COMMON PROCESSES FOR PASSIVE OPTICAL COMPONENT MANUFACTURING

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ABSTRACT

Permeation of fiber optic communication systems at the end-user level (i.e. ‘fiber-in-the-home’) is predicated on a reliable supply of individual components, both active and passive. These components will most likely have price and volume targets that can only be satisfied by full automation of the packaging processes. Polarization dependent optical isolators are examples of a typical passive optical component that is widely deployed at all levels of the network. We will use these isolators as an example for our discussion.

Intelligent contemplation of the options available for isolator manufacturing requires comprehension of some basic optical principles and component functionality. It can then be seen that isolator performance is directly influenced by process variations and part tolerances. We present a discussion of issues relating to cost, ease of manufacturing, and automation, highlighting component design, materials selection, and intellectual property concerns.

INTRODUCTION

The nascent optoelectronic component industry will require a combination of design for manufacturing and further development of materials, processes, systems and equipment to mature into the integrated, automated state that has made microelectronic products so incredibly affordable. Economies of this systems-level transition are heavily dependent upon the cost and availability of all necessary components. With the sponsorship of an international consortium of companies from across the industry, we are researching the issues involved in nurturing this transition. Our present work addresses aspects of the adaptation in the case of a polarization dependent optical isolator.

An example of a passive component commonly integrated into high performance laser diode assemblies is the polarization dependent optical isolator. Laser diode assemblies are often hermetically sealed for deployment in communications systems used under adverse environmental conditions. As a consequence, laser vendors often require optical isolators to be fabricated free of any organic materials, including adhesives. Economic consequences of this specification will become increasingly obvious as design efforts are focused on cost-conscious mass production. This attention will eventually lead to a critical re-examination of the actual needs versus the perceived package requirements, and perhaps to a strong increase in the incorporation of adhesives into high-performance optical component packages.

We start with an outline of current practice in the assembly of single, semi-double, and double stage optical isolators. A brief description of the optical principles and requirements, notably with respect to accuracy and handling of the extremely small parts involved, is followed by a discussion of some potential

short and long term innovations. This includes suggestions for improved materials selection and handling, design for manufacture, and fully automated component production. We also address current trends, such as the monolithic integration of isolators with the laser chips in planar devices, as well as the potential consequences of intellectual property on the development of other components and systems.
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FIRST PRINCIPLES

Optical isolators (or, more simply, isolators) are passive components commonly integrated into high performance laser diode assemblies. The function of an isolator in an optical system is analogous to that of a diode in an electronic circuit. An isolator permits transmission of light in the forward direction and blocks transmission in the reverse (or reflected) direction.

All optical isolators rely on non-reciprocal Faraday rotation. The Faraday effect is the rotation of the plane of polarization of light passing through a transparent medium that is under the influence of a magnetic field. A reciprocal element rotates the polarization in opposite directions relative to the reference on the forward and reverse paths, resulting in no net rotation for the trip. A non-reciprocal element rotates the polarization in the same direction for both forward and reverse paths, for a net rotation twice that imparted on each trip through the element. The direction of rotation for the non-reciprocal element may change with the direction of the applied magnetic field with respect to the rotator element.

Within the realm of optical isolators, there are two prevalent isolator designs. The designs are differentiated by the method in which isolation is achieved. Polarization dependent isolators prevent back-reflection by using dichroic polarizers that absorb undesired polarization states. This type of device is primarily configured with free-space coupling between the laser and collimator. Polarization independent devices rely on displacement of the beam induced by birefringent materials for isolation. The light fails to focus for effective coupling in the reverse direction and does not proceed through the system. Because of this reliance on beam displacement, polarization independent devices are most commonly used in pigtailed applications. It should be noted that it is not impossible to find pigtailed polarization dependent isolators or free-space coupled polarization independent isolators in the marketplace. The present discussion is, however, restricted to an examination of free-space coupled polarization dependent isolators.

