Evolution of optical subassemblies in IBM data communication transceivers

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Optical subassemblies (OSAs) are the highest-cost component of datacom transceivers, and therefore the component that is most constrained by production cost concerns. While transceiver costs have declined, operating rates have increased from 266 Mb/s to 10.3 Gb/s. Corresponding OSA designs, based on multimode fiber, have evolved incrementally through several generations, to 2.4 Gb/s. Costs have been lowered in successive generations by reducing the number of parts, material costs, and complexity of assembly, and by using lower-cost optoelectronic devices—vertical-cavity surface-emitting lasers (VCSELs). This paper traces the mechanical aspects of OSAs that have been developed and introduced into products or developed as demonstration projects.

Introduction

The two major data communication (datacom) standards for optical transceivers are Fibre Channel in the storage area network (SAN) and Ethernet within the local area network (LAN) [1]. Their link distances range from a few meters to 10 km. The electronic functionality of transceivers has changed from the 1990 introduction of the Optical Link Card with multiplexing, coding, and framing functions to small-form-factor transceivers (1999), which only convert electrical to optical signals and vice versa using optoelectronic devices. Success in the data communications marketplace has required, for each generation, ever-higher speed as well as lower transceiver costs. The major cost components of a transceiver are the transmitter optical subassembly (TOSA), which converts an electrical signal into an optical signal coupled into an optical fiber, and the receiver optical subassembly (ROSA), which receives an optical signal from a fiber and converts it back into an electrical signal. The projected cost of producing the OSAs of a transceiver is one of the dominant concerns when designing the components of a fiber optic link for data communication applications. Costs are reduced by a number of strategies: using fewer parts, simpler assembly processes, wider dimensional tolerances, and less expensive components and materials.

While both ROSAs and TOSAs are key components of a transceiver, ROSAs are invariably less difficult to design and manufacture because of their larger optomechanical alignment tolerances. Accordingly, the discussion below is confined to the more difficult problem of designing, assembling, and testing TOSAs. Optical data links may have a serial structure—i.e., all data is transmitted by a link from one point to another by modulating the light intensity of a single optical source and passing that signal through a single fiber; or they may have a parallel configuration, either using multiple fibers or combining the signals from many lasers of different wavelengths onto a single fiber through wavelength division multiplexing (WDM). OSAs based on exploiting the advantages of these parallel forms are not covered in this paper.

OSAs of various designs share a number of common features. At the optical end of an OSA, a receptacle, or bore, is provided to accept a "ferrule." The ferrule, typically ceramic, has a precision hole for the optical fiber and is contained within the connector housing of a fiber

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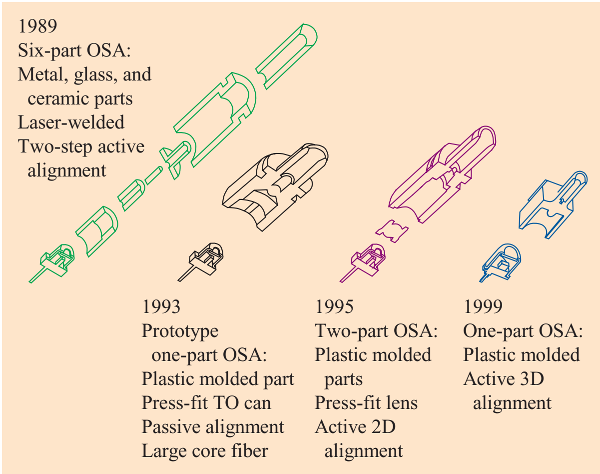

Figure 1

Progression of OSA development in IBM.

optic cable. At the electrical end, a suitable means for transferring power and electrical signals to and/or from the OSA is provided. As a mechanical structure, the body of the OSA must be physically robust: It must maintain accurate optical alignment, over a defined temperature and humidity range and under mechanical stress conditions, for at least five years. Optically, the OSA must efficiently pass light from a light source (an illuminated fiber, in the case of a ROSA, or a laser, in the case of a TOSA) to the receiving element. Inevitably, a significant amount of power is lost in this process. The efficiency with which the available light, the optical signal, is coupled from its source to its receiving element is designated as the coupling efficiency. Coupling efficiencies can range from about 20% to 90% depending on the application. The coupling efficiency requirements are determined by an optical link budget for the entire system, and the absolute coupled power is specified in the Fibre Channel and Ethernet standards.

