NASA Electronic Parts and Packaging (NEPP)

Space Qualification Guidelines of Optoelectronic and Photonic Devices for Optical Communication Systems

Quiesup Kim
Jet Propulsion Laboratory, Pasadena, California

January 2001

JPL Publication 01-22

NASA Electronic Parts and Packaging (NEPP)

Space Qualification Guidelines of Optoelectronic and Photonic Devices for Optical Communication Systems

Quiesup Kim
Jet Propulsion Laboratory, Pasadena, California

January 2001

Space Qualification Guidelines of Optoelectronic and Photonic Devices
for
Optical Communication Systems

Abstract

Key elements of space qualification of optoelectric and photonic devices optical were overviewed. Efforts were concentrated for the reliability concerns of the devices needed for potential applications in space environments. Ultimate goal for this effort is to gradually establish enough data to develop a space qualification plan of newly developed specific photonic parts using empirical and numerical models to assess the lifetime and degradation of the devices hopefully for potential long term space missions.

Space Qualification Guidelines of Optoelectronic and Photonic Devices
for
Optical Communication Systems

Contents

Contents (Continued)

List of Illustrations

List of Tables

vi

Space Qualification Guidelines of Optoelectronic and Photonic Devices

Chapter 1. Qualification Methodologies

1.1   Introduction

A recommended procedure for acceptance of optoelectronic and photonic devices (OPDs) for Space mission is outlined. Although the methodologies recommended here may appear rigid and specific, they should not be viewed as such. In fact, the qualification methodology not only permits but rather requires both the manufacturer and the customer to determine many of the details. Instead of presenting specifications for reliability, this chapter presents the questions an OPD user should ask of the manufacturer to assure a reasonable level of reliability, and at the same time it tries to present to the OPD manufacturer the methodologies that have been accepted and practiced by some members of the industry in the hope that a standard qualification procedure may develop. Furthermore, it should be used with the other chapters: the details of this qualification methodology depend on the type of circuit being fabricated and the devices incorporated into the circuit, along with the reliability concerns and failure mechanisms, the testability of the circuit and the effect the package has on the OPD reliability.

A general guideline practice for the space qualification of the OPDs is recommended based on the Qualified Manufacturers Listing (QML) programs [1] with screening procedures from more traditional qualification methodologies. The steps are (1) Company Certification, (2) Process Qualification, (3) Product Qualification, and (4) Product Acceptance, as summarized in Figure 1-1. Company Certification outlines the procedures and management controls the manufacturer should have in place to assure the quality of its optoelectronic and photonic devices (OPDs). Process Qualification outlines a procedure the manufacturer should follow to assure the quality, uniformity, and reproducibility of OPDs from a specific fabrication process. Product Qualification encompasses a set of simulations and measurements to establish the electrical, thermal, and reliability characteristics of a particular circuit design. Lastly, Product Acceptance is a series of tests or screens performed on the deliverable that is normally practiced by OPD manufacturers and their customers to satisfy high reliability program requirements and provide specific reliability and qualification information pertinent to that particular OPD product.
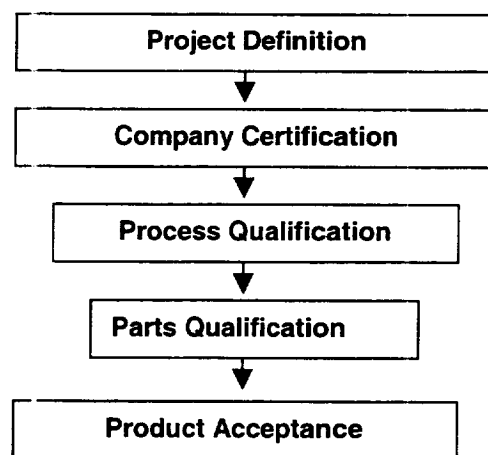
Figure 1-1. Recommended Qualification Methodology

Before these four steps are presented in detail, a few important aspects of OPD qualification must be discussed. First, although the manufacturer is ultimately responsible for delivering a reliable OPD, the reliability of the total system rests with the OPD user. Therefore, it is within both parties' interests to understand the expected electrical performance requirements and operating environment of not just the OPD, but the system itself. While this helps the manufacturer select the best technology for the OPD and deliver a more reliable part, it requires the OPD user to share information with the manufacturer. Furthermore, although the organization of the qualification methodology is representative of what OPD manufacturers and users currently use, the content of the qualification process is the essential ingredient. The OPD user should not discount a manufacturer's proposal because the manufacturer does not organize its procedures in the same way or use the same terms and phrases described here.

The rationale for not publishing a strict qualification standard is derived from the fact that the OPD industry is rapidly evolving, and, therefore, it would not be prudent to set limits on that evolution. In addition, it is not possible to guess the needs of every system being planned or the reliability requirements of every system. For example, OPD users may request a relaxation of the recommended qualification methodology to lower the part cost, if the mission has a short expected lifetime or if the total satellite cost is small. Alternatively, very expensive satellites with a long projected lifetime will normally be qualified to a higher standard than even that recommended in this guide. The important point is that whenever reliability qualification is relaxed, either through the deletion of some tests, or screens, or a reduction in the number of parts tested, up-front OPD costs are lowered at the price of increased risk of system failure.

1.2   Project Definition
Prior to qualifying the parts for a hardware of a specific mission, the mission should be well defined including its objectives, environments, duration, and any specific conditions or unknown variables.

1.2.1   Objectives
Objectives should be specific and in detail, so that the needed information of the parts selection can be determined.

For example, the mission of Mars Global Surveyor (MGS) is part of the Mars Surveyor Program. This program focuses on understanding present and past climate conditions on Mars, determining whether Mars developed prehistoric compounds and life, and identifying resources of use during human expeditions to the surface. Determining the locations and states of water reservoirs today and in the past are key objectives. Missions in the Program are designed to make measurements from orbit, from the surface, and from returned samples. MGS represents a primary orbital component of the Program, collecting information on the characteristics and dynamics of the magnetosphere, atmosphere, surface and interior on a global basis. In detail, the MGS science objectives are to:

-Characterize surface morphology at high spatial resolution to quantify surface characteristics and geological processes.
-Determine the composition and map the distribution of surface minerals, rocks, and ices, and to measure surface thermophysical properties.
-Determine globally the topography, geodetic figure and gravitational field.
-Establish the nature of the magnetic field and map the crustal remnant field.
-Monitor global weather and thermal structure of the atmosphere.
-Study surface-atmosphere interaction by monitoring surface features, polar caps, polar thermal balance, atmospheric dust, and condensate clouds over a seasonal cycle.

1.2.2 Environment

The device shall be designed to meet the functional requirements as specified in a document of a mission when operating in the expected mission environment described in JPL D-11513 "Spacecraft Environmental Estimates", with the design margins specified herein and when under test in accordance with the provisions of JPL D- 11510, "Performance Assurance Provisions." Except where specified otherwise, all environmental design requirements shall equal or exceed the corresponding protoflight test requirements in JPL D-11510. The required design margins are to be applied to the environmental estimates of JPL D-11513.

1.2.3 Duration

The device shall have a design lifetime on-orbit and be capable of supporting science data collection in the communicating phase, supporting spacecraft relay operations during the relay operations phase, and achieving a quarantine orbit if necessary.

1.2.4 Extreme Conditions

The device shall operate safely in extreme conditions that may exist during the mission including launch preparations and launch.

1.2.5 Unknown Variables

Appropriate block, functional, or alternative mode redundancy shall be employed to avoid single-point mission-critical failures. Specific exceptions to this requirement shall be identified and evaluated; they will be approved only if the failure mechanism is found to be acceptably improbable.

A mission-critical failure is defined to be a failure that results in the permanent loss of data from more than one scientific instrument during the mapping phase, loss of the relay capability during the relay phase, the failure to achieve and maintain the proper orbit or pointing control to within specified tolerances, the loss of science-critical engineering telemetry required for attitude determination, or the failure to achieve the quarantine orbit (if required) prior to the end of the mission.

The design shall also accommodate OPD operation in degraded modes. A degraded mode of operation is defined to be one in which the primary scientific objectives of the mission can still be met, but at the expense of a loss of some scientific data and/or an increase in the complexity of the device operations.

1.3 Company Certification

Procurement of OPDs is often the result of a long-term partnership between the customer and the manufacturer in which both parties add knowledge and experience to the process to assure reliability of the final devices and satisfaction of the required performance specifications. This close working relationship evolves after mutual trust is established. If the parties have never worked together, the OPD user can still gain the necessary confidence in the manufacturer if the manufacturer can show that it has documentation, procedures, and management practices that control the facilities, equipment, design processes, fabrication processes, and personnel. These items are typically part of an overall Quality Management Program and outlined in a Quality Management Plan. This step of the qualification process is often referred to as "company certification" and is usually verified by the OPD user through either a written or facility audit. It is recommended that the audit and company certification should be completed before a contract for the purchase or development of an OPD is established. The OPD user may even consider this the first and most important criterion in selecting a company from which to buy parts. A company that cannot demonstrate a formal structure to address the issues of quality and reliability should not be used as a supplier of OPD for high reliability or space applications.

Since most of the information sought during company certification is based on established qualified manufacturer list (QML) programs [1] and standard industry methodologies, the audit should be easy and inexpensive for both the user and manufacturer. In fact, most of the data

sought in the audit should be compiled and available for distribution by the manufacturer. Furthermore, if the manufacturer has passed previous audits, either for other OPD procurements or ISO 9000 certification, this step in the qualification process may be reduced to a simple updating of past audits, or eliminated entirely.

A simplified version of the audit is shown in Figure 1-2. The audit for a specific OPD must be developed on a case-by-case basis. The major items in the Quality Management Program are presented in the rest of this section, but it must be remembered that this is only a partial list. As stated before, company certification is the first opportunity an OPD user has to determine the credibility of a manufacturer's reliability program. This credibility should be established before a contract has been signed. Beyond the following list, the inclusion of additional items in the company certification procedure that are specific to the user's needs would be expected.

1.3.1 Technology Review

To assure the quality and reliability of OPDs, manufacturers will typically have a permanent committee or board in place with knowledge of the entire OPD fabrication process and the authority to change the process if the quality of the parts is not maintained. This board is commonly called the Technology Review Board (TRB) from the QML program [1]. The TRB is responsible for

(1) The development, implementation, and documentation of the manufacturer's Quality Management Program and Quality Management Plan.
(2) The development, implementation, and documentation of the manufacturer's Process Qualification, Product Qualification, and Product Acceptance plans.
(3) Compiling and maintaining all records of the fabrication process, statistical process control (SPC) procedures, SPC data certification and qualification processes, reliability data analysis, and corrective actions taken to remedy reliability problems.
(4) Examining standard evaluation circuits (SECs) and OPD reliability data and establishing and implementing corrective actions when the reliability of the circuits decreases.
(5) Notifying customers when the reliability of a wafer lot is questioned and supplying the customers an evaluation of the problem and any corrective actions required.
(6) Supplying reliability data to customers.

Because of these great responsibilities that cover a broad area of knowledge, the members of the TRB should have good hands-on knowledge of device design, technology development, wafer fabrication, assembly, testing, and quality-assurance procedures. The members of the TRB are normally from the manufacturing company, but a customer requesting custom products may request a seat on the board for those products only.

1.3.2 Definition of Customer Requirements

Not all customers express their specifications in the same way, and not all manufacturers publish OPD performance specifications and operating guidelines in the same way. For example, a user will not normally specify the type of diode, substrate thickness, or transmission lines they want in the fabrication of a circuit. Instead, they simply ask for an OPD with a maximum output power of 1 W at 10 GHz. For the OPD manufacturer, these performance specifications are the starting point in determining the type of OPD, substrate, and wavelengths, among other things, required. Only after conversion from the customer's specifications to the manufacturer's specifications can the manufacturer bid on the contract and the user know what reliability questions to ask. It is recommended that the procedure by which customer requirements – as expressed for example, in specifications and purchase orders – are converted into working instructions for the manufacturer's personnel be documented. A typical document will describe the procedures a company performs, the order in which they are performed, and the typical schedule. Some of the items commonly found in such a conversion are

```
┌─────────────────────────────────────┐
│   Conduct Written or Oral  Audit     │
└─────────────────────────────────────┘
                    │
                    ▼
           Does the company
          management structure
        address quality and reliability
                 issues?
                    │
                    ▼
          Does the company have and
           follow design guidelines to
            assure quality parts?
                    │
                    ▼
          Does the company have
          fabrication, process
        characterization, and
        production guidelines to
            assure quality?
                    │
                    ▼
          Does the company final
         inspection and testing
        program assure quality and
              reliability?
                    │
                    ▼
       Is the fabrication process        Is the company willing to
       evaluated for reliability and     perform product qualification
        space qualification?                        test?
                    │
                    ▼
            ┌──────────────┐
            │  Pass audit  │
            └──────────────┘
```

Company not a good
candidate for space
qualified OPD parts supplier
without corrective action by
the company.

Figure 1-2. Reliability audit for company certification.