A simple free-space polarization dependent isolator consists of a non-reciprocal Faraday rotator with a dichroic polarizer astride both the input and output paths (Figure 1). The transmission axis of the input polarizer is used as the reference position, and the transmission axis of the output polarizer is positioned coincident

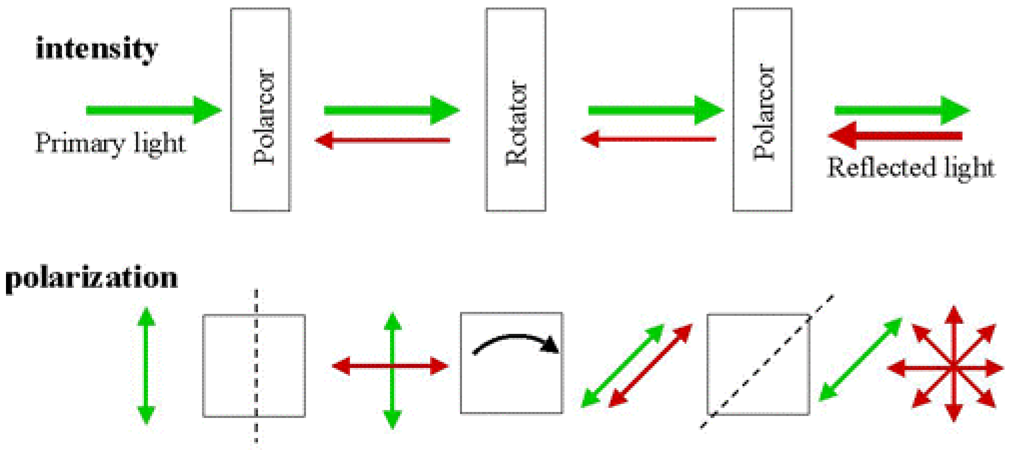

Figure 1: Polarization dependent isolator principle

with the polarization of the light upon exiting the Faraday rotator in the forward direction. Faraday rotators employed in both polarization dependent and independent devices are fabricated to yield 45^{O} of rotation for each pass through the element. A double pass (forward and reverse) through the Faraday rotator yields a net rotation of 90^{O}, which is ideal for maximum attenuation with dichroic polarizers (or for the transformation of the ordinary to the extraordinary ray in the polarization independent device).

In the forward direction, light of an unknown or random polarization enters the isolator via the input polarizer. The dichroic polarizer absorbs all light not polarized coincident to the transmission axis and passes the rest into the Faraday rotator element. Upon exiting the faraday rotator, the light has been rotated 45^{O} relative to the input and passes through the exit polarizer with a minimum of attenuation.

In the reverse direction, light of an unknown or random polarization encounters the exit polarizer. The resulting light has a polarization angle of 45^{O} relative to the input and subsequently transits the Faraday rotator. Within the rotator, the light is rotated an additional 45^{O}, for a net rotation of 90^{O} relative to the input axis. Virtually all the light incident on the input polarizer from the reverse path through the isolator is absorbed, as the transmission axis of the input polarizer is orthogonal to the polarization of the incident light.

Polarization dependent isolators may be conjugated or used in tandem to increase the isolation. Several common configurations are readily available in the open market. A component in the spirit of the configuration used in the example of the ideal isolator, consisting of two dichroic polarizers astride the beam path through the Faraday rotator, is referred to as a “single stage” isolator. When two single-stage devices are aligned to work in tandem, the configuration is a “true double” isolator. True double isolators offer a significant increase not only in isolation, but also in insertion loss and cost. To reduce the cost and insertion loss while attempting to preserve the increase in isolation, the “semi-double” configuration is offered. Two conjugated single-stage isolators share a common polarizer between the Faraday rotator elements. There are other special isolator configurations that may be used in specific applications.

PERFORMANCE AND PACKAGING

Two cardinal performance criteria for optical isolators are insertion loss and isolation. Insertion loss is the extinction ratio of the output to input power in the forward direction,

(-10 log [P(output)/(Pinput)]) (1)

and isolation is the same ratio in the reverse direction. An ideal isolator has no insertion loss in the forward direction and infinite loss in the reverse direction. In practice, the materials and processes used in isolator fabrication yield typical values of 0.15 dB for insertion loss and 40 dB of isolation.