This paper describes the key mechanical challenges that were overcome in each of the stages of OSA development in IBM (**Figure 1**) from the early OSAs fabricated from many precision parts, to the prototype plastic OSAs made of a single piece of injection-molded plastic [2], to the first production plastic OSAs, which incorporated both a structural plastic housing and an optical plastic lens [3], to the final reduced-size single-piece plastic OSA for use with low-cost VCSEL laser devices [4].

Early OSAs

Starting in the 1980s, interest arose in using the relatively inexpensive lasers of compact disk players as transceiver sources. Initially the thermal, environmental, lifetime, and noise characteristics of high-volume, commercial laser diodes packaged in TO cans were evaluated [5]. Over a period of several years, a series of laser diodes from several manufacturers were selected as suitable candidates for optical data communications applications. In some cases, special processes were instituted at the manufacturer to guarantee acceptable device performance and reliability. Laser devices mounted in TO cans became the standard building block for the OSAs.

The first generation of OSAs were constructed from six precision-machined parts, including custom-designed metal flanges, a housing and a bushing which mated with commercially available ceramic bores, and a gradient index (GRIN) lens. Several of the parts had to be specified with very tight tolerances, a major contributor to cost. The parts were assembled through a series of “active alignment” steps through which the laser was turned on (activated) and the laser, lens, and fiber were moved relative to one another to align the converging rays onto the input surface of the fiber while the power coupled into the fiber was monitored. The alignment tolerances were very tight, within 1 μm for the single-mode TOSA and 5–10 μm for the multimode parts. A Nd:YAG laser was used to weld the machined parts in place after alignment.

Most critical in the case of the TOSA is the coupling efficiency, defined here as the proportion of the laser power which is coupled into the optical fiber. By selecting an appropriate GRIN lens for the multimode application, an average coupling efficiency of 50% with a tight (σ = 4%) distribution was demonstrated after alignment and welding. Achieving acceptable coupling efficiency during assembly is only part of the challenge; maintaining consistent coupling efficiency over a variety of stress conditions that simulate impact shock and vibration as well as the effects of thermal shock, storage conditions, and life testing is also required. The most severe stress occurred under high temperature (80°C) and humidity (85% RH) emulating the OSA storage conditions. All of the first-generation TOSAs survived 2000 hours of such stress with less than 5% variation in the coupling efficiency measured every 500 hours at room temperature and humidity. This variation could be explained by the repeatability of ferrule connection (typically ±5% unstressed) rather than being due to changes in the OSA caused by stress. These OSAs were extremely robust and provided a high quality standard which could not be compromised during cost-reduction programs.

Requirements for both single-mode and multimode fiber applications were met by a single mechanical design. The appeal of this approach was compelling; a single set of assembly tools accomplished the production goals of two product types, with the fixed asset costs shared by two product lines.

Many of the practical concerns of manufacturing a profitable low-volume product set were met by this design point. With volumes anticipated to rise dramatically, capital costs for products tailored to specific market requirements could be justified. A product set design capable of supporting single-mode operation, along with its alignment (where tolerances are some five to ten times tighter than in multimode operation) and stability requirements, no longer made economic sense when the demands of the market could be met with 50-μm multimode fiber, and perhaps even with large-core 200-μm multimode fiber. Besides tolerance issues, the parts count and the fabrication steps associated with the subassembly were seen as major cost contributors. Creating a design that integrated these observations and financial concerns became the driving force behind the development of a radically new prototype.

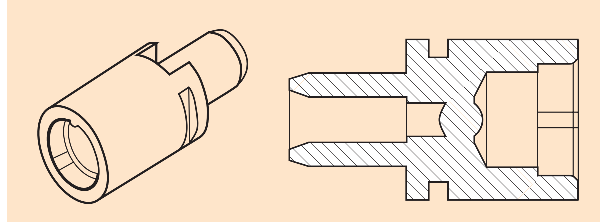

Figure 2

Solid model and cross-section view of prototype. Adapted from [2], with permission; © 1996 IEEE.