5

(1) Relating customer circuit requirements to manufacturer circuit requirements.
(2) Converting circuit requirements to a circuit design, using controlled design procedures and tools (i.e., established geometric, electrical, and reliability design rules).
(3) Establishing a design review team.
(4) Selection of examining standard evaluation circuits (SECs) and Parametric Monitors (PMs).
(5) Mask generation procedure within the controlled design procedure.
(6) Wafer-fabrication-capabilities baseline.
(7) Circuit-fabrication procedures in accordance with approved design, mask, fabrication, assembly, and test flows.
(8) Incoming inspection and supplier procurement document covering design, mask, fabrication, and assembly.
(9) Establishment of screening and traveler documents.
(10) Technology Conformance Inspection (TCI) procedures.
(11) Marking requirements.
(12) Rework procedures.

1.3.3 Manufacturing Control Procedures

OPD manufacture is a very complicated process involving many materials and steps, all of which are critical to OPD performance and reliability. Only a properly controlled manufacturing line can be expected to routinely produce quality OPDs. Thus, the customer should be assured that the manufacturer is using only certified processes and qualified technologies at every step in the manufacture of the OPD from the ordering of materials to the shipping of the OPD. To obtain that level of assurance, the company certification audit should review the manufacturer's procedures for

(1) Traceability of all materials and products to the wafer lot.
(2) Incoming inspection to assure conformance to the material specification.
(3) Electrostatic discharge (ESD) control in handling the material in all stages of manufacturing.
(4) Conformance with design requirements at
  (a) Device procurement specification.
  (b) Simulation-model verification.
  (c) Layout verification.
  (d) Testability and fault coverage verification.
  (e) Electrical parameter performance extraction.
  (f) Archived data.
(5) Conformance of fabrication requirements at
  (a) Mask fabrication.
  (b) Mask inspection.
  (c) Wafer fabrication.
(6) Assembly and package requirements.
(7) Electrical testing.

Most of this information can be obtained if the OPD user asks for documentation of the manufacturer's production flow.

1.3.4 Equipment Calibration and Maintenance

It would be difficult to maintain the quality of OPDs produced on equipment that is not properly maintained and calibrated. Therefore, all equipment used in the design, fabrication, and testing of the OPD should be maintained according to the equipment manufacturer's specifications. In addition, the equipment should be calibrated on a regular basis. Documentation showing the maintenance and calibration schedule, deviations from the calibration and maintenance schedules, and any corrective action taken will normally be kept by the manufacturers. This documentation will also highlight any major discrepancies found in the calibration and

maintenance of a piece of equipment since it may affect the reliability of the OPDs. The TRB will review this document to determine if any corrective action is required. Further information on equipment calibration and maintenance documentation can be found in [2].

1.3.5 Training Programs

Even well maintained and calibrated equipment cannot produce quality OPDs without skilled operators. To assure the skills of the personnel employed in the design, fabrication, and testing of the OPDs, each engineer, scientist, and technician should have formal training relative to their tasks. Furthermore, retesting and retraining should be provided regularly to maintain the worker's proficiency, especially if new equipment or procedures are introduced into the manufacturing process. It is therefore recommended that the work training and testing practices employed to establish, evaluate, and maintain the skills of personnel engaged in reliability-critical work be documented as to form, content, and frequency.

1.3.6 Corrective Action Program

One of the best ways to continuously improve the reliability of manufactured OPD parts is to test and analyze failed parts – including returns – from all stages of manufacturing, and, based on the findings, make corrective actions to the manufacturing process or the education of the OPD users. The plan that describes these corrective actions is normally documented. The corrective action plan should describe the specific steps followed by the manufacturer to correct any process that is out of control or found to be defective and the mechanism and time frame that a manufacturer will follow to notify customers of potential reliability problems.

1.3.7 Self-Audit Program

To promote continual quality improvement, manufacturers regularly review their manufacturing procedures through an internal, independent self-audit program under the direction of the TRB. The self-audit program should identify the critical review areas, their frequency of audit, and the corrective action system to be employed when deviations from requirements are found. Typical areas included in a self-audit are

(1) Calibration and preventive maintenance
(2) Fabrication procedures
(3) Training programs
(4) Electrical tests
(5) Failure analysis programs
(6) Test methods
(7) Environmental control
(8) Incoming inspection
(9) Inventory control and traceability
(10) Statistical Process Control (SPC)
(11) Record retention.

The self-audit checklist, the date of the previous audits, and all findings from the audits are maintained typically by the TRB, which will use these findings to recommended corrective actions and prepare a self-audit follow-up.

1.3.8 Electrostatic Discharge (ESD) Handling Program

Because of the catastrophic failure that normally follows ESD, all personnel that work with GaAs OPDs should be trained in the proper procedures for handling the devices. Furthermore, these procedures should be documented and available for reference. Typically, the procedures include the methods, equipment, and materials used in the handling, packaging, and testing of the OPDs. Further guidance for device handling is available in the Electronics Industry Association (EIA) JEDEC Publication EIA 625 [3] and MIL-STD-1686 [4].

1.3.9 Cleanliness and Atmospheric Controls

The quality of InGaAs/InP OPDs and the yield of the fabrication line is directly linked to the manufacturer's control over the cleanliness of the environment in which the parts are fabricated. Therefore, manufacturers often spend a large amount of their resources to assure that the OPDs are fabricated in ultra clean rooms where the atmosphere is tightly controlled. Since the yield of the fabrication process is so strongly dependent on the success of maintaining those conditions, regular measurements are taken to assure the temperature, humidity, and cleanliness of the fabrication areas. In addition, during transit and storage prior to seal, the die/wafer should be protected from human contact, machine over spray, or other sources of contamination. All of these procedures and measurements are recorded and compiled into a single document by the clean-room manager or alternate for future reference.

1.3.10 Record Retention

Documentation is the only method to gauge the reliability of OPDs fabricated today vs. those produced last week or last year and to correlate changes in the reliability to variations in the processing steps. Although many sections in this guide recommend the documentation of certain data or procedures, it is helpful if a list of documents and the period of retention for each document is made. Furthermore, the list should contain a record of when each document was last changed, who is responsible for maintaining the document, and where the document is stored. The typical documents to be retained are relevant to

(1) Inspection operations (i.e. production processes, screening, qualification).
(2) Failure and defect reports and analyses.
(3) Initial documentation and subsequent changes in design, materials, or processing.
(4) Equipment calibration.
(5) Process, utility, and material controls.
(6) Product lot identification.
(7) Product traceability.
(8) Self-audit report.
(9) Personnel training and testing.
(10) TRB meeting minutes.

1.3.11 Inventory Control

The proper inventory of all incoming materials and outgoing parts is not only required for the management of a profitable company but also for the manufacture of reliable OPDs. Many materials and chemicals used in the fabrication of OPDs have shelf lives that must be adhered to if process yield and reliability are to be maintained. The tracking of in-process and completed OPDs is essential for the establishment of OPD history, which is critical if failure analysis is ever necessary. Therefore, the methods and procedures used to control the inventory of all materials related to the OPD manufacturing process should be documented. Typically documented inventory control procedures include

(1) Incoming inspection requirements and reports.
(2) Identification and segregation of non-conforming materials.
(3) Identification and control of limited-life materials.
(4) Control of raw materials.
(5) Data retention for required receiving reports, test reports, certification, etc.
(6) Supplier certification plan.

1.3.12 Statistical Process Control (SPC)

The establishment of a statistical baseline for judging the continuous improvement of a manufacturer' s processes is important. To establish that baseline, the manufacturer should develop an SPC program using in-process monitoring techniques to control the key processing steps that affect device yield and reliability. As part of the SPC process, every wafer lot typically has built-in control monitors from which data are gathered. The resulting data should be analyzed by appropriate SPC methods to determine the effectiveness of the company's

continuous improvement plans. Additional information on SPC analysis can be found in the Electronics Industry Association JEDEC EIA 557A [5] and in MIL-I-38535 [1].

1.4   Process Qualification

A manufacturer who has standardized production around a single technology will often qualify the entire production line. In doing so, the manufacturer attempts to demonstrate that the entire process of designing and fabricating an OPD using the stated technology is under its control. In addition, the manufacturer establishes an optoelectrical performance and reliability baseline for all components fabricated using the process. This has advantages for both the manufacturer and the user of the OPD. For the manufacturer, it saves costs and time on the fabrication of future OPDs, since the reliability and functional performance of the components constituting the OPD have already been established. For the OPD user, there is a certain level of comfort in buying parts from a production line with a history of supplying reliable OPDs, in addition to the reduced qualification time and therefore delivery time that should be possible.

The term usually applied to this procedure is "process qualification." Process qualification is a set of procedures a manufacturer follows to demonstrate that they have control of the entire process of designing and fabricating an OPD using a specific process (e.g., Laser diode, PIN Detectors, JFET, HEMT). It addresses all aspects of the process including the acceptance of starting materials, documentation of procedures, implementation of handling procedures, and the establishment of lifetime and failure data for devices fabricated using the process. Since the goal of process qualification is to provide assurance that a particular process is under control and known to produce reliable parts, it needs to be performed only once, although routine monitoring of the production line is standard. It is critical to remember that only the process and basic circuit components are being qualified. No reliability information is obtained for a particular OPD design.

Although process qualification is intended to qualify a defined fabrication procedure and device family, it must be recognized that InGaAs/InP technology is constantly evolving, and this technology evolution requires the continual change of fabrication procedures. Furthermore, minor changes in the fabrication process to account for environmental variations, incoming material variations, continuous process improvement, or minor design modifications may be required. All of these changes in the process are permitted and frequently occur under the direction of the TRB. Thus, strict application of the commonly used phrase, "freezing the production process" does not apply.

The internal documents and procedures used by most manufacturers for process qualification are summarized in Figure 1-3. In addition, the QML program [1] provides guidelines for process qualification. The first step in the procedure is for the manufacturer to determine the family of devices to be fabricated and the technology that will be used in the fabrication-for example, a 0.5 μm, Zn-diffused JFET technology with Si_3N_4 capacitors and various ohmic contacts. Second, the manufacturer will establish a TRB to control the process qualification procedure. After all of the processing steps have been defined and documented, the workmanship, management procedures, material tracking procedures, and design procedures should be documented. The information contained in the documentation describes the process domain that is being qualified.

9

Process Qualification

```
          ┌─────────────────────────┐
          │  Determine Type of Device│
          └─────────────────────────┘
                      │
                      ▼
          ┌─────────────────────────┐
          │      Establish TRB       │
          └─────────────────────────┘
                      │
                      ▼
          ┌─────────────────────────┐
          │  Develop Processing Steps│
          └─────────────────────────┘
```

Develop and Document Standard Workmanship, Management Procedures and Material Tracking Procedures.		Document Design Standard and Processing Procedures

Determine Fabricate Technology Vehicle, Circuits, and Parts to be qualified

Determine Device Models, Electrical Circuits, and Parts	Process Reliability Evaluation

Process Qualified

Figure 1-3 Recommended process qualification.

The qualification process also involves a series of tests designed to characterize the technology being qualified. This includes the electrical as well as the reliability characteristics of components fabricated on the line. Some of these tests are performed at wafer level and include the characterization of parametric monitors, Technology Characterization Vehicles (TCVs), and standard examining circuits. Other tests require the mounting of circuits or elements onto carriers. All of these tests and the applicable procedures are an integral part of the qualification program and provide valuable reliability and performance data at various stages of the manufacturing process. The number of circuits or devices subjected to each test will normally be determined by the TRB and the rationale for their decision will become part of the process qualification documentation. In general, a higher level of confidence in the reliability data exists if more circuits are tested, but this is offset by the fact that after a certain level of testing, the incremental gain in confidence is minor compared to the cost of testing. Since the stability of the process is being determined as part of the process qualification, the manufacturer will typically fabricate and test components from several wafer lots. A series of tests that is recommended to characterize the electrical and thermal limitations of the devices or circuits should be provided. The performance limitations obtained from these tests often become the basis for limits incorporated into the design and layout rules.

Note that the process-qualification procedure is QML-like and therefore addresses topics similar to those of the company certification. The major difference is that company certification is performed by the customer, whereas process qualification is self-imposed by the manufacturer, often before customers are identified.

1.4.1 Process Step Development

Although all of the items described in here are important to the process qualification procedure, the actual process of turning a bare multi-layered wafer into a OPD by technicians in a clean

10

room is often the only task associated with process qualification. Indeed, it may be the most critical step in the process and probably requires the most time and resources to develop. In addition, it is truly the fabrication procedures and the components fabricated on the line that distinguish one production line from another. Therefore, it follows that the first step in the process-qualification procedure is the development and documentation of the processing steps required to build an OPD. Although all of the steps in the fabrication process, including wafer surface preparation, photolithography, active layer formation, passivation, and the metallization system and formation, should be included in the documentation, the details are typically considered proprietary by the manufacturer. Therefore, the OPD customer may expect to see a general list of processing steps or the process flow, but not the level of detail actually required to fabricate the parts.

1.4.2 Wafer Fabrication Documentation

Once a process is qualified, reliability concerns may still arise from minor variations in the process flow, environment, or starting materials. Therefore, all wafer fabrication steps and conditions will normally be recorded by the manufacturer in order to maintain repeatability of the product. Documentation of these steps and fabrication conditions should be maintained to trace any future quality or reliability concerns to a specific step. Although process travelers can be used to document the fabrication and manufacturing steps, they usually lack the detail necessary to trace quality or reliability problems to specific fabrication steps. The wafer fabrication steps themselves and the documentation describing them are usually considered proprietary by the manufacturer or subcontractor.

1.4.3 Parametric Monitors

Parametric monitors (PMs) are essential for monitoring a production line's quality or continuous improvement. They are mentioned in this section only to emphasize the fact that choice of the PMs is dependent on the process and technology being monitored. Therefore, this choice is a critical element in the process-qualification procedure. The complete list of PMs is each wafer fabricated on the line to all of the other wafers. This permits determination of process stability.

1.4.4 Design-Rule and Model Development

The reliability of OPDs fabricated using a qualified process will greatly depend on whether they are designed with qualified components and according to prescribed rules. In addition, the standardization of the component types also brings a certain degree of cost reduction. Therefore, part of the process-qualification procedure is to determine and document design rules that are specific to the process. Typical information included is the minimum cavity size, the maximum capacitance, the minimum wavelength variation, the minimum separation between via holes, and the active device geometry. In addition to these characteristics, a list of rules relating to such issues of circuit design as the maximum power handling capability, maximum linear gain, and minimum noise figure of the devices should also be included. Finally, manufacturers will often develop standard cells or small circuits that perform specific functions, such as couplers, gain blocks, bias networks.

To fully use the standard components in circuit designs, models must be developed; although models contained in commercial software packages may be adequate, they often need to be adapted to fit the measured characteristics. Commercial software packages are available to extract the RF and dc characteristics from measurements and fit the model to the data. Once each of these components and cells is described and characterized, circuit designers can use them to increase the chance of first time design success.

1.4.5 Layout-Rule Development

Layout rules should be followed in any circuit design to assure manufacturability and reliability. The layout rules may be specific to a particular process, and therefore, must be developed for the process being qualified.

1.4.6 Wafer-Level Tests

The InGaAs/InP industry strives to reduce production costs by shifting as much testing as possible to the earliest possible point in the production cycle – this to weed out bad wafer lots before more value has been added to them. The best strategy performs wafer level tests that include dc and RF characterization, PM characterization data, and temperature performance. Limitations may exist in the level of test detail depending on the device design and the manufacturer's test capabilities. In general, wafer-level tests are performed, but they should be supplemented with other verifications, such as test fixture or in-package tests. Once agreement between the wafer level and the package-level tests has been established, the manufacturer may rely on the wafer-level tests for production monitoring.

1.4.7 TCV (Technology Characterization Vehicle) and SEC (Standard Evaluation Circuit) Tests

One of the most important steps in the process-qualification procedures is to determine the thermal, electrical, and reliability characteristics of devices fabricated within the domains of the process. This data is obtained through the characterization of TCVs and SECs. All data obtained from these tests should be gathered and stored by the TRB. In most cases, the success of a manufacturer in qualifying the process will depend on the data from these tests.

1.4.8 Starting Materials Control

The manufacturer should have in place a mechanism to assure the quality and characteristics of every starting material from the wafers and chemicals used in the processing steps to the shipping containers used for die/wafer transportation and storage, since they all have a direct impact on the quality and reliability of the final product. Analyses of the chemicals and gases used in multilayer grow processing $In_xGa_{1-x}As$ on InP is normally performed by the device manufacturer or the supplier of the chemicals. Traceability and documentation of the characterization results to the individual wafer process lot are essential in resolving any process variation questions or concerns. The facility audit program can be the vehicle used to determine the manufacturer's level of control.

Most device manufacturers procure the device wafers from outside suppliers. Procurement requirements imposed by the device manufacturer identify the dislocation density, type of starting material, resistivity, and other characteristics that are very important to the optoelectric device user. This information can help determine the suitability of the starting material to the process and the material's capabilities. The traceability and documentation of the procurement requirements and wafer characterization can be used to resolve any process variation concerns. Wafer preparation steps, such as initial surface cleaning, can also alter device characteristics and are an important aspect of process control.

Integral to the complete process flow is the mask preparation and the method of identification of any changes to the applicable mask set. The repeatability and quality of the masks should be assessed and documented prior to initiation of the fabrication process.

1.4.9 Electrostatic Discharge Characterization and Sensitivity

If not handled properly, several elements used in OPDs can be damaged by ESD. Damage may occur at tune-and-test, assembly, inspection, and other places, if proper precautions are not taken. Therefore, every process and design should be characterized to determine ESD

sensitivity. Regardless of the test results, all InGaAs/InP-based devices should be treated as highly sensitive to ESD damage. An ESD handling and training program is essential to maintain a low level of ESD attributed failures.

Inspection, test, and packaging of OPDs should be carried out in static-free environments to assure that delivered products are free of damage. Devices should be packaged in conductive carriers and delivered in static-free bags. All handling and inspection should be performed in areas meeting "Class 1 " handling requirements. Both the manufacturer and the user share the responsibility of assuring that an adequate procedure is in place for protection against ESD.

In general, the following steps can help reduce or eliminate the ESD problems in device manufacturing and test areas:

(1) Ensure that all workstations are static free.
(2) Handle devices only at static-free workstations.
(3) Implement ESD training for all operators.
(4) Control relative humidity to within 40 to 60%.
(5) Transport all devices in static-free containers.
(6) Ground yourself before handling devices.

1.5   Product Qualification

A consumer expects the manufacturer to verify that products are properly designed. The consumer may also expect the manufacturer to specify the operating environment for which the product was designed. The manufacturer can give these assurances and information only if the product has been tested after fabrication.

For OPDs, the processor obtaining this data is called product qualification or design validation, and, as implied above, every OPD design should pass product qualification before it is sold. Because the data desired in product qualification is specific to a particular OPD design, this applies as well to circuits fabricated on process-qualified fabrication lines. Figure 1-4 shows a product qualification procedure that addresses the issues critical to OPDs. The first step of design verification occurs before mask generation and includes design, simulation, and layout verification of the circuits. The rest of design verification includes full electrical characterization of the device to establish its operating performance, thermal analysis, and electrostatic discharge characterization, and verifies the results of the voltage ramp test, temperature ramp test, and temperature cycling tests. Although the sequence of the tests may be altered, it is recommended that design and layout verification be performed first, and this should be followed by electrical performance verification, since any out-of-specification parameters found during these tests will require a redesign of the device. This is a recommended approach, and all of the tests may not be required for some device designs. All participants in the OPD design, manufacture, and end-product integration should be involved in deciding which tests are required.

The rationale for and a description of the steps recommended in the design validation follow.

Product Qualification

Chip/Die — Chip or Package — Package

Lot Acceptance for the Die

Product Acceptance Test

Pass or Fail? — Fail — Reject Parts — Fail — Pass or Fail?

Pass

Pass

Process Identification Documentation

Parts Now Space Qualified

Delivery to the Customer

Process Identification Documentation

Build Multi-chip Packages

Product Acceptance Test

Pass or Fail? — Fail — Reject Parts

Pass

Parts Now Space Qualified

Figure 1-4 Product qualification procedure.

1.5.1 OPD Design, Model, and Layout Verification

One of the best ways of reducing OPD engineering cost and improving reliability is to verify the design, model or simulation, and layout of the OPD before fabrication begins. During the OPD design cycle, these verifications are normally addressed through a series of design reviews that include representatives from all companies involved in the manufacture and use of the OPD. Furthermore, the representatives should come from all departments involved in the OPD integration, including the OPD designers, the fabrication staff, the wavelength calibration personnel, the packaging engineers, and the system designers.

Typically, the reviews are held before the circuits are sent to layout, after layout but before mask making, and after final OPD characterization.

1.5.2 Thermal Analysis and Characterization

Thermal analysis determines the hottest part of the device during normal bias conditions and the temperature difference between the hottest point on the surface of the die and the case temperature; this is critical in determining the expected life of the OPD. The analysis should be performed over the entire temperature range of the OPD's intended application. Typically, this theoretical analysis is difficult and requires detailed knowledge of the power dissipation, geometry of the lasing cavity layers around the channel, method of attaching the die to the substrate, and

14

the thermal boundary conditions of the substrate. A preferred method is actual thermal measurements using either liquid crystal or infrared scanning techniques.

1.5.3   Electrostatic Discharge Sensitivity Tests

AlGaAs/GaAs devices are somewhat sensitive to ESD damage, and therefore the ESD characterization given in [6,9] should be conducted to determine the sensitivity of the design. OPD structures can be damaged by ESD voltages in the 20- to 2000-V range [4]. Thus, classification and treatment of the devices from the fabrication stage to the actual application as a Class I ESD-sensitive device is highly recommended. The device's normal electrical parameters should be used as a reference for degradation of performance due to testing.

Devices which have internal defects and/or absorption at the facet can show a lower threshold voltage. ESD tests on buried-tripe type 980 nm laser diodes employing human-body-model stressing with a capacitance of 100pF and a resistance of 1.5kΩ have shown a slight increase of the threshold current and a decrease of a slope efficiency. A current probe in the discharge circuit was used to monitor current flow and a fast photodiode was employed to detect the optical output in real time. In forward bias testing, a series of discharge pulses starting from 4kV with a 500V increment step. In the reverse case -10kV, -20kV, and –30kV pulses were applied to the devices.[9]

Thin-film capacitors and resistors can be damaged by static charges of less than 2000 V and are therefore also "Class I" devices. The voltages needed to damage these components are, however, much higher than those needed to damage field effect transistors (FETs). Several hundred volts would damage these circuit elements; FETs are more susceptible to damage than capacitors and resistors.

Input and output blocking capacitors will not protect internal FETs from damage in most cases since ESD is usually present in the form of voltage transients and as such will be coupled through most capacitors. Therefore, it is recommended that all operators be careful when connecting these devices to RF test setups. Grounding the test technician prior to connecting the bias or RF leads is good practice.

It is not known what impact non-catastrophic damage will have on device lifetime. Tests on intentionally damaged devices have shown that they continue to operate for over 500 h at 85°C without further degradation. It is anticipated, however, that lifetime will be shortened when compared to undamaged devices.

1.5.4   Voltage Ramp

The sensitivity of an OPD design to voltage overstress and the absolute maximum voltage ratings are determined during the voltage ramp test. Testing is normally done by ramping each device's power supply until a catastrophic failure occurs. Ramp rates and step duration are a function of the design limitations, but the test should allow thermal stabilization of the device at each successive step. After the test, an analysis to determine the exact failure site is recommended. Failure-point definition should be in conservative agreement with the device data sheet and design limits.

1.5.5   Temperature Ramp and Step Stress

Temperature ramping can serve more than one purpose. It can indicate which portion of the design is most sensitive to high-temperature operation, indicate the absolute maximum ratings applicable, give an indication of high-temperature operation characteristics, and it can determine the appropriate temperatures applicable for life tests. The test is normally done by ramping the temperature of the devices until catastrophic failure. Ramp rates and step duration should be designed to allow thermal stabilization of the devices at each successive step. Afterwards, failure

analysis to determine the exact failure site is recommended. Failure point definition should be in conservative agreement with the device data sheet and design limits.

1.5.6   High/Low Temperature Tests

Data sheets will always specify the highest and lowest temperature at which an OPD will operate, and they will give the percentage change in electrical parameters at the temperature extremes. The high/low temperature test is designed to obtain that data. The test temperature at both extremes may be obtained from step stress tests or from system requirements. Once the data have been measured for a specific OPD design, the temperature limits and percent change in electrical parameters can be used in product acceptance screens.

1.6   Product Acceptance

Although an OPD may be designed by highly qualified engineers, fabricated on a process qualified production line, and verified through measurements to meet the design goals, parts with poor reliability characteristics still exist. This may be due to variations in the fabrication process, or material flaws that were undetected, or, as is more often the case, to the OPD package and stresses imposed on the OPD during packaging. Regardless of the cause, these weak OPDs must be found and removed before they are integrated into the system. Therefore, manufacturers of all high reliability systems, including space systems, require the OPDs to pass a series of product acceptance screens, whose sole purpose is to increase the confidence in the reliability of the OPDs. Note that this step in the qualification methodology is the major difference between space qualified OPDs and commercial grade OPDs.

The level of testing performed under product acceptance is a function of the form of the deliverable. For example, the first level of acceptance testing, called "wafer acceptance tests' is performed at the wafer level to assure the uniformity and reliability of the fabrication process through a wafer to wafer comparison. "Lot acceptance test for die" is a second level of testing that provides further reliability information, but only on a sample of the OPDs because of the difficulty in performing full characterization on unpackaged OPDs. It is used if the OPD user has requested the OPDs to be delivered in die form for integration into a larger module. This sample testing will provide the user with only an estimate of the OPDs reliability. Furthermore, the user will not have an understanding of the OPDs performance in the final package and any of the reliability issues that the package may cause. If Packaged parts are requested though, a full 100% screening can be performed and the user should have assurance that the delivered parts are reliable. The OPDs are not space qualified until they have passed the 100% screening tests, and the user takes responsibility for final space qualification screening if they request unpackaged parts.

The recommended product acceptance test for die deliverables is shown in Figure 1-5.[7,8] Note there are three levels of testing within the procedure and each starts with the wafer acceptance test. The lowest level of testing is required for OPDs that have already been product qualified and have been manufactured on a qualified process line, whereas the highest level of testing is required for a new circuit design that is fabricated on an unqualified process line. Whichever level of testing is required, the same level of reliability assurance should be granted to the OPD upon completion of the lot acceptance test. The cost and time advantage of buying OPDs from manufacturers with qualified processes and validated circuit designs can be large, and it is for this reason that manufacturers incur the cost of qualifying their processes.