Isolator performance is a function of the alignment of the optical axes in the optical train. Misalignment of the axes can have a significant impact on the performance of the device. Since the device is an optical isolator, the logical place to start is to optimize the isolation while minimizing the insertion loss. An approximate isolation value for a given angular misalignment may be determined using the relationship

$$\mathrm{I} = -10 \cdot \log\left(\sin^2 \Delta\theta_1\right) \qquad (2)$$

where $\Delta\theta_1$ is the angular misalignment between the input (blocking) dichroic polarizer and the Faraday rotator. Likewise, angular misalignment has a similar relationship

$$\mathrm{I.L.} = -10 \cdot \log\left(\cos^2 \Delta\theta_2\right) \qquad (3)$$

where $\Delta\theta_2$ is the angular misalignment between the Faraday rotator and the exit polarizer. It can be seen that a small angular misalignment has a great impact on isolation performance and a correspondingly small impact on the insertion loss.

Angular misalignment comes from two sources: process related sources and material deficiencies. Assembling isolators for maximum performance requires compensation for both of these sources. Early component assembly processes relied on component design alone to minimize the performance impact of angular misalignment. These early processes were designed around components with the capacity to be actively “tuned” (or peaked). Tuning takes place under known temperature and wavelength conditions to minimize the impact of variations from the Faraday rotator and maximize performance over the entire set of service conditions (including wavelength band). With knowledge of the Faraday rotator temperature and wavelength coefficients and the component service conditions, it is possible to build an isolator under ambient environmental conditions and expect an optimized component. Accurate geometric and angular characterization of the materials in the optical train was not necessary, as the tuning process would compensate for these errors. There was a patent granted to Konno and Kume (US Patent 5,204,868) for a similar tuning scheme, but the process is so simple and widely deployed that enforcement of this patent would be extremely difficult at best.

Actively tuned components are most often round, and are built with multiple mechanical components to accommodate the tuning process. Incorporation of the tuning process into the assembly on a device level has a significant impact on the economy of production. In addition, it is difficult to use round devices directly in surface-mount applications. Additional mechanical housings, or ‘clips’ are used to retrofit the round devices for use with “pick-and-place” equipment.

The combination of the need for surface-mount compatible isolators and economic pressures gave rise to a second generation of miniaturized optical isolators. These isolators leverage economies of scale by relying on the transfer of accurate and precise characterization data for all bulk optical materials into the fabrication and assembly process in lieu of tuning each device.

Surface-mount isolators may use a variety of substrate materials, depending on the need for CTE matching and/or specific process requirements. Plated and unplated austenitic stainless steels, Kovar alloy, alumina, aluminum nitride, zirconia, and silicon have all been employed as substrate materials.

Large slabs (up to 15 mm square) of dichroic polarizer material are measured prior to the dicing process to ascertain the alignment of the transmission axis to the geometric edge. This information may be employed to either correct the axial error during the cutting process or to bin the lots of cut slabs according to the axial error. In practice, the geometric edge of the bulk polarizer slab from the vendor typically deviates about 15 minutes from the transmission axis, though the vendor specification is for a much wider tolerance.

Characterization of Faraday rotator material is a complex undertaking compared to work with the polarizer material. The earlier concept of the ideal isolator mandates perfectly aligned polarizers, which in turn requires exactly 45^{O} of rotation when passing linearly polarized light through the Faraday rotator element. The magnitude of the Faraday rotation in the magneto-optic materials most commonly used is a function of the Verdet constant (degrees rotation per unit path length), wavelength, and temperature. Magnetic field strength is considered fixed and is encompassed as part of the Verdet constant as the material in isolators is always used in a saturated state. The temperature and wavelength coefficients are intrinsic properties commonly treated as being linear over the wavelength range for which the devices will be used. Most Faraday rotators are LPE (liquid-phase epitaxially) grown films, typically a substituted rare-earth iron garnet grown on a lattice-matched substrate. The substrate is polished off to yield the garnet film, which ranges from ~250μm thick for 1310-band devices to over 500μm for 1610 (L-band) devices. Careful polishing is critical, and it is not unusual to use a lot of rotators with an angular rotation tolerance as high as +/- 2^O (fixed conditions) across the entire lot. Material with tighter tolerances is available with a correspondingly higher cost.

A rotational error of 2^o would reduce the isolation to about 30dB (Eq. 2), but once the Faraday rotator and the axial error of the dichroic polarizer have been characterized, any tuning can be done prior to the assembly process. For this purpose the individual component-scale dichroic polarizers are fabricated such that, when placed on a geometric edge, the transmission axis is in the optimal position for maximum isolator performance. Depending on the equipment the rotational error may also be compensated for (passively) in placement.

ANALYSIS AND DISCUSSION

Once the magnitude of the rotation of the Faraday rotator and the axial error of the dichroic polarizer are known, any tuning can be done prior to the assembly process. Individual component-scale dichroic polarizers are fabricated such that, when placed on a geometric edge, the transmission axis is in the optimal position for maximum isolator performance. This “passive” tuning allows simple pick-and-place operations to be used in lieu of manual labor. As a result, significant economies of scale can be realized by moving the tuning process from the individual device to the bulk material level. Isolator packages were no longer restricted to the round, complex devices using an active tuning process. Passively tuned flat structures with streamlined processes could be mass produced.

Assembly of the isolator requires optical components to be orthogonal to the substrate and within a tight tolerance for rotation on the plane of the substrate. Polarization dependent isolators often have those optical components prior to and including the first Faraday rotator angled off normal to the beam. This angle ranges from 4^O to 8^O to reduce reflections from the isolator input back into the source. Consequently, a small amount of walk-off, or relocation of the beam from the input position, is introduced into the system. The beam still exits parallel to the input path but is offset from the input coordinates. Optical materials that are deficient by virtue of having a tapered section normal to the beam can also introduce angular displacement on top of walk-off and cause problems in systems with a tight beam path tolerance.

The package design should of course take the magnetic field strength and uniformity into account. In round packages, toroidal or bar magnets could be used to provide the necessary field strength to saturate the Faraday rotator and provide consistent rotation. In flat packages, we are left with a choice between bar and U-channel magnets. The latter have the advantage of being able to create a more homogeneous field by distributing the magnetic material about three sides of the rotator. Park (U.S. Patent 6,055,102) cites the use of a U-channel magnet, but there would appear to be sufficient leeway in this patent to allow for commercialization. Tokin, a Japanese isolator manufacturer, is presently marketing a U-channel device.

During the 1990's Lucent developed and commercialized "latching" Faraday rotators. The latching material is grown and processed so that the rotator works without the presence of an external magnetic field. This has a number of obvious advantages for both the component design options and the packaging process. However, the material is covered by a well-defined set of patents and is no longer commercially available from Lucent. At present, it appears that Lucent may require licenses for the deployment of latching films in components rather than for the growth of the material itself and several Japanese concerns (Sumitomo, Mitsubishi Gas Chemical) have developed and/or grown latching material for sale. However, the use of latching materials is likely to remain limited until the associated intellectual property issues have been resolved.

Material properties have a direct impact on fabrication costs and process yields in the fabrication of components in the optical train. One unilateral specification for all free space coupled optical isolators (inside or outside the pigtailed package) is the clear aperture. The clear aperture may be defined as area traditionally centered on the input face and propagated along the optical path through the device that must be free of all optical and mechanical defects.

For a given clear aperture, it becomes necessary to make allowances for chipping during the fabrication process and margins to accommodate placement tolerances for the die. Both the dichroic polarizer and Faraday rotator slabs are more brittle than silicon and require special attention during the fabrication process. Measures that minimize the chipping of these materials may act in opposition to efforts to increase the material yield. For example, it may be necessary to use a blade with a wider kerf to minimize chipping. The tighter the part placement tolerance, the less material is required in the margins. This reduction can be carried through to the system level, where the overall aperture size of the isolator can be reduced as the placement tolerances for other components are reduced.