Prototype plastic OSA

The goal of the prototype was to push the limits to the extreme in low cost and simplicity of assembly while conforming with the form factor of the OSAs in production by fabricating a single-body OSA that required no alignment to assemble. The selection of large-core, 200-μm-diameter fiber as the transmission medium of the optical signal provided a target area 16 times larger than that of 50-μm-diameter core fiber. Therefore, the alignment tolerances to achieve high coupling efficiency into large-core fiber were relaxed dramatically. Most significantly, objections to using plastic as the housing material, and injection molding as the fabrication process, based on concerns about holding dimensional tolerances, decreased given the new relaxed tolerance requirements and potential cost savings.

The design point called for using the production laser packaged in the standard TO can but replacing the other six metal, ceramic, and GRIN lens parts with a single optically clear plastic, injection-molded housing with an integral lens, as shown in **Figure 2**. The plastic housing incorporated mechanical stops, latches, and an accurate bore for the ferrule of the fiber optic cable. The other end of the OSA contained mechanical features for keying and press-fitting the TO can. In the early OSAs, the six-piece housing and the OSA assembly were the dominant OSA cost; with the cost of the plastic housing less than a dollar in volume and the assembly reduced to a keyed press-fit, the prototype OSA cost was significantly reduced and became dominated by the standard TO-can-packaged laser.

In order to achieve the press-fit assembly, the optical and mechanical design of the OSA had to accommodate the tolerances of the individual components—the TO-can-packaged laser, the ferrule-packaged fiber, and the OSA housing. Generally the lateral tolerances (perpendicular to the optical axis) are the most critical for achieving optical coupling efficiency. By far the item with the largest tolerance was the laser, which was placed to ± 80 μm in x, y, and z relative to a reference surface of the TO can. Ferrules for large-core fiber typically fabricated from metal or plastic have much looser tolerances (± 15 μm) than the ceramic ferrules made for 50-μm-diameter core fiber.

The mechanical design of the OSA included an interference fit for the laser TO-can reference surface. This minimized any added lateral tolerance in the laser position and made possible simple, adhesive-free assembly. The dimension of tightest tolerance was the inside diameter of the bore which accepts the ferrule; it had a tolerance of $+10$ μm and -0 μm. The diameter was a very difficult dimension to achieve and to measure accurately because it was subject to distortion during measurement. Most of the parts met all specifications; however, a few parts fell at and just beyond specification for the bore. The accommodation of these large tolerances led to an optical design centered at unity magnification, with modeled coupling efficiencies of 35% nominally and 20% with laser and fiber offset to the worst-case edges of their tolerance ranges.

Another aspect of the design was to control the total angular spread of light that was incident on the fiber. Although the large-core fiber has a large numerical aperture (NA) of 0.4 and thus can transmit optical modes incident at wide angles, for short distances the bandwidth of the large-core fiber can be greatly increased by limiting the incident NA to 0.16. This results, even over bends and twists of the fiber, in an effective 3-dB bandwidth of 160 MHz, supporting the Fibre Channel Standard at 266 Mb/s over distances up to 100 m [6]. Implementation of the controlled incident NA was achieved through the use of a flat rough ring molded around the lens area to form an integral aperture in the housing.

Polycarbonate was selected as the material to be used on the basis of both mechanical and optical considerations.

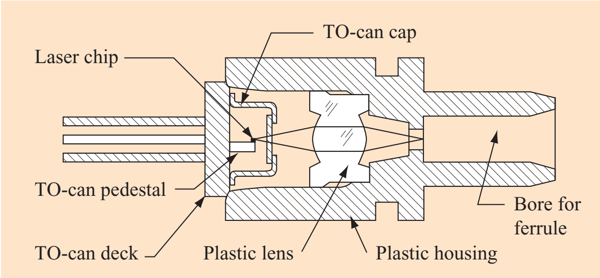

Figure 3

Schematic cross section of assembled TOSA showing laser TO can, plastic housing, and plastic lens. The ferrule fits into the bore on the right side of the housing. From [3], with permission; © 1997 IEEE.

Temperature stability was a key concern. The parts had to function in a temperature range of 10°C to 50°C with minimal performance degradation. Mechanical strength of the material to be used was important because of impact shock requirements and wear requirements during ferrule insertion tests. The availability of optical-grade polycarbonate due to its use in the manufacture of optical disks, together with its ease of molding, added to its attractiveness.

It was tested functionally through thermal cycling and repeated ferrule insertion tests of the completed OSAs. Thermal cycling data showed that the coupled power varied by 15% between minimum and maximum operating temperatures. The change was reversible and was caused by changes in the index of refraction of the polycarbonate with temperature. The ferrule insertion test gave an indication of a potential problem with material wear. Although the OSAs passed the Fibre Channel Standard specification of less than 7% change in coupling efficiency over 250 repeated ferrule insertions for both the plastic and the metal ferrule, testing with the metal ferrule clearly showed degradation starting after 200 insertions.

The prototype OSA extended the technology by using a single body fabricated from optical-grade industry-standard injection-molded plastic with passive press-fit assembly; however, it required the use of 200-μm-diameter core fiber.

First introduction of plastic OSA into production

Starting in the 1970s, the telecommunications segment of the fiber optics industry created high-volume production capacity for two multimode fibers, namely 125-μm-diameter fiber having either a 50-μm or a 62.5-μm-diameter gradient index core. Given the availability of these fibers and the superiority of their bandwidth performance over that of 200-μm-diameter core fiber, a new design point would use plastic as the housing material, but would accept only standard multimode fiber. The smaller fiber core size(s) did not allow for a purely mechanical alignment, so active alignment techniques were required. For plastic to meet various rigorous quality standards, a number of concerns had to be addressed: dimensional tolerances (both part-to-part and batch-to-batch) and material strength, sensitivity to humidity and temperature, abrasion resistance, long-term mechanical stability, the adherence of adhesives, and optical coupling efficiency targets. Each of the concerns was addressed by a combination of material selection, studies to evaluate the performance of parts subjected to mechanical and environmental stresses, carefully chosen assembly processes, and a simplified design that anticipated laser placement tolerances.

Selection of the material was aided by separating the optical requirements of the lens from the mechanical requirements of the housing using a design consisting of three parts: a standard TO can containing the optoelectronic device, a bi-aspheric injection-molded plastic lens, and an injection-molded, filled plastic housing (**Figure 3**). Two assembly steps were required. In the first step, the lens was inserted into its bore in the housing and attached; no alignment or test was done. The second assembly step consisted of applying adhesive to the housing, bringing the deck of the TO can in contact with the adhesive-coated surface of the housing, turning the laser on, moving the TO can laterally to maximize the coupling efficiency into the fiber, and finally heating the TO can to cure the adhesive. The heating was accomplished by rf induction, using the TO can as the susceptor. This heating method was chosen because it did not require physical contact between the heat source and the TOSA parts.

The housing closely resembled the prototype single-body OSA with an integral bore to accept a standard 2.5-mm-diameter ferrule and a locating surface (perpendicular to the optical axis) against which the deck of the TO can rested. As in the prototype OSA, this locating surface served to position the optoelectronic device at a point determined by the housing (i.e., no focusing step was performed) along the optical axis. Two aspects of the housing not found in the prototype OSA were the following: 1) the opening for the locating surface was oversized to allow for the lateral position of the TO can to be adjusted during the active alignment step; and 2) an additional accurately molded bore and stop were provided to position and locate the lens within the housing. The housing material was a carbon-filled plastic which can be injection-molded to tolerances in the range of about 2 μm. Its inherent stiffness was adequate to withstand the lateral forces applied by an inserted ferrule under typical field conditions and without exhibiting wear during multiple ferrule insertions. The material has a high heat-deflection temperature which allowed it to withstand the thermal epoxy curing cycle during which the aligned TO can was fixed to the housing.

The lens was made of polyolefin, a material that is virtually impervious to water, and formed by injection molding. The design of the lens involved a careful balancing of competing requirements [7], the most important of which was maintaining a minimum coupled power given the tolerances with which the component parts were manufactured. Two major contributors to optical power loss were 1) the displacement of the ferrule within the bore of the housing, in response to lateral forces on the fiber cable; and 2) uncorrected focus error at assembly (a major contributor was a ± 80-μm tolerance range about the nominal position of the laser relative to the TO-can reference surface). By purposely distributing the optical power over a well-defined and small area of the input face of the optical fiber, and by permitting the loss of some of the optical power (to some 30% of the total output power of the laser), the mechanical and optical design achieved a degree of fault tolerance. As with earlier TOSAs, the plastic TOSAs passed even the most stringent stress testing at high temperature and humidity. For the plastic TOSAs there was heightened interest in another challenging test, cable deflection, where the change in coupled power is monitored while an off-axis load is applied to the cable. This test became more critical because, despite the use of a high-modulus plastic, the distortion was much more than that of standard OSAs fabricated from metal and ceramic.

Cable deflection testing was required by users to demonstrate continuous functionality of the module in the event that a cable was pulled in the field. Testing consisted of pulling the fiber ferrule with a tensile force of 3 N at 45° to the optical axis of the TOSA. This was carried out for four different projections of the pulled cable (spaced at 90° intervals), with the coupled power recorded for the projection with the most loss. The OSAs successfully passed the cable deflection test with a change in coupled power of less than 20% (1 dB).

Reducing complexity further and moving to smaller footprint

Transceiver market and industry trends have made a shift toward transceivers with half the width and reduced height of the older-generation products in order to fit more transceivers along the edge of a single card. Industry groups have formed multi-source agreements (MSAs) to determine the external footprint and electrical connector requirements of the new small-form-factor (SFF) transceivers. Other industry trends have been to utilize emerging lower-cost vertical-cavity surface-emitting (VCSEL) lasers that were replacing edge-emitter CD-type lasers and to introduce open-bore-laser-safe products. Satisfying these requirements has required some innovation. In order to make the transceiver 13.6 mm wide and 9.8 mm high, a new fiber connector had to be used. A variety of options have been introduced by manufacturers, each using a different technical approach to fitting two fibers, one transmit and one receive, into the reduced space.

Choices included the LC connector based on a miniaturization of the Fibre Channel Standard SC connector with half-sized 1.25-mm-diameter cylindrical ferrules, the MT-RJ connector [8], based on the 8–12-channel MT** parallel connector, which used a rectangular ferrule with fibers on a 250-μm pitch, the SC-DC** connector [9], which maintained the 2.5-mm-diameter cylindrical ferrule of the SC connector but broke the axial symmetry of the ferrule by putting two fibers in the single ferrule, and the VF-45** connector [10], which eliminated the ferrule and used the 0.125-mm-diameter outer diameter of the fiber itself along with V-grooves for reference surfaces.

Technical evaluations were performed on each of these SFF connectors [11], and the techniques needed to develop transceivers incorporating these connectors were examined. The LC connector design [12] offered a low-risk-path means to produce an SFF transceiver, since the OSAs could be a reduced version of the plastic-molded OSA technology already in production. The LC connector also exhibited high performance for single-mode fiber applications; hence, it provided a consistent platform for all fiber types.

The earlier OSAs used the TO-56-type TO can containing a CD edge-emitting laser placed accurately with respect to the outside diameter and reference surface of the TO-56 deck. In contrast, a VCSEL device, being a surface emitter, was better suited to the lower-cost TO-46-type TO can. The TO-46 package does not provide for precise control of either the outside diameter or the emitter in the direction of the optical axis. The looser tolerances forced the OSA design to allow for full three-axis active alignment, and the clearance between the can and the plastic housings had to be increased. The required smaller-size and lower-cost target of the OSA, as well as experience gained through use of plastics in the existing product line, made it possible to take more advantage of the work done on the early prototype OSAs and shift to a single-body OSA with integral lens design (**Figure 4**). UV adhesives were adopted which made it possible to use lower-temperature optical-grade plastic materials for the SFF OSAs while allowing for active optical alignment of the TO-can-packaged laser. A new mechanical feature added to this OSA was a gap at the end of the ferrule stop which functioned as a dust catcher, preventing any contamination on the ferrule tip from grinding into the

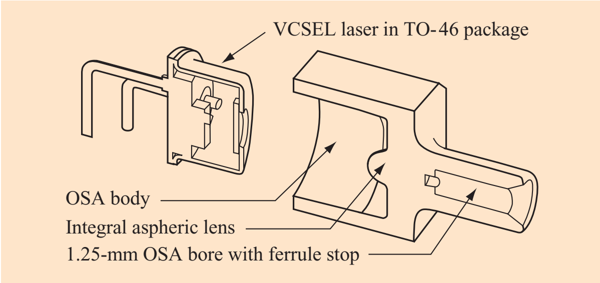

Figure 4

Exploded view of SFF TOSA cross section. From [4], with permission; © 2000 IEEE.

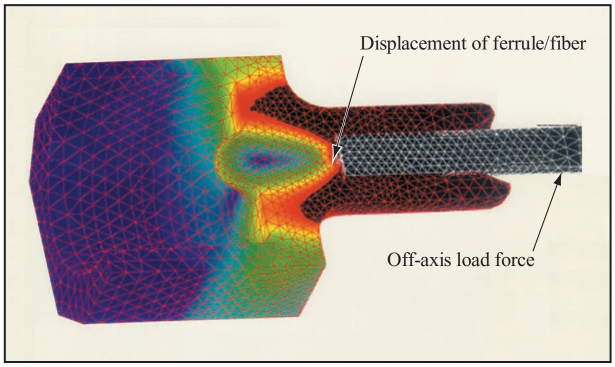

Figure 5

Example of ferrule displacement predicted by FEA analysis. From [4], with permission; © 2000 IEEE.

relatively soft OSA material at the focal point of the OSA lens.

Optical-grade plastics have lower strength and are more sensitive to the effects of increased temperature than filled plastics. OSA strength was decreased by the changes in materials, and was reduced further because of the reduction in size and thickness of OSA walls. Both the larger two-piece plastic OSA and the SFF OSA were studied by finite element analysis (FEA) to evaluate the effects of mechanical and thermal stress. **Figure 5** shows an example of predicted displacement or deflection of the fiber/ferrule, ferrule bore, and lens under an applied off-axis load. It is seen that high stresses are induced around the base of the bore (serpentine, light-colored region). To separate the effect of material changes from that of size reduction, both OSAs were modeled assuming the use of both optical and filled plastics. This analysis predicted the robustness and performance of the SFF optical plastic OSA compared to the earlier plastic OSA; for example, the displacement values were used in optical modeling to predict the coupling efficiency stability over cable deflection stress testing of worst-case-aligned OSAs.

The optical design of the OSA, including the open-bore-laser safety requirement, was simplified because VCSELs have lower divergence than edge-emitting lasers. Lower divergence means higher coupling efficiency into the fiber, allowing the laser to be run at a lower total open-bore output power.

The reduced size of the LC ferrule added challenges to the OSA optical design. The ferrule diameter, tolerances on the ferrule tip bevel, and the worst-case fiber NA of 0.275 together determined the maximum fiber-to-lens distance and lens clear aperture. On the TO-can side of the lens, the position of the optoelectronic device in the TO can was considered fixed and determined the minimum distance for the optoelectronic device to the first lens surface. Minimizing this distance was desirable because of the constraint that the overall OSA length be minimized to meet the required maximum outer dimensions of the SFF module.

The lens thickness and the distance from the fiber to the second lens surface were determined from the following competing considerations:

- Use of a minimum lens thickness would reduce the introduction of bubbles and particulates during molding.
- Use of a low magnification ($<1\times$) would result in wide lateral tolerance of the laser in the TOSA.
- Use of high magnification ($>1\times$) would result in higher coupling efficiency by accommodating the mismatch of the fiber NA with the divergence of the laser beam.

Taking into account these considerations, the TOSA optical design was optimized for a high coupling efficiency of 70% and wide lateral tolerances of ± 15 μm with less than 1 dB of misalignment loss.

Inherent in the tooling for fabrication of the single-body plastic OSA was a large concentricity tolerance of the aspheric lens surface to the OSA bore. Errors of up to 60 μm were modeled; with the proper offset compensation of the TO can during assembly, the concentricity error caused less than a 5% change in the coupling efficiency. The design of the TO-can side of the OSA accommodated this additional tolerance.

The SFF TOSAs, like the earlier TOSAs, had to endure environmental and cable deflection stress tests; this was achieved without increasing specification limits.

Summary

Beginning in the 1980s, the mechanical aspects of OSAs for the IBM optical transceivers evolved through multiple design cycles, resulting in decreased complexity and the use of precision-machined ceramics and metals, to plastic injection-molded parts. The number of parts used decreased from seven in the first cycle, to three, and finally to two. OSA assembly throughput was greatly increased as assembly techniques progressed from multiple steps of alignment and Nd:YAG welding to a simple two-axis alignment of a single element with thermally cured adhesives in the first production plastic OSAs. The advantages offered by lower-cost and lower-divergence VCSEL lasers and the quick cure time of UV adhesives far outweighed the added complexity of a required three-axis alignment for the TO-46 TO can of the SFF OSAs. A simple alignment technique involving the press-fitting of a TO can into the OSA housing was demonstrated in prototype assemblies; however, the requirement for larger core fibers precluded its use in production OSAs. The development efforts described in this paper have contributed significantly to the achievement of the high quality, yet low cost, of the IBM optical transceivers.

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