Product Acceptance

```
┌─────────────────────────────────────────────┐
│          Lot Acceptance Test for Die         │
└─────────────────────────────────────────────┘
                      │
                      ▼
┌─────────────────────────────────────────────┐
│         Die Mounting and Wire Bonding        │
└─────────────────────────────────────────────┘
                      │
                      ▼
┌─────────────────────────────────────────────┐
│          Nondestructive Bond Pull Test       │
└─────────────────────────────────────────────┘
                      │
                      ▼
┌─────────────────────────────────────────────┐
│            Pre-cap Visual Inspection         │
└─────────────────────────────────────────────┘
                      │
                      ▼
┌─────────────────────────────────────────────┐
│            Serialization and Marking         │
└─────────────────────────────────────────────┘
                      │
                      ▼
┌─────────────────────────────────────────────┐
│                   IR Scan                    │
└─────────────────────────────────────────────┘
                      │
                      ▼
┌─────────────────────────────────────────────┐
│                    Seal                      │
└─────────────────────────────────────────────┘
                      │
                      ▼
┌─────────────────────────────────────────────┐
│             Temperature Cycle Test           │
└─────────────────────────────────────────────┘
                      │
                      ▼
┌─────────────────────────────────────────────┐
│                  Vibration                   │
└─────────────────────────────────────────────┘
                      │
                      ▼
┌─────────────────────────────────────────────┐
│          Particle Impact Noise Detection     │
└─────────────────────────────────────────────┘
                      │
                      ▼
┌─────────────────────────────────────────────┐
│              Temperature/Electrical          │
└─────────────────────────────────────────────┘
                      │
                      ▼
┌─────────────────────────────────────────────┐
│                DC Measurement                │
└─────────────────────────────────────────────┘
                      │
                      ▼
┌─────────────────────────────────────────────┐
│                   Burn-in                    │
└─────────────────────────────────────────────┘
                      │
                      ▼
┌─────────────────────────────────────────────┐
│               Hermetic Seal Test             │
└─────────────────────────────────────────────┘
                      │
                      ▼
┌─────────────────────────────────────────────┐
│             Radiographic Inspection          │
└─────────────────────────────────────────────┘
                      │
                      ▼
┌─────────────────────────────────────────────┐
│                Final Electrical              │
└─────────────────────────────────────────────┘
                      │
                      ▼
┌─────────────────────────────────────────────┐
│                External Visual               │
└─────────────────────────────────────────────┘
```
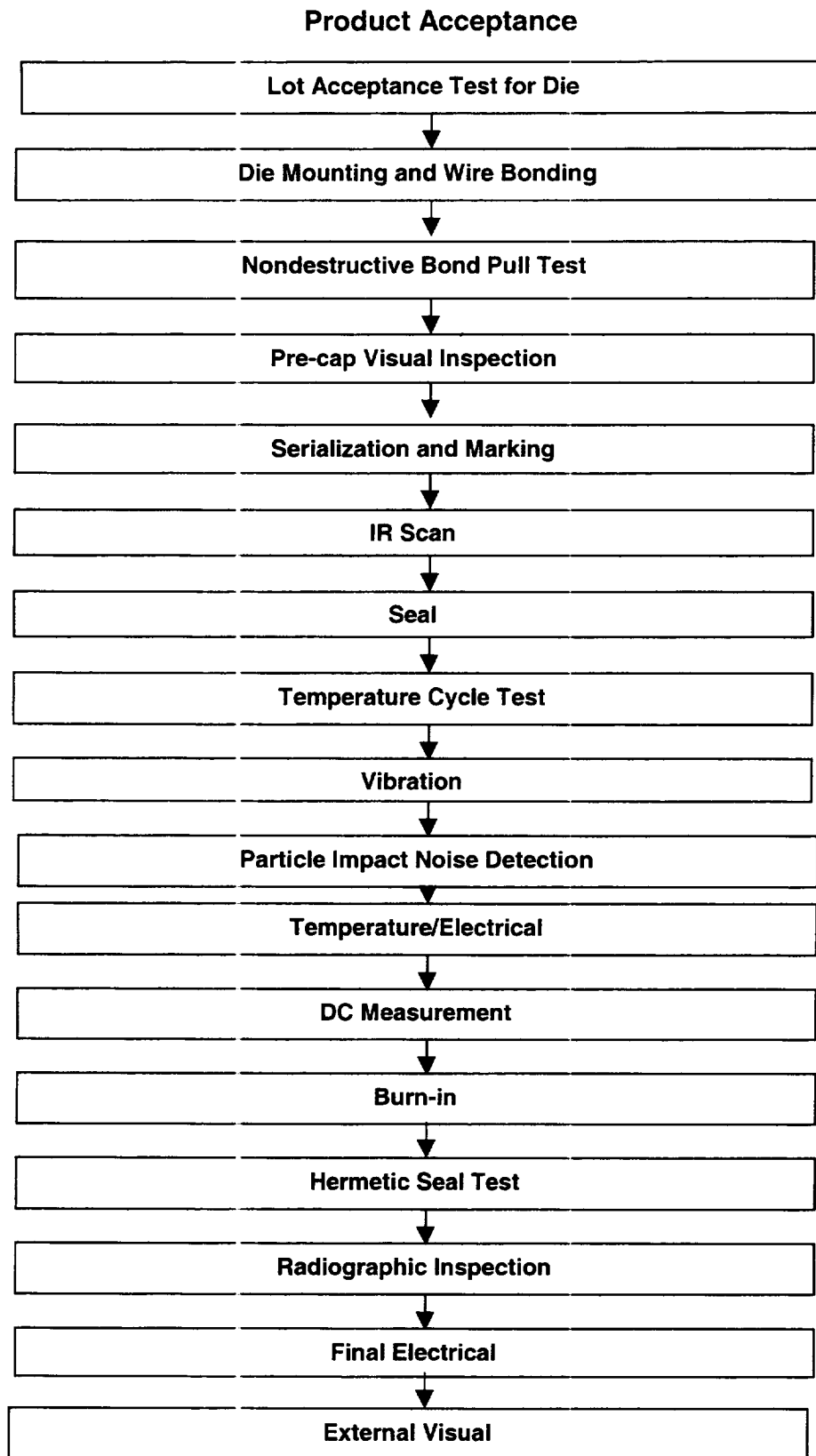
Figure 1-5. Product Acceptance

It is assumed that a product acceptance of die deliverables is performed on the OPDs before they are inserted into the packaging process, or a subgroup of the parts can be removed from the packaged parts and life testing performed on them in a way similar to that recommended for the die deliverables. Thus, this screen adds further reliability information to the data obtained from the wafer and lot acceptance tests. As stated above, 100% of the packaged OPDs is recommended to be screened. Some of the steps require the selection of a particular screen, and this must be based on the intended application and device type.

Table 1 -1 shows the recommended screening tests that can be used for OPD packaged devices and the reference for the screen. This information is modified from MIL-PRF-38534 Class K requirements and should be applied after careful consideration of the applicability and the desired requirements.

Throughout the rest of this chapter, a brief description of and the rationale for product acceptance test or screen will be given.

1.6.1   Stabilization Bake

Some GaAs circuits have an initial period when their electrical parameters vary vs time. Most of the parametric variations decay to a steady-state value within 20 h, but during the initial life of the circuit, the variations can be large. Measured variations in I_{DS} of 20% over 2 h have been reported. The degree of instability varies between different manufacturers and between different fabrication processes at the same manufacturer. In fact, circuits from some manufacturers do not exhibit any electrical parameter variations. It is therefore necessary to characterize the circuit performance over its early life to determine if electrical parametric variations occur. If they do occur, they must be eliminated before wafer acceptance, life testing, or product delivery can be made. If they are not eliminated, they will distort the life test results by shifting the "normal" operating parameters of the circuit; this will cause many circuits that are inherently good to appear defective.

Table 1-1. Typical packaged device screening.

Test	Reference
Nondestructive bond pull	MIL-STD-883, Method 2023
Internal visual inspection	MIL-STD-883, Method 2017
IR-scan (prior to seal)	JEDEC Document JES2 [7]
Temperature cycling or	MIL-STD-883, Method 1010
Thermal shock	MIL-STD-883, Method 1011
Mechanical shock or	MIL-STD-883, Method 2002
Constant acceleration	MIL-STD-883 Method 2001
Particle impact noise detection	MIL-STD-883, Method 2020
Electrical	Customer's specification
Burn-in	MIL-STD-883, Method 1015
Electrical (high/low temp)	Customer's specification
Fine leak	MIL-STD-883, Method 1014
Gross leak	MIL-STD-883, Method 1014
Radiographic	MIL-STD-883, Method 2012
External visual	MIL-STD-883, Method 2009

Chapter 2. Overview of Optical Communications

2.1   The Optical Communication

The objective of a communication system is the transfer of information from one point to another. This information transfer is accomplished most often by superimposing (modulating) the information onto an electromagnetic wave (carrier). The modulated carrier is then transmitted (propagated) to the destination, where the electromagnetic wave is received and the information recovered (demodulated). Such systems are often designated by the location of the carrier frequency in the electromagnetic spectrum. In radio systems, the electromagnetic carrier wave is selected with a frequency from the radio frequency (RF) portion of the spectrum. Microwave or millimeter systems have carrier frequencies from those portions of the spectrum. In an optical communication system, the carrier is selected from the optical region, which includes the infrared, visible, and ultraviolet frequencies.[10]

The principal advantages in communicating at optical frequencies are (1) the potential increase in modulation bandwidth, (2) the ability to concentrate power in extremely narrow beams, and (3) the significant reduction in component sizes. In any communication system, the amount of information transmitted is directly related to the bandwidth (frequency extent) of the modulated carrier, which is generally limited to a fixed portion of the carrier frequency itself. Thus, increasing the carrier frequency theoretically increases the available transmission bandwidth, and therefore the information capacity of the overall system. This means frequencies in the optical range will have a usable bandwidth approximately 10^5 times that of a carrier in the RF range. This available improvement is extremely inviting to a communication engineer vitally concerned with transmitting large amounts of information. In addition, the ability to concentrate available transmitter power within the transmitted electromagnetic wave also increases with carrier frequency. Thus, using higher carrier frequencies increases the capability of the system to achieve higher power densities, which generally leads to improved performance. Lastly, operation at the extremely small wavelengths of optics produces system devices and components that are much smaller than their equivalent electronic counterparts. For these reasons, optical communication has emerged as a field of special technological interest.

Communicating at optical frequencies has several major differences from RF communications. Because optical frequencies are accompanied by extremely small wavelengths, optical component design requires essentially its own technology, completely different from design techniques associated with RF, microwave, and millimeter devices. As a result, optical devices, although emulating equivalent electronic devices, may have performance characteristics significantly different from their electronic counterparts. Another drawback to optical communications is the detrimental effect of the propagation path on the optical carrier wave. This is because optical wavelengths are commensurate with molecule and particle sizes, and propagation effects are generated that are uncommon to radio and microwave frequencies. Furthermore, these effects tend to be stochastic and time varying in nature, which hinders accurate propagation modeling. A vast amount of experimental data has been collected to aid in understanding this optical propagation phenomenon and, although certain models have been established, continued exploration is required for refinement and further justification.

The development of optical components and the derivation of propagation models, however, are only part of the overall system design. A communication engineer must also be concerned with the choice of components, the selection of system operations, and finally the interfacing or interconnecting of these operations in the best possible manner. These interfacing decisions require reasonably accurate mathematical models, which indicate component performance, anomalies, and degradations, knowledge of which can be used to advantage in system design. It is this aspect of optical communications that this book attempts to elucidate. Our objective is to understand system capability and to formulate system-design procedures and performance characteristics for the implementation of an overall optical communication system.

2.1.1 Optical Systems

The block diagram of a generic optical communication system is shown in Figure 2-1. The diagram is composed of standard communication blocks, which are endemic to any communication system. A source producing some type of information (waveforms in time, digital systems, etc.) is to be transmitted to some remote destination. This source has its output modulated onto an optical carrier (a carrier frequency in the optical portion of the electromagnetic spectrum). This carrier is then transmitted as an optical light field, or through the optical channel (free space, turbulent atmosphere, fiberoptic waveguide, etc.). At the receiver, the field is optically collected and process (photodetected), generally in the presence of noise interference, signal distortion, and inherent background radiation (undesired light fields or other electromagnetic radiation) Of course, except for the fact that the transmission is accomplished in the optical range of carrier frequencies, the operations just mentioned describe any communication system using modulated carriers. Nevertheless, the optical system employs devices somewhat uncommon to the standard components of the RF system. These devices have significant differences in their operation and associated characteristics, often requiring variations in design procedures.

The modulation of the source information onto the optical carrier can be in the form of frequency modulation (FM), phase modulation (PM), or possibly amplitude modulation (AM). Each of which can be theoretically implemented at any carrier frequency in the electromagnetic range [1]. In addition, however, several other less conventional modulation schemes are also often utilized with optical sources. These include intensity modulation (IM), in which information is used to modulate the intensity (to be defined subsequently) of the optical carrier, and polarization modulation (PLM), in which spatial characteristics of the optical field are modulated.
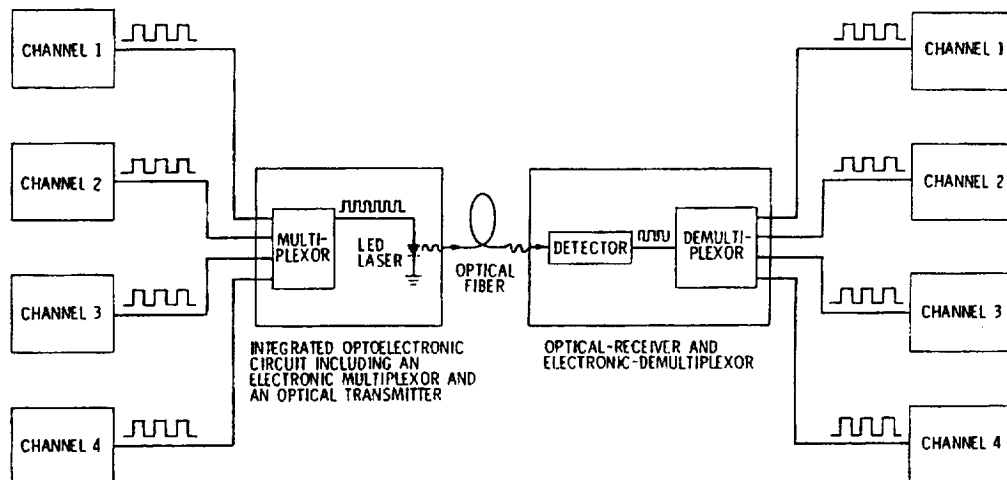

Figure 2.1. Of the two integrated optoelectronic circuits shown, one is composed of an electronic multiplexer and a laser and the other of a multiplexer and a light detector. The circuits could link a number of electronic data channels to an optical fiber for transmitting data at a rate four times faster than that of each electronic channel.

The optical receiver collects the incident optical field and processes it to recover the transmitted information. A typical optical receiver can consist of an optical receiving front end (usually containing some form of lens or focusing hardware), an optical photodetector, and a post detection processor. The lens system filters and focuses the received field onto the photodetector, where the optical signal is converted to an electronic signal. The processor

20

performs the necessary amplification, signal processing, and filtering operations to recover the desired information from the detector output.

Optical receivers can be divided into two basic types: power detecting receivers and heterodyning receivers. Power detecting receivers (often called direct detection, or non-coherent, receivers) have the Front end system. The lens system and photodetector operate to detect the instantaneous power in the collected field as it arrives at the receiver. Such receivers represent the simplest type for implementation and can be used whenever the transmitted information occurs in the power variation of the received field.

Heterodyning receivers have the front end system. A locally generated lightwave field is optically mixed with the received field through a front end mirror, and the combined wave is photodetected. Such receivers are used whenever information is amplitude modulated, frequency modulated, or phase modulated onto the optical carrier. Heterodyning receivers are more difficult to implement and require close tolerances on the spatial coherence of the two optical fields being mixed. For this reason, heterodyned receivers are often called (spatially) coherent receivers. For either type of receiver, the front end lens system has the role of focusing the received or mixed field onto the photodetector surface. This focusing allows the photodetector area to be much smaller than that of the receiving lens.

The receiver front end, in addition to focusing the optical field onto the photodetector, also provides some degree of filtering. These filters are employed prior to photodetection to reduce the amount of undesired background radiation. Optical filters may operate on the spatial properties of the focused fields or may filter in the frequency domain: that is, they pass certain bands of frequencies and reject others. The latter filters determine the bandwidth of the resulting optical fields subsequently photodetected.

The detection of optical fields is hampered by the various noise sources present throughout the receiver. The most predominant in long-distance space communication is the background light or stray radiation that is collected at the receiver lens along with the desired optical field. Although this radiation may be reduced by proper spatial filtering, it still represents the most significant interference in the detection operation. The background effect can be eliminated when direct-coupled fiber optic waveguides can be used for the transmission path. A second noise source is the photodetector itself, which, not being a purely ideal device, produces internal interference during the photodetection operation. This induced noise is referred to as detector noise. The last noise source is the circuit and electronic thermal noise generated in the processing operations following photo-detection. The thermal noise is accurately modeled as additive white Gaussian noise, whose spectral level is directly related to the receiver temperature, just as in any RF or microwave communication system. Each of these noise sources must be properly accounted for in any receiver analysis.

The models in Figures 2-3, 2-4, and 2-5 are common to any optical communication system. In a space system the transmitted optical field is focused into a beam of light and transmitted as a propagating electromagnetic field through a medium. Examples of these are shown in Figure 2-5. The system can be a terrestrial (ground-based) link, a ground-to-space (atmospheric) link, a space-to-space cross-link, or even a space-to-underwater link. All such systems use optical beams transmitted as unguided fields and are susceptible to the effects of the medium (atmosphere, clouds, water, etc.) over the communication path.

A fiber-optic system confines the transmitted field to an optical waveguide (fiber) during its propagation. The system, therefore, is operated as is any cable-connected link. Because the field is guided, only the properties of the fiber itself affect the field transmission. In particular atmospheric and background noise effects are no longer important to system performance. The enormous improvement in fiber quality has permitted long communication links and fiber-optic distribution systems to be readily established. Today fiber-optic systems are rapidly replacing the more traditional cable and wire-line systems of the past.

2.1.2 Optical Sources, Modulators, and Beam Formers

The key element in any optical communication system is the availability of a light source that can be easily modulated. Such a source should produce energy connected in a narrow wavelength band. The primary sources of light in modern optical system are the light-emitting diodes (LED), the laser, and the laser diodes (LD). Although the physical descriptions of these devices are beyond our scope here, their output properties and characteristics will be important in assessing the performance when used in an optical communication system.

An LED is formed from semiconductor junctions that interact when subjected to external current so as to radiate light energy. A detailed theory of band energy is needed to describe this interaction and is not pursued here. The choice of the junction materials determine the emitted wavelength. Light-emitting diodes are typically formed from compounds of gallium arsenide, and produce light in the 0.8- 0.9 μm wavelength bands. An LED is small in size (centimeters), relatively inexpensive, and can produce radiation with low-current drive levels. However, they are limited in output power (1 to 10 mW), and the emitted light tends to be unfocused. Table 2-1 summarizes these basic characteristics.

A laser tube is constructed as an optical cavity filled with light amplification material (gas or solid) and mirrored facets at each end. If the propagation gain of the material overcomes the reflection losses of mirrors, then an initiated optical field reflected back and forth by the mirrors will be self-sustaining. We say the cavity "lases," and optical energy is produced within the cavity. By placing a small aperture in one mirror, some internal energy will escape as radiated light. As a result the laser can produce high power levels (0.1 to 1 W) with output radiation that can be more focused than an LED.

Many different materials can be used in the cavity to produce lasing (Table 2-1), each having specific atomic structures that form particular wavelength bands. In addition, the cavity length must be such that a propagating internal field will exactly reinforce (be phase aligned) after two-way mirror reflections. This means the cavity length must he precisely an integer multiple of a half wavelength of the internal field. That is, the lasing wavelength λ must be related to the cavity length L by $\lambda = 2L/n$, for some integer n. The lasing material sustains those wavelengths that are commensurate with its propagation gain profile. Laser tubes are therefore high-power devices, but are much bulkier than diode sources.

Laser diodes are semiconductor junction devices that contain substrate that are etched, or cleaved, to act as reflecting facets for field reinforcements over the junctions. They therefore combine the properties of an LED and the cavity reflector, producing an external light radiation that is higher in power (10 to 50 mW) and better focused than a simple LED.

Table 2-1. Optical Sources.

Laser material	Wavelength (μm)
Solid state	
GaAs	0.87
IngGaAs	1.0 – 1.3
InGaAsP	0.9 – 1.7
AlGaAs	0.8 – 0.89
Ruby	0.694
Nd-Yag	1.06
Gas	
CO_2	10.6
HeNe	0.63

Laser Types	Output Power (mW)	Linewidth(nm)
Diodes		
LED	0.1—10	20—100
Laser diode	1.0—40	1 —5
Distributed feedback laser	1.0—40	0.1
Tubes		
CO_2	1000—5000	0.01– 1.0
HeNe	50—100	0.01—1.0

The important communication characteristics of any optical sources are in modulation bandwidth (the rate at which the source can be modulated), its input/output power curve, and its frequency spectrum. Light Sources, generated from extremely narrow cavities, can be modulated at bandwidth up to 1 to 4Ghz. This provides enormous potential advantage over RF communications, where modulation bandwidths of only hundredths of megahertz are available.
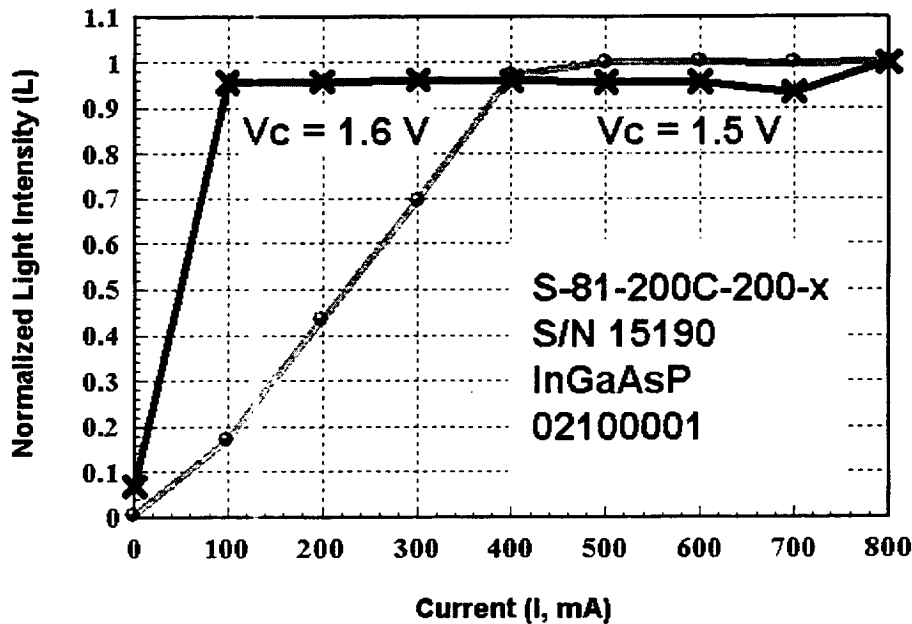

Figure 2-2. Characteristics of the light sources.

Figure 2-2 sketched typical diode and laser power characteristics, plotting output light power versus external bias current. The threshold current is that needed to produce output light. The linear range defined the modulation range, where input current converts proportionally to output power. The saturation level limits the minimum available output power. Light-emitting diodes have low thresholds and can operate at low-current values, but they have limited peak powers. Laser diodes require more drive current, but have higher peak power. Laser tubes generally have to be pumped above threshold and are difficult to stabilize in the linear range. Hence, high - power lasers are usually operated as continuous-wave devices at their peak power capability.

The frequency spectrum of an optical source indicates the spectral extent, or purity, of the light source. The spreading of the spectrum around the desired wavelength indicates the presence of unwanted frequencies, or undesired noise modulations, superimposed on the output wavelength. This spectral spreading can hinder the ability to recognize desired information modulated on the source. Light-emitting diodes have relatively wide spectral extent n, whereas, lasers significantly improve the light purity.

Modulators superimpose the information signals (analog or digital) on the source. Optical modulators [11] are of two basic types: internal or external. An internal modulator is one in which the source itself is directly modified by the information signal to produce a modulated optical field. Amplitude or intensity modulation can be imposed by varying the bias current. Frequency or phase modulation can be inserted on a laser tube by varying its cavity length. Pulse modulation is easily applied to a diode by driving it above and below threshold. Such modulations are generally limited to the linear range of the power characteristic.

In external modulation, the source light is focused through an external device, whose propagation characteristics are altered by the modulating signal. Such systems have the advantage of utilizing the full power capability of the source. Modulation is achieved via the electro-optic or acousto-optic effect of the material, in which external currents can modify the transmission properties (index of refraction, polarization, direction of flow, etc.) of the inserted light. These effects produce delay variations (phase modulation) or polarization changes (intensity modulation) on the excited beam. Pulsed outputs can be achieved by blocking or deflecting the light path. Unfortunately, external modulators insert significant coupling losses, limit the modulation range, and generally require relatively higher modulation drive power.

Light fields from the radiating surfaces of optical sources and modulators are emitted with varying degrees of focusing, usually described by its emission angle. The light emission is further characterized by the source brightness function, $R(\theta)$, which is in units of watts/steradian-area, that describes the normalized light power emitted in a given direction angle θ out from the source. The power is usually normalized to a unit solid angle per unit of source area. Hence the source brightness indicates the distribution of power radiated out from the source. A uniformly radiating source will have the same brightness at all angles within its emission solid angle Ω_s'.

The total power in watts emitted from a uniform source with area A_s and emission angle Ω_s, is then

$$P_s = B\,A_s\,\Omega_s \qquad\qquad (2\text{-}1)$$

Figure 2-3. Beam forming and focussed light.

