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Introduction

High-precision packaging of optoelectronic (OE) components continues to be a labor-intensive and expensive process. For example, performing sub-micron alignments and attachments of a single mode fiber to an OE device, known as fiber pigtailing, may require many tens of minutes by a highly-skilled technician. Stress and fatigue result in a relatively small number of successful alignments per day by each technician and significant part-to-part variations in the resulting alignment accuracies. Much progress is being made in automating various aspects of high-precision pigtailing. Passive alignment techniques [1,2] using v-grooves and other features etched in silicon wafers show promise for lowering the cost of fiber pigtailing and are compatible with array geometries, however, obtaining sub-micron accuracies using passive alignment has proven to be difficult. Many techniques to obtain sub-micron accuracies involve active alignment to maximize the coupling efficiency before attachment. Although very fast (sub-second) algorithms have been developed to maximize the coupling [3,4,5], one of the major drawbacks of active alignment is obtaining sufficient alignment to couple some light between the OE components in the first place. Laser welding techniques [6,7] are very robust and provide sub-micron accuracies, but require a large initial investment for the laser welder. Other alignment techniques using robotics [8] and batch processing [9,10] show promise for lowering the cost of sub-micron alignment and attachment of fibers to OE devices. Because labor accounts for a significant fraction of pigtailing costs, a fully automated pigtailing station should be capable of operating unattended for significant periods of time. Such topics as parts handling and feeding, initiating coupling of light, and attachment must be considered. Many OE companies are small and cannot afford a large initial investment for such a workstation, therefore low cost is essential. Finally, flexibility to pigtail different types of OE devices greatly reduces the costs of retooling for different products.

The goal of this 2-year ARPA-funded project was to design and build low-cost machines to perform sub-micron alignments and attachments of single-mode fibers to different OE devices. These Automated Fiber Pigtailing Machines (AFPMs) are intended to be compatible with a manufacturing environment and have a modular design for maximum flexibility and standardization of parts. Machine vision enables the AFPM to perform sufficient alignment to couple light for maximization. This work was a collaboration among Uniphase Telecommunications Products (formerly United Technologies Photonics, UTP), Ortel, Newport/Klinger, the Massachusetts Institute of Technology Manufacturing Institute (MIT), and Lawrence Livermore National Laboratory (LLNL). UTP and Ortel are the industrial partners for whom two of the AFPMs were built. MIT and LLNL made up the design and assembly team of the project, while Newport/Klinger was a potential manufacturer of the AFPM and provided guidance to ensure that the design of the AFPM is marketable and compatible with a manufacturing environment. The AFPM for UTP pigtails LiNbO3 waveguide devices and the AFPM for Ortel pigtails photodiodes. Both of these machines contain proprietary information, so the third AFPM, residing at LLNL, pigtails a non-proprietary waveguide device for demonstrations to US industry and further development.

AFPM Design

The AFPM (Figure 1) was designed to be low-cost (<$150K), modular, flexible, and compatible with a manufacturing environment. The performance goals of the AFPM were to perform each pigtailing operation in less than 3 minutes (including the epoxy curing time) and to operate unattended for up to 1 hour. During the alignment operation, the OE device is held fixed while the ends of the fibers are moved by the high-precision stages. These machines incorporate a 2-step procedure to perform sub-micron alignments. The first step uses computer vision to align the fiber sufficiently close (few microns) to the OE device to couple light between the fiber and the device; the second step then achieves the sub-micron alignment by maximizing the

Figure 1. The various modules of the AFPM mount onto a standard frame which measures 25" long by 22" high. The Ortel AFPM shown here has one high-precision stage mounted on the left side of the frame, while a waveguide device would require 2 high-precision stages.
light throughput. The overall design of the AFPM was carefully considered to minimize the requirements for high-precision machining tolerances; this greatly reduced the cost of building the AFPM. The modular nature of the AFPM means that each machine may be easily customized for a particular application. For this project, a basic set of modules was designed to build prototype AFPMs which can pigtails devices with 3 very different geometries including a photodiode and two different types of waveguide devices; a different set of the same modules would allow laser diodes to be pigtailed, for example. Considerable effort was put into different photodiode and two different types of waveguide devices a devices with 3 very different geometries including a means that each machine may be easily customized for a significant amounts of time. A conveyor system is provided to deliver the OE devices to the alignment stages and vision system. A description of several modules is given in the following sub-sections.

High-precision Stages

The high-precision stages were designed and built by MIT after extensive discussions with UTP and Ortel regarding the required resolution and range. The required resolution was determined by the mode size of the UTP waveguide device operating at 830 nm and the corresponding single-mode fiber to be pigtailed. The resolution of the stages needs to be a small fraction of the waveguide dimensions to ensure high coupling efficiencies. For the AFPMs, the chosen resolutions for the stages were 0.1 micron in the lateral dimensions and 0.5 micron in the longitudinal dimension. The range of the stages was determined by the working volume required by the AFPM to access the interior of the 14-pin DIP package of the Ortel photodiode; for this project, the range of the high-precision stages was chosen to be 25 mm in each of three translation directions. The issue of whether to include fiber roll in the AFPM created considerable discussion. Ultimately, roll was not included for this project once satisfactory mechanical fixturing was designed to accommodate this degree of freedom.

Vision Module

The vision system greatly reduces mechanical fixturing constraints by requiring the OE device and the fibers to be positioned only within the field of view of the camera. The camera field of view for all 3 AFPMs is approximately 1 mm by 1.2 mm with approximately 2 micron resolution (Figure 2). Achieving mechanical precisions sufficient to locate the OE device and the ends of the fibers within this field of view is fairly straightforward. Object-recognition algorithms written by LLNL allow the AFPM to determine the initial locations of the OE device and the fiber; this image analysis takes between 1 second to 6 seconds, depending upon the complexity of the image. The object recognition algorithms of the vision system would need to be customized for each OE application. The 2-micron resolution of the vision system allows the fiber to be moved to within a few microns of the desired initial position. This is sufficiently accurate to ensure that some coupling of light between the OE device and the fiber will occur. At this point, the AFPM switches to active feedback to perform the sub-micron alignment, that is, the AFPM performs a series of peak-finding motions until the coupling efficiency is maximized.

Kit Trays

One of the original design criteria for the AFPM was that it should operate unattended for at least an hour; this implies that at least 20 pigtails will be performed without operator intervention. The issue of parts handling and feeding becomes important for an automated system compatible with a manufacturing environment. Many aspects of the electronics industry are fully automated in terms of feeding parts to the assembly stage, so the technology is well developed. For this project, however, a parts handling scheme was developed which relies upon the operator to load the OE device and the fibers into a tray, the so-called kit tray (Figure 3). A set of six loaded kit trays is placed onto a pallet by the operator who then places the pallet onto the conveyor system of the AFPM. The conveyor system may be chosen to have any length necessary to allow the desired time of unattended operation. The operator is now free to continue loading kit trays while the AFPM performs the pigtailing operation.

The kit tray is designed for easy placement of the OE device and the fibers with sufficient accuracy to allow alignment by the AFPM. The overall design of the kit tray body is standard for all applications. The tray body is cast from hard plastic which allows 25 micron repeatability of the placement of the OE device with respect to the vision system from tray to tray. The kit tray can hold up to four spoons of fiber depending upon the type of OE device to be pigtailed. Unfortunately, every OE device has a different geometry so no standardization of the kit tray was possible for the fixture to hold the device. Therefore, the kit tray body is designed to accommodate a device cartridge which fits onto the top of the tray body; the device cartridge is one of the few AFPM components which must be custom designed for each OE device application.

Spools

One of the requirements of UTP and Ortel was that the

![Figure 2. This schematic of a camera image shows the waveguide device on the left side of the image and the end of a fiber on the right side. Fiducials indicate where the invisible waveguides are located. The dotted lines indicate the computer-found locations for the waveguides and the fiber end.](image-url)
OE devices be pigtailed with approximately 2 meters of fiber. This single criteria had a great impact upon the design of the AFPM parts handling scheme. The only tenable method to handle such long fiber in an automated manner was to wind the fiber onto spools. Adopting the notion of having spools led directly to the idea of needing some form of tray to hold the fiber and the OE device as described above.

Neither UTP nