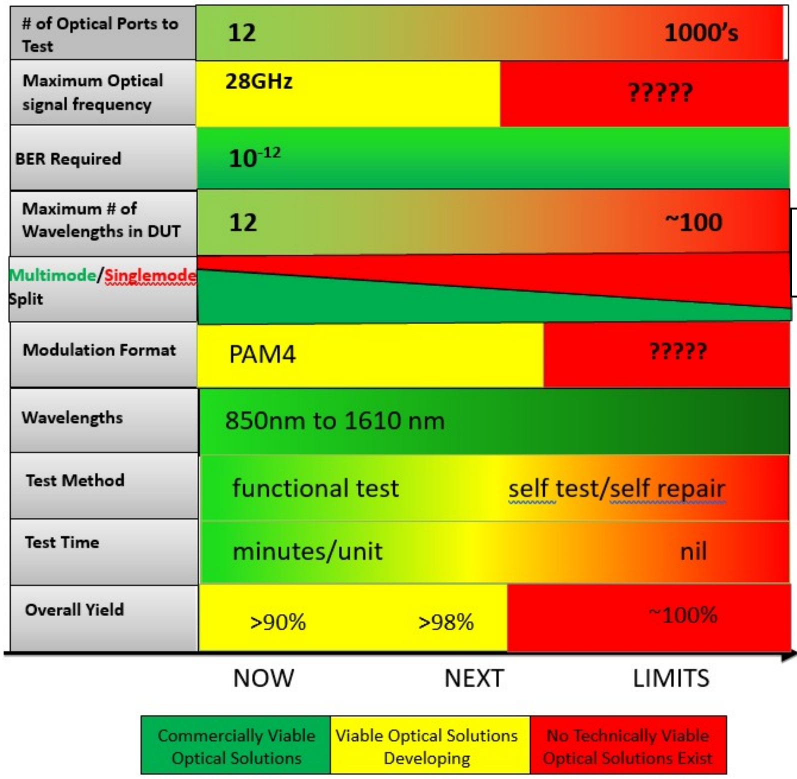

Figure 6: Test, Key Attributes

TECHNOLOGY NEEDS

Prioritized Research Needs (< 5 year results)

- Processing ever faster (100Gbps+) data streams.
- Test time is often determined and limited by memory IO data rates, so increasing these will remove a barrier to lower cost.
- Developing test equipment with more capability than the devices to be tested is a continually moving target!
- Flexible Test Platform, compatible with the test needs of different applications.
- Ability to test photonic properties of wafers during fab to ensure wafers are good.

Prioritized Development & Implementation Needs (> 5 year result)

Eventually, the ability to support 500 Tbps/fiber data transfer rates is going to be needed. An important issue is the nature of the data stream; how much parallelism, what modulation format, etc.

Gaps & Showstoppers

Table 5. Gaps and Showstoppers
The 50 GHz barrier resulting from conventional CMOS capability forcing parallel solutions rather than higher baud rates.
Low speed of suitable assembly, test and other process equipment resulting in high costs.
Inability to overcome the cost driving, rate limiting step/bottle neck of manufacturing/testing such as the number of assembly steps or length of time to perform test, especially BER testing. "Time is money"
Limits resulting from adapting existing equipment, materials and methods to optical test because more specific equipment is not available because the demand is not sufficient to incentivize equipment manufacturers to make it available.
Designing for Manufacturing and test: • Maximizing output to reduce cost • Studying designs to trade off accuracy and speed
Inability to utilize materials or processes due to environmental related constraints (RoHS, REACH, WEEE, etc.)

RECOMMENDATIONS ON POTENTIAL ALTERNATIVE TECHNOLOGIES

Table 6. Recommendations for Potential Alternative Technologies
Utilize laser processing to make optical waveguides in-situ to effective optical connections and optical structures.
Utilization of plasmons to minimize size and maximize functionality

Table 7. Types of Instruments Used for Optical Device Testing

Optical Vector Network Analyzer (OVNA)	Optical Wavemeter
Lightwave Communication Analyzer (LCA)	RIN measurement system
Electrical Vector Network Analyzer (VNA)	Frequency noise test system
Optical Backscatter Reflectometer (OBR)	Polarization controllers/analyzers
Swept tunable laser source (TLS)	Optical attenuators and amplifiers
Fixed laser sources	Real-time Oscilloscope
Power meters – optical and RF/microwave	Digital Communication Analyzer (DCA)
Fast photo-receivers	Bit-Error Rate Tester (BERT)
Optical Modulation Analyzer (OMA)	IR camera to look at mode profiles, and scattered light
Optical Modulation Generator	Ellipsometer
Optical Spectrum Analyzer (OSA)	White light surface profilometer
Electrical Vector Spectrum/Signal Analyzer	Optical microscope; SEM
Electrical Vector Signal Generator	AFM