For symmetrically radiating sources, the solid angle can be related to the planner emission angle in Figure 2-3 by

$$\Omega_s = 2\pi\,[1 - \cos(\theta_s/2)]. \qquad\qquad (2\text{-}2)$$

Light field from radiating sources can also be collected and refocused by means of beam-forming optics. The latter is usually combinations of various types of lenses placed at the source or modulator output that orient the light into particular directions. Although light focusing shows a simple type of beam formation common in long-range space links. A combination of a converging and a diverging lens placed at the source is used to produce a collimated beam. An ideal converging lens focuses the source field light to a point, and the diverging lens expands it to a perfect beam. In practice, the source field is instead focused to a spot, and the expanded beam spreads during propagation with a planar beam diameter of approximately [12]

$$d_z = d_t [1 + (\lambda z/d_t^2)^2]^{1/2}, \qquad (2-3)$$

where λ is the wavelength, d_t is the output lens diameter, and z is the distance from the lens. At points in the near field ($\lambda z/d_t^2 < 1$), the emerging light Is collimated with a diameter equal to the lens diameter. That is, the light appears to uniformly exist over the entire lens. In the far field ($\lambda z/d_t^2 > 1$) the beam diameter expands with distance, and appears as if the light is emerging from a single point with a planar beam angle of approximately

$$\theta_b \sim \lambda/d_t \text{ rad.} \qquad (2-4)$$

The angle θ_b is called the diffraction-limited transmitter beam angle. The expanding field far from the source is therefore confined to a two-dimensional solid angle of approximately

$$\Omega_b = 2\pi [1 - \cos(\theta_b/2)] \sim (\pi/4)\theta_b^2 \qquad (2-5)$$

Figure 2-10 shows a plot of Eq. (2-4) as a function of diameter d_t for several optical wavelengths. For example, a 6-in. lens at an optical wavelength of 0.5 μm has a beamwidth on the order of 3×10^{-6} rad or approximately 0.16 mdeg. This is a spectacular advantage compared to RF transmitters where antenna beams are usually on the order of degrees. This ability to concentrate field flow to small beam angles with relatively small size optics is a significant advantage in long-range space communications.

The optical advantage of this source focusing can be further emphasized by converting to an effective antenna gain. From antenna theory [13], a transmitter with the beamwidth in Eq. (2-4) will have an effective antenna gain of

$$G_t = 4\pi/\Omega_b \sim (4d_t/\lambda)^2. \qquad (2-6)$$

2.2   Space Optics

2.2.1   Pointing, Acquisition, and Tracking

Before any data transmission can occur in a space communication system, it is necessary that the transmitter field power actually reach the receiver detector. This means that the transmitted field, in addition to having to overcome the effects of the propagation path, must also be properly aimed toward the receiver. Likewise, the receiver detector must be aligned with the angle of arrival of the transmitted field. The operation of aiming a transmitter in the proper direction is referred to as *pointing*. The receiver operation of determining the direction of arrival of an impinging beam is called *spatial acquisition*. The subsequent operation of maintaining the pointing and acquisition throughout the communication time period is called *spatial tracking*. The problems of pointing, acquisition, and tracking become particularly acute when dealing with fields having narrow beamwidths and long propagation distances. Because both these properties

characterize long-range optical space systems, such as intersatellite links and Earth-space links, these operations become an important aspect of the overall communication design problem.

2.2.1.1 Optical Pointing Problem

A typical optical beam in a space link could be confined to an angular beamwidth of less than 1 arcsecond. If this beam is to be detected at a receiver, then this beam must be pointed to within a fraction of this beamwidth. Alternatively, if the beam can be aimed toward a desired receiver (considered as a point) with an accuracy of only, say $\pm \Psi_e$ radians, then the beamwidth must be at least $2\Psi_e$ to ensure receiver reception.

2.2.1.2 Spatial Acquisition

Spatial acquisition requires aiming the receiving lens in the direction of the arriving optical field. That is, it must align the normal vector to the aperture area with the arrival angle of the beam. Often alignment is acceptable to within some degree of accuracy. That is, the arrival angle can be within a specified solid angle from the normal vector. This acceptable angle is called the resolution angle (or resolution beamwidth) of the acquisition procedure, and is denoted Ω_2 in Figure 2-3, in subsequent discussion. The minimal resolution angle is obviously the diffraction-limited field of view, but, in practical design, desired resolution is generally larger. This allows for the possibility of the source blurring into many modes, and for compensating for pointing errors and ambiguities. Although resolution angle must be considered a design specification, its value plays an important role in subsequent analysis. Acquisition can be divided into one-way and two-way procedures. In one-way a single transmitter, located at one point, is to transmit to a single receiver located at another point. If satisfactory pointing has been achieved (or equivalently, if the transmitter beamwidth covers the pointing errors), the optical beam will illuminate the receiver point. The receiver knows the transmitter direction to within some uncertainty solid angle Ω_u, defined from the receiver location. The receiver would like to aim its antenna normal to the direction of the arriving field to within some uncertainty solid angle Ω_r: that is, it wants its antenna normal vector pointed to within Ω_r steradians of the transmitter line-of-sight vector. In general, Ω_r << Ω_u, so that the receiver must perform an acquisition search over the uncertainty angle to acquire the transmitter with the desired resolution.
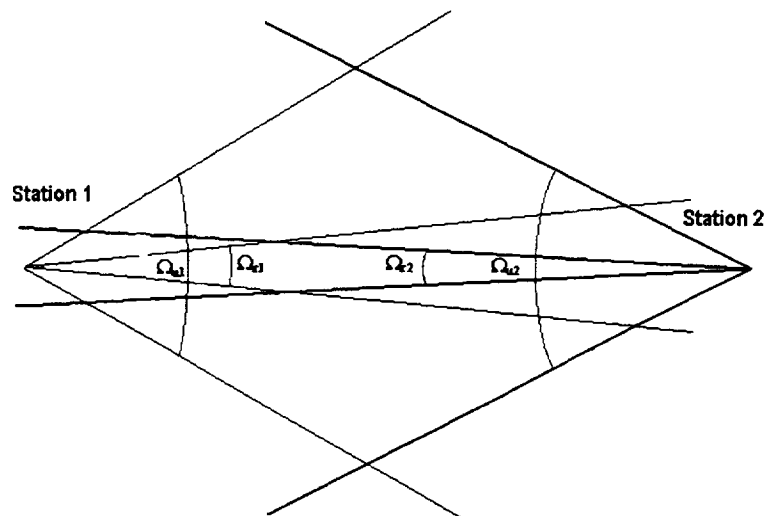

Figure 2-3.Two-way spatial data acquisition.

In two-way acquisition, both communicating stations contain both a transmitter and a receiver. Both must spatially acquire a two-way communication link. In typical situations, one of the

stations has somewhat accurate knowledge of the location of the other and can therefore transmit a beam wide enough to cover its pointing errors. It uses a receiving antenna with a similar field of view aimed along the line of sight of the transmitted beam. The second station may not have the a priori knowledge for pointing and must therefore search its uncertainty field of view Ω_{u2} to acquire. After successful spatial acquisition with resolution Ω_{r2}, the second station transmits with beamwidth Ω_{r2} to the first station, using the arrival direction obtained from the acquisition. The second station has now acquired and is pointed properly. The first station can now acquire the return beam with its desired resolution Q_{r1}. The link is now complete with the desired resolutions, and communication can begin. The operation can be repeated with narrower beams for further refinement, if desired. The first station would now narrow its transmit-and-receive beam, and the second station would reduce its resolution requirement Ω_{r2}, reacquire, and retransmit with a narrower beam.

2.2.1.3 Spatial Tracking

After pointing and spatial acquisition have been achieved, there remains the task of maintaining the transmitted beam on the detector area in spite of beam wander or relative transmitter-receiver motion. This operation of keeping the receiver aperture properly oriented relative to the arriving optical field requires spatial tracking. This tracking is achieved by generating instantaneous pointing error voltages that are used to continually realign the optical hardware. After successful acquisition of the incoming light beam, the beacon field should be focused at the center of the acquisition array, which is coaxially aligned to the position error sensor of the tracking subsystem. The acquisition threshold removes the array processing and enables the tracking operation using the centered, focused beam. The tracking subsystem then generates the error signals as the focused beam moves off-center, due to either line-of-sight beam motion or receiver platform jitter. The tracking subsystem usually uses two separate (azimuth and elevation) closed loops, as shown in Figure 2-4. The tracking error is determined instantaneously for both azimuth and elevation coordinates by means of the position error sensor, which iterates the error signals. The error signals are then used to control the alignment axis of the receiver lens. This is accomplished by some type of control loop dynamics, generally with separate servo control functions, typically of the form of some type of low-pass integration filtering that smoothes the error signals for position control as shown in Figure 2-5. The filter bandwidths must be wide enough to allow the tracking loop to follow the expected beam motion, yet allowing minimal noise effects within the loop.
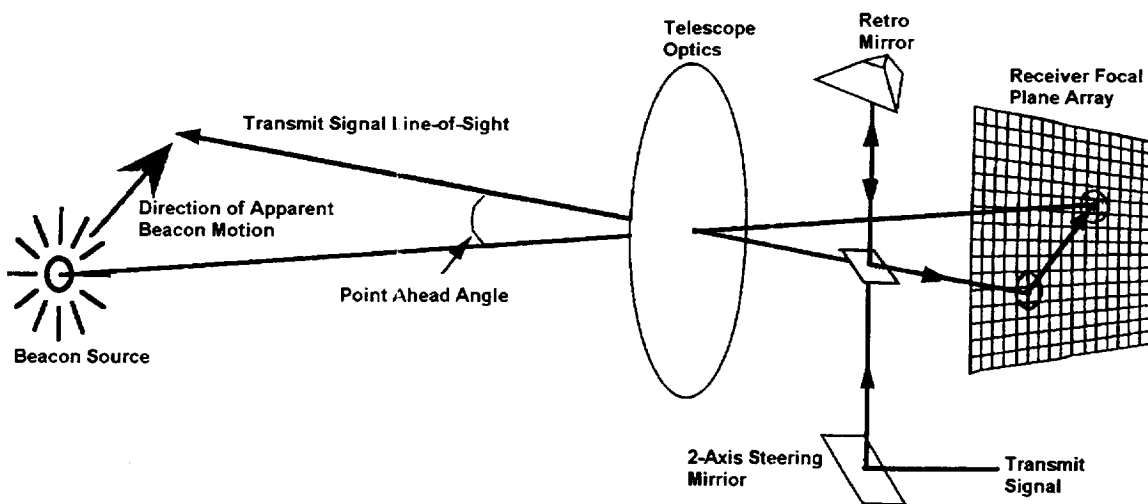

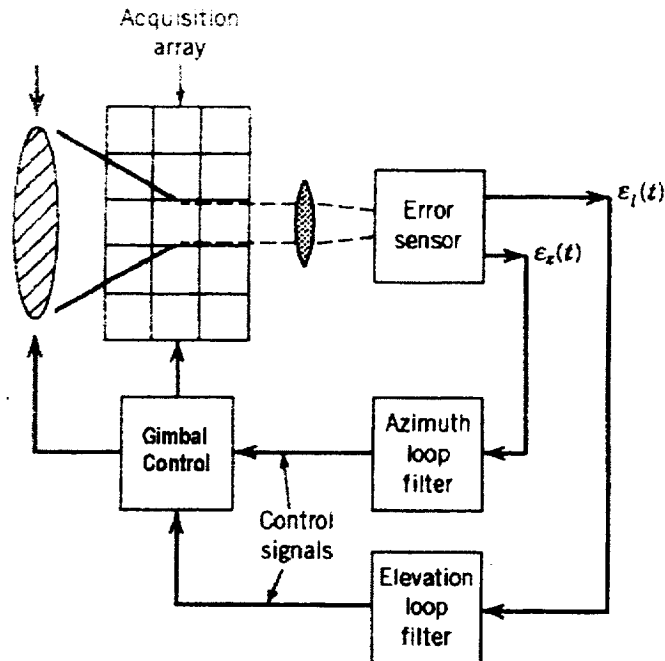Figure 2-4 Closed loop tracking subsystem.

27

Figure 2-5. Error iterating system.

2.2.3 Recievers

2.2.3.1 p-n, p-i-n and Avalanche Photo Diodes (APDs)

Photo diodes can be broadly categorized into two types: those without internal gain such as p- n and p-i-n diodes and those with such as APDs. The penetration depth of light before it is absorbed within a material increases with its wavelength. Thus a wider depletion region is necessary for long wavelength operation. In the p-n junction, this is achieved by making the n-type material so lightly doped that it can be considered intrinsic; an n+ layer is added to reduce ohmic contact. This modified device is known as a p-i-n photo diode. The intrinsic layer is wide enough to maximize absorption for a given wavelength and the low doping means it is fully depleted under normal reverse bias resulting in fast collection of photo generated electron hole pairs. Due to the spectral limitations of Si and thermal instabilities and large dark currents associated with Ge, p-i-n diodes have been designed and fabricated using InGaAs which are sensitive over 0.95 to 1.65 μm wavelength range and have dark currents in the pA range at room temperature. Substrate entry heterojunction p-i-n based on InGaAs p+ and i layers and InP n layers have been used to eliminate absorption in the top p+ layer. However, this design suffers from charge trapping in the InGaAs/n-InP heterointerface although it is not a severe limitation to its performance [14].

In avalanche Photo Diodes (APD), the structure of the basic p-n diode is further modified to create an extremely high electric field; the APD consists of a n-p-i-p+ type layer structure. In addition to the depletion n-p region where the majority of absorption takes place, the high field region (i region) accelerates the primary photo generated pairs to acquire sufficient energy to excite new electron-hole pairs by impact ionization [15]. This is known as carrier multiplication; hence these devices have inherent gain. In order to minimize noise, the electric field at avalanche breakdown must be as low as possible. In Si, this has been achieved by using a reach through structure (RAPD) where the multiplication region is much wider than the n-p region. Much of the material problems associated with Si and Ge p-i-n diodes are also relevant to APDs and heterojunction devices have been realized using various compound semiconductor material

28

systems including InGaAs/InP. However, the narrow bandgap of InGaAs gives rise to an unacceptably high level of band-to-band defect tunneling currents which precede avalanche field. In common with the Si RAPD, this problem is significantly reduced by using a separate absorption and multiplication region in the SAM-APDs with the gain occurring at InP p-n junction where tunneling is much less. As in InGaAs/InP p-i-n, the issue of charge trapping at the heterointerface discontinuity is also a limitation in these APDs. However, Campbell et al [16] have reported the use of a InGaAsP (with a bandgap located between InGaAs and InP) quaternary grading layer to smooth out the discontinuity and hence improve speed performance in separate absorption, grading and multiplication (SAGM) APDs. Noise arising from multiplication region in APDs has been addressed by Capasso et al [17] by incorporating a super lattice structure (SL) in AlGaAs/GaAs and Kagawa et al [18] in the InGaAs/InAlAs SL-SAM-APDs.

A summary comparison with some of the key performance parameters for various types of optical detector devices is shown in Table 2-2. These represent typical figures quoted in the literature for advanced III-V detectors and are not necessarily the best data which is now available. Following the discussion on individual devices in previous sections, the purpose of this table is to present a "at a glance" figures of merit for these devices. For a more careful comparison, one needs to take into account several other factors such as material systems, the layer structures and the wavelength of the optical radiation amongst others; one such performance comparison between HPTs, p-i-n/FETs and APD/FETs has been made by Tabatabaie-Alavi et al. In some cases, where no data is reported, an estimate is presented.

It can be noticed from the above comparison that p-i-n devices are designed to provide high speed whereas APDs are essentially high gain devices. Since from a system point of view, the product of the gain and the bandwidth is important, there will a region of overlap where either device may be equally suitable. Another noticeable feature of this table is the inherent trade- off between the quantum efficiency, η, and the bandwidth of the detector; the two ITO/n- GaAs Schottky detectors [19] can be used to illustrate this point at a first order comparison: a slightly (10%) narrower absorption region enhances speed at the cost of lowering the η. APDs have also come into contention with advancements in device technology and material growth techniques; these devices combine high speed and high gain and can be used as mixers. Finally, it is clearly seen that the use of ITO as both transparent Schottky and emitter ohmic contacts improves the η without fundamentally reducing the bandwidth[26].

Table 2-2. Summary of detector types and their performance parameters.

Device Type	Advantages/Disadvantages	η	Bandwidth	Gain	Ref. No.
p-i-n	high speed, no internal gain	80%	25 GHz		[20]
SL-PD	internal gain, reduced noise	83%	3.6 GHz	25	[18]
Metal Schottky	high speed, no internal gain, low optical coupling		100 GHz		[21]
Metal Schottky	high speed, no internal gain, low optical coupling	19%	25 GHz (Estimated)		[22]
ITO Schottky	high speed, high optical coupling, no internal gain	32%	52 GHz		[19]
ITO Schottky	high speed, high optical coupling, no internal gain	25%	110 GHz		[23]
Metal HPT	high gain and speed, low quantum efficiency, suitable for mixing	50%	30 GHz	270	[24]
ITO HPT	high gain and speed, improved suitable for mixing quantum efficiency		17 GHz (Estimated)	22	[25]

29

Chapter 3.   General Failure Modes

Following are the list of general failure modes in photonic devices published elsewhere:

Surface Degradations
Facet oxidation/slow
Aluminum/inhibit diffusion: AlGaAs/GaAs
Output power: 200mW
Catastrophic optical damage/fast
Facet melting: AlGaAs>InGaAs/InP
Bandgap shrinking: non-absorbing mirror (<0.1 MW/cm^2)
Alloy electrodes
Metal diffusion
AuZnNi: Dark spot defects
Schottky type electrode: TiPtAu
Bonding parts
Soft solders: In, Sn, and Au rich solders/sudden failures
Hard solders: Au rich solders/reduce instability
Optical degradation/Modes
Dislocations
Metal diffusion
Oxidation
Inner material Degradations
Point Defects
Crystal structures vacancies
AlGaAs/GaAs>InGaAs(P)/InP
Quality of the Crystal
110 Crystal axis
Impurity level of the material
Workmanship/reproducibility
Radiation Damages
Total Ionizing Dose (25K Rad)
Replacement Damage (>25K Rad)
Single Event Upsets (75MeV/mg/cm^2)
Single Event Latch ups
Single Event Gate Ruptures.
Single Event Burn outs

It has been shown that when device parametric variations exist, the decay time is inversely proportional to the test temperature. In addition, it has been shown that a high temperature bake may be used to stabilize the electrical parameters. These results may indicate that some of the fabrication processes, especially those that require bakes, are not adequately performed during fabrication. The alloying of ohmic contacts and the ion implantation activation bake are the two fabrication processes most often blamed. Another possibility is the development of mechanical stress in the InGaAs/InP lattice and in the metal deposited on the wafer during processing; this stress is relieved at high temperatures.

The bake performed to eliminate the parametric variations is called a stabilization bake. The stabilization bake is usually performed on the wafers immediately prior to dicing, but may be performed even before lapping and backside processing. The stabilization bake is an unbiased bake and should not be confused with the burn-in screen, which is a biased testing of the circuits at an elevated temperature. In addition, the stabilization bake is not the same as the Hi-Temperature Storage test, which some manufacturers perform as part of the qualification process.

Although the stability of all electrical parameters is required before wafer acceptance, some manufacturers do not require a stabilization bake. Furthermore, some manufacturers who require stabilization bakes do not consider it a part of the wafer acceptance or reliability screening procedures, but rather a part of the fabrication process. Therefore, the stabilization bake may not appear in some manufacturers' reliability or product-acceptance procedures, while it does appear in others. Since the requirement for a stabilization bake is dependent on the manufacturer's processes, the bake temperature and time varies; typically, bake temperatures are between 200 and 300°C.

Following are the methods recommended to test for the screening of the photonic devices.

3.1   SEM Analysis

Scanning Electron Microscopy analysis can provide valuable information regarding the step coverage and quality of the metallization and passivation of OPD devices. Thus, this tool is required as part of the wafer acceptance tests. Some accept/reject criteria are provided in MIL-STD-883, but they may need some modification to cover OPD technology.

3.2   Nondestructive Bond Pull Test

The integrity of wire bonds cannot always be judged through visual and electrical tests. Therefore, some qualification procedures recommend the implementation of a nondestructive bond pull test of each bond. The pull force selected for this test is generally dependent on the material and wire diameter in question. MEL-STD-883, Method 2023, is normally used for this application. Obviously, selecting the required pull force is critical and must be decided by the manufacturer and the user.

Mechanical damage to good bonds as a result of this test is possible. Additionally, for microwave circuits, the wire bond's impedance can be changed when the shape of the wire loop is changed, which results in a change in the RF characteristics of the OPD. Due to the problems associated with this test, some manufacturers have removed this step from their qualification and screen procedures and resorted to in-process controls and testing to provide the necessary information. The decision to require this test must be made by the OPD user after careful consideration of the system application and the workmanship of the manufacturer.

3.3   Visual Inspection

Many defects in OPDs, such as metal voids, substrate cracks, poor wire bonds, and foreign materials, reduce the OPD reliability. Small voids or cracks in the metallization will cause increased electrical resistance, increased current density, and an increased possibility of failure due to electromigration. Furthermore, microwave circuits radiate power at gaps and discontinuities in transmission lines. Edge chips and cracks created during wafer sawing or dicing easily propagate and cause circuit failures or die breakage during thermal cycling and wafer handling. This is especially true for InGaAs/InP monolithic circuits since InGaAs wafers are more brittle than InP wafers and they are often thinned to 100 µm or less. The stray particles of InP created during wafer sawing or other byproducts of the circuit fabrication process may deposit themselves onto the wafer. Since InP is highly insulating, InP particles will usually not cause problems. However, other materials, especially metal particles, may adversely affect circuit performance. If the particles are on the gate of the transistors or on other circuit elements, the circuit performance will be degraded. This is especially true if the circuits have not been passivated. Since free particles may move during circuit testing, packaging, or in zero gravity space environments, even free particles away from the circuit elements may cause failures. During die attach, eutectic alloys and epoxies are used that may adhere to the sides or top of the circuit where it could short RF transmission lines and biasing pads to the ground plane. Lastly, the electrical connections between the package and the circuit must be made. These connections are usually made by ball or wedge bonds comprised of thin (typically 17 µm in

31

diameter), gold wires attached to gold pads. The location and the quality of the bonds are critical for good OPD performance and reliability.

These obvious defects and others not listed here in materials, construction, and workmanship must be eliminated since they degrade circuit performance and reliability. Furthermore, it is better to eliminate circuits with obvious defects before additional resources have been spent on them in bonding, packaging, and burn-in. Luckily, these defects are easily detected by performing a visual screen of every circuit with the aid of a microscope. The visual screen is performed during wafer acceptance tests for defects of the die and during the packaged OPD screens for packaging and bonding defects.

3.4   IR Scan

Some defects such as substrate cracks and die-attach voids may not be visible, but they must be detected. Since these types of defects have a different thermal conductivity than the surrounding defect-free region, they may be detected through thermal mapping. The baseline for the comparison is the thermal profile of the OPD that was made as part of the product or design verification step. For example, during design verification, it may have been determined that the final stage of an amplifier was the hottest part of the OPD at 90°C, while the rest of the OPD had a 15°C temperature variation. If a similar OPD were thermally mapped and found to have a hot spot of 100°C or the wrong temperature variation across the die, a defect would be indicated. Typically, variations greater than 5°C are considered a reject. Thus, a simple comparison between the OPDs in the screening process and the OPD thermal profile can be used to detect defects not visible to the eye.

Although infrared microscopes are expensive, require calibration, and have a minimum resolution of approximately 15 μm, they are the best method of mapping the OPD's thermal characteristics since they do not damage the OPD surface. Furthermore, the microscope can be computer controlled to scan the surface, make the required map, and perform the comparison to the thermal profile stored on file.

This screening step is not typically imposed as a requirement following MILPRF-38534. However, it is recommended for high-power devices and in applications that require good thermal stability. This step should be performed after die attach and before attachment of the package lid.

3.5   Temperature Cycling and Shock Screen

In the same way that electrical devices can be made to fail quicker at higher temperatures, mechanical devices can be made to fail quicker by applying thermal stress. These tests are used to detect flaws or weak points in the die attach, wire bonds, and package seals that would normally result in early failures. Temperature cycling consists of cycling the packaged OPDs between extreme temperatures many times. Typically, the temperatures used are -65 and 200°C, and the number of cycles is 15. The temperature shock screen is similar to the temperature cycle screen in that the test involves subjecting the packaged OPD to extreme low and high temperatures (-65 and 150°C) over many cycles. The difference is a sudden change in temperature created by immersion of the parts into a bath, rather than the gradual change in air temperature used in the cycle test. Failure detection for both screens occurs during final electrical and visual inspections. Typically, only one of the screens is required, and the manufacturer and user decide on the appropriate screen for their application.

3.6   Mechanical Shock Screen

This screen is intended to detect weak parts that are required to undergo severe shocks during transportation, handling, satellite launch, or other operations. The test subjects the packaged

OPD to a number of short shock pulses with a defined peak. Failures are detected during final visual and electrical screens.

3.7   Constant Acceleration

This screen is intended to detect failures due to mechanical weakness by subjecting the packaged OPD to a constant acceleration. Typical failures occur in the bonds and die attach, and these are detected during the final visual and electrical screens. Although this screen is typically required, it is not because of the forces caused during launch but rather as an effective tool to detect poor workmanship.

3.8   Particle Impact Noise Detection

During encapsulation, thermal stress screens, and mechanical stress screens, particles may break off the OPD or package. These loose particles may mechanically damage the OPD during handling, launch, or in operation, or they may cause short circuits. The particle impact noise detection screen is a nondestructive test used to find parts that have this defect. During the test, the part is vibrated and a sensor is used to detect anomalous noise. Failure criteria are given in the reference listed in Table 3-1.

3.9   Burn-In

Ideally, a well-controlled GaAs fabrication line, which employs proper wafer handling and fabrication procedures along with visual, direct, and RF screens, would eliminate circuits containing defects that result in the early failures that were discussed. In fact, in some InGaAs fabrication lines, the early failure rate is very small. However, in state-of-the-art circuits with 0.1 to 0.25-μm gate HEMTs, complex circuits with many air bridges, or packaged circuits with many wire bonds, latent defects may cause early failures at a higher rate. These are detected through the burn-in screen.

The burn-in screen stresses the circuits above their normal operating conditions to accelerate any early failures that would occur from latent defects. Although burn-in is often performed at elevated temperatures to shorten the time of the burn-in test, the temperature must be kept low enough so inherently good circuits do not fail due to failure mechanisms accelerated by the test. Also, since circuits that pass burn-in are used in either accelerated life testing or as flight deliverables, bum-in at too high of a temperature will distort the results of the accelerated life tests and reduce circuit lifetime during the mission. It is inevitable that the burn-in screen will use some circuit life, but if the circuit has an inherently long lifetime and the burn-in screen is not performed at too high of a temperature, only a few percent of the life will be lost. This small cost in circuit lifetime is accepted by the space industry, since the alternative is a failed mission or satellite.