Dichroic polarizer material is available in slab sizes up to 15 mm square and Faraday rotator material is commercially available in 10.5 mm or 11 mm squares. At present, there is no cost advantage to acquiring non-standard material configurations for either the dichroic polarizer or Faraday rotator except for those few companies (i.e. Sumitomo, TDK, Lucent) that are involved in both the material and device side of the isolator market. Those companies not vertically integrated are economically constrained to make the best of the commercially available material dimensions. Squares have been found to provide the maximum yield when the unfinished die size is an integer divisor of the slab size. In addition, the squares are most easily accommodated into an automated process because of the similarity to an open die and the optical self-registration of the passive alignment process. Only in situations where package size is at a premium do other cutting configurations, such as hexagons or core-drilled pieces, become economically feasible.

Another concern in the development of isolator assembly processes is the marking and orientation of parts. In devices where air is present between the components in the optical train, it is necessary only to mark the transmission axis of the polarizer. It is not necessary to mark the Faraday rotator, as there is no discrimination between polarization states (aside from the intrinsic problems of polarization dependent loss and polarization mode dispersion). Assembly of laminated devices introduces additional complexities as different antireflective coatings are used for air and epoxy interfaces. One solution is to preserve the identity of material lots and to “notch” one edge of the dies during the cutting process. The small amount of additional material sacrificed in the cutting process may be a comparably light price to pay for eliminating another set of process steps. An alternative solution is to use laser marking of an area outside of the clear aperture, though this can be capital intensive and require additional process steps.

Precautions must be taken when handling the individual dies that compose the optical train. Contamination is one of the primary concerns. The clear aperture must be free of all contaminants, which would seem to obviate handling of the dies in the area of the clear aperture. It is advisable that assembly processes are executed in a clean room environment to minimize the chances of particulates being sealed in the component. Chipping and scratching also become of paramount importance not only from the potential for damage to the area inside the clear aperture, but also from the particulates that can be created from the minute pieces of material that have been chipped off the surface. Rotator materials range from around 500μm down to 200 μm in thickness, while the dichroic polarizer can be as thin as 30 μm! Automated handling of approximately 1mm square pieces of these very brittle materials while touching them only near the edges is by no means trivial, particularly within a magnetic field. Assembling the whole structure before magnetizing it can alleviate this concern.

A major concern these days is the presence of epoxy in the beam path. Epoxies that are transparent in the common wavelength ranges may be used to laminate the optical components together in the package. This lamination is economically favorable at the microscale level, though at the macroscale level the kerf losses become prohibitively large due to the thicker blades required to cut the laminated structures. There is a concern that, over time, epoxies can degrade in the beam path from overexposure, rendering the component useless. There is also the potential for outgassing from the epoxy that could contaminate the clear aperture. These concerns account for many of the reasons that laminated, or even epoxy-containing isolators are excluded from the hermetically sealed devices used in severe duty or remote applications that are not easily accessible.

There are alternatives to epoxy in these applications. A solder process can be used to fasten the optical components to the substrate. Gold-tin eutectic solder is the number one candidate for this type of assembly as it may be used in the absence of flux. This process does have its drawbacks, including the use of expensive materials and the requirements for solder reflow in the presence of a reducing atmosphere to mitigate effects of surface oxides. Another possibility is to mechanically bind the components together, through the use of mechanical parts and fastening processes or injection molding around the entire assembly with a stable polymer or other material, analogous to the method expounded by Clark and Werth (US Patent 4,730,335).

CONCLUSION

There are shared concerns in the manufacture of any passive optical component. Several approaches to the manufacture of a polarization dependent optical isolator are considered. Cost and volume targets required for widespread deployment are achievable with fully automated manufacture. This will most likely be realized with passive alignment and tuning processes, including compensation for unavoidable tolerances. Design optimization, careful characterization, and complete automated tracking of the individual optical elements through the entire process are several of the essential elements.