To prevent creation of failures in inherently good circuits due to excessive stress conditions, burn-in should be performed only once on each circuit and appropriate test conditions should be selected. Circuits that fail burn-in should not be reworked and re-tested. If the circuits are to be delivered to another company for further processing or packaging, it is critical that the burn-in screen is coordinated to assure that it is not duplicated. An exception can be made if the system builder performs a burn-in on the entire assembly, since assembly bum-ins are normally performed at lower temperatures and for shorter times than the InGaAs die burn-in. Therefore, the total stress to the OPD from the additional assembly burn-in is small and should not affect the circuit's lifetime.

It should be noted that only a small percentage of InGaAs circuits fail the burn-in screen, and the burn-in screen increases the circuit cost. Furthermore, the increased handling of the circuits during the screening procedures increases the chance of creating failures in the circuits due to introduced mechanical, ESD, and handling defects. Therefore, most suppliers of commercial

OPDs do not perform burn-in screens, but all satellite manufacturers require burn-in of all electronic parts.

The screen is typically performed at 125°C ambient temperature for 320 h with the circuits biased to their maximum stress levels. However, careful consideration of the resultant device channel temperature is recommended to avoid undue stress of the device during test and the introduction of thermally accelerated failure mechanisms. If the OPD is classified as a large-signal (greater than 1 -dB compression) device, RF energy should also be applied to the input port with the output port matched. Failure is usually specified as an electrical parametric drift from the initial conditions by a specified percentage. These conditions have been shown to be effective in removing weak OPDs.

3.10   Leak Tests

There was considerable discussion earlier in this chapter about failure mechanisms that result from contamination and humidity. To eliminate these problems, OPDs, as well as all other electronic components intended for high-reliability applications, are sealed in hermetic packages, and the reliability of the OPDs is dependent on the integrity of these packages. To find weak packages that would result in loss of the hermetic seal, thermal and mechanical stress screens are performed. Although some gross package failures are visually detectable, most defects in the package require a leak test.

Fine leak tests consist of placing the packaged OPD in a chamber pressurized with a known gas; some of the gas will enter cracks or defects in the package if they exist. Usually, helium or nitrogen gas with a small concentration of a radioactive isotope is used, since either is detectable in very small concentrations using standard, commercially available equipment. After a time, the chamber is cleansed by circulating air, and the packages are tested to determine if gas leaks from them. Although the use of radioactive isotopes sounds hazardous, it is the preferred method in high-volume production lines because it is easier to detect for a longer period of time. The disadvantage of fine leak testing is that the gas will leak from gross defects before it can be detected. Therefore, a gross leak test is required after the fine leak test. The principle of the test is the same except that a pressurized liquid bath is used instead of the gas.

3.11   Radiographic Tests

The final screen is usually a radiographic "picture" of the inside of the sealed package taken in the same way that a doctor takes X-rays to image the skeletal structure of the human body. This nondestructive test uses radiation to penetrate the package walls and produce a shadow image on a photographic plate. It is useful for checking the location and position of wire bonds and for detecting loose particles that may have moved or broken off during the screening process. In some cases, this screen can also be useful in determining the presence of die-attach voids.

3.12   Optical and Electrical Tests

Optical and electrical parameters of a photonic devices should be determined by varying operating conditions within the defined mission environment. Optical specifications should be met within the electrical parameters supplied by the manufacturers. Optical parameters should include wavelength, intensity, and bandwidth of the optical output under specified electrical and thermal conditions.

Table 3-1. Laser Diodes (Single Stripe CW Devices), 0 to 820 nm Devices

DEVICE SPECIFICATIONS

Optical Specifications[1]	S-81-50OC-50-x	S-81-65OC-50-x	S-81-1OOC-100-x	S-81-120OC-100-x	S-81-200OC-150-x	S-91-200OC-200-x
CW Output Power	500 mw	650 mW	1000 mW	1200 mW	2000 mW	2000 mW
Center Wavelength	800 to 820 nm	800 to 920 nm	800 to 820 nm	800 to 820 nm	800 to 820 nm	800 to 820 nm
Emitter Area	50x1μm	50x1μm	100x1μm	100x1μm	150x1μm	200x1μm
Spectral Width	<2 nm	<2 nm	<2 nm	<2 nm	<2 nm	<2 nm
Wavelength Temperature Coefficient (Typical)	0.28 nm/°C	0.28 nm/°C	0.28 nm/°C	0.28 nm/°C	0.28 nm/°C	0.28 nm/°C
Boom Divergence, slow axis[3]	<10°	<10°	<10°	<10°	<10°	<10°
Beam Divergence, fast axis[3]	<3 5c	<35o	<35o	<35o	<35o	<35o
Polarization	TM	TM	TM	TM	TM	TM
Electrical Characteristics - Typical						
Differential Quantum Efficiency	>1.0W/A	>1.0W/A	>1.0W/A	>1.0W/A	>1.1W/A	1.0W/A
Total Conversion Efficiency	40%	40%	40%	40%	45%	40%
Threshold Current	250 mA	250 mA	350 mA	350 mA	500 mA	650 mA
Operating Current	750 mA	900 mA	1350 mA	1550 mA	2300 mA	2650 mA
Operating Voltage	<2V	<2V	<2V	<2V	<2V	<2V
Series Resistance	0.17Ω	0.17Ω	0.12Ω	0.12Ω	0.01Ω	0.09Ω
Thermal Characteristics - Typical						
Thermal Resistance	12 to 14°C/W	12 to 14°C/W	10 to 12°C/W	10 to 12°C/W	8 to 10°C/W	5 to 8°C/W
Recommended Operating Temperature	-20 to 30 o C	-20 to 30 0 C	-20 to 30 0 C	-20 to 30 0 C	-20 to 30 o C	-20 to 30 o C
Recommended Heat Sink						
Capacity[4]	1.5w	1.5W	3W	3W	6W	6W
Thermal Resistance	<0.2°C/W	<0.2°C/W	<0.2oC/W	<0.2°C/W	<0.2°C/W	<0.2°C/W
Package						
Style available (-x)	C, T, Q or H	C, T, Q or H	C, T, Q or H	C, T, Q or H	C, T, or H	C, T, or H

[1]All values measured at case temperature (T.) = 250.
[2]Custom center wavelengths are available, some from stock.
[3]FWHM.
[4]Values suggested are for operation of laser diode only. Operation of a TEC will require larger heat sink.

OPERATING NOTES
  ESD precautions must be taken when handling unit.
  Negative current transients greater than 25 µA and/or reverse voltage>3V, can destroy the unit.
  Unit requires an adequate heat sink. Failure to supply an adequate heat sink will destroy the unit. A dry environment should be provided when storing or operating a device for an open laser diode facet at room temperatures below the ambient temperature and below the ambient dew point. Failure to do so will cause condensation on the unit and can destroy it. Output powers in excess of specification will accelerate device aging.
  Operation at higher temperatures will accelerate device aging, increase threshold current and lower slope efficiency.

35

References

[1] *MIL-1-38535B, Integrated Circuits (Microcircuits) Manufacturing,* Department of Defense, Washington, D.C., June 1, 1993.

[2] MIL-STD-45662, *Calibration System Requirements,* Department of Defense, Washington, DC, 1988.

[3] *Distributor Requirements for Handling Electrostatic Discharge Sensitive (ESDS) Devices,* JEDEC Publication EIA 625, EIA & JEDEC Standards & Engineering Publications, 1994.

[4] MIL-STD- 1686, *Electrostatic Discharge Control Program for Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices),* Department of Defense, Washington, D.C., 1992.

[5] *General Standard For Statistical Process Control,* JEDEC Publication EIA 557A, EIA & JEDEC Standards & Engineering Publications, 1995.

[61 MIL-STD-883, *Test Methods and Procedures for Microelectronics,* Department of Defense, Washington, DC, November 15, 1991.

[7] *Transistor, Gallium Arsenide Power FET, Generic Specification,* JEDEC Publication JES2, July 1992, EIA & JEDEC Standards & Engineering Publications.

[8] *GaAs MMIC Reliability Assurance Guideline for Space Applications,* JPL Internal Publications 96-25, December, 1996

[9] "Highly reliable buried-stripe type 980nm laser diodes for practical optical communications", H. Horie, H. Ohta, Y. Yamamoto, N. Arai, B. Kelly, T. Fujimori, H. Gotoh, M. Usami and Y. Matsushima, SPIE Proc. *Laser Diodes and LEDs in Industrial, Measurement, Imaging, and Sensors Applications II; Testing, Packaging, and Reliability of Semiconductor Lasers V,* Vol. 3945, p. 280, 2000.

[10] *Optical Communications,* Robert M. Gagliardi, and Sherman Karp, Wiley, New York, 1995.

[11] A. Yariv, *Quantum Electronics,* 2nd ed., Wiley, New York, 1975.

[12] M. Born and E. Wolf, *Principles of Optics* 4th ed., Pregammon Press, London, 1970.

[13] J. Kraous, *Antennas,* McGraw Hill, New York,1950.

[14] T. P. Pearsall, M. Piskorski, A. Brochet and J. Chevrier, "A Ga0.47In0.53As/InP Heterophotodiode with Reduced Dark Current", IEEE Journal of Quantum Electronics, QE-17(2), pp. 255 - 259, 1981.

[15] J. M. Senior, "Optical Fiber Communications", (Published by: Prentice Hall Inc., New Jersey, USA), 2nd Edition, 1992.

[16] J. C. Campbell, A. G. Dentai, W. S. Holder and B. L. Kasper, "High Performance Avalanche Photodiode with Separate Absorption 'Grading' and Multiplication Regions", Electronics Letters, 19, pp. 818 – 820, 1983.

[17] F. Capasso, W. T. Tsang, A. L. Hutchinson and G. F. Williams, "Enhancement of Electron Impact Ionization in a Superlattice: A New Avalanche Photodiode with a Large Ionization Rate Ratio", Applied Physics Letters, 40(1), pp. 38 – 40, 1982.

[18] T. Kagawa, H. Asai and Y. Kawamura, "An InGaAs/InAlAs Superlattice Avalanche Photodiode with a Gain Bandwidth Product of 90 GHz", IEEE Photonics Technology Letters, 3(9), pp. 815 – 817, 1991.

[19] D. G. Parker and P. G. Say, 'Indium Tin Oxide/GaAs Photodiodes for Millimetric-Wave Applications", Electronics Letters, 22(23), pp. 1266 – 1267, 1986.

[20] D. Wake, R. H. Walling, I. D. Henning and D. G. Parker "Planar-Junction, Top- Illuminated GaInAs/InP p-i-n photo diode with Bandwidth of 25 GHz", Electronics Letters, 25(15), pp. 967 – 968, 1989.

[21] S. Y. Wang and D. M. Bloom, "100 GHz Bandwidth Planar GaAs Schottky Photodiode", Electronics Letters, 19, pp. 554 – 555, 1983.

[22] N. Emeis, H. Schumacher and H. Beneking, "High Speed GaInAs Schottky Photodetector", Electronics Letters, 21(5), pp. 180 – 18, 1985.

[23] D. G. Parker, P. G. Say and A. M. Hansom, "110 GHz High Efficiency Photodiodes Fabricated from Indium Tin Oxide/GaAs", Electronics Letters, 23, pp. 527 – 528, 1987.

[24] D. Wake, D. J. Newson, M. J. Harlow and I. D. Henning, "Optically Biased, Edge- Coupled InP/InGaAs Heterojunction Phototransistors", Electronics Letters, 29(25), pp. 2217 – 2218, 1993.

[25] W. Q. Li, M. Karakucuk, J. Kulman, J. R. East, G. I. Haddad and P. K. Bhattacharya, "High Frequency GaAs/Al$_{0.25}$Ga$_{0.75}$As Heterojunction Bipolar Transistors with Transparent Indium Tin Oxide Emitter Contacts", Electronics Letters, 29(25), pp. 2223 – 2225, 1993.

[26] Shabbir A Bashar, Ph.D. thesis, "Study of Indium Tin Oxide (ITO) for Novel Optoelectronic Devices", 1997.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE January 2001	3. REPORT TYPE AND DATES COVERED JPL Publication

4. TITLE AND SUBTITLE

Space Qualification Guidelines of Optoelectronic and Photonic Devices for Optical Communication Systems - NASA Electronic Parts and Packaging (NEPP)

5. FUNDING NUMBERS

C.- NAS7-1407

6. AUTHOR(S)

Quiesup Kim

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109-8099

8. PERFORMING ORGANIZATION REPORT NUMBER

JPL Publication 01-22

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

SUBJECT CATEGORY: 32   DISTRIBUTION: Nonstandard

AVAILABILITY: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Key elements of space qualification of optoelectric and photonic optical devices were overviewed. Efforts were concentrated on the reliability concerns of the devices needed for potential applications in space environments. The ultimate goal for this effort is to gradually establish enough data to develop a space qualification plan of newly developed specific photonic parts using empirical and numerical models to assess the lifetime and degradation of the devices for potential long term space missions.

14. SUBJECT TERMS optical communications, space qualification guidelines, optoelectronic devices, diode lasers, pin diodes	15. NUMBER OF PAGES 44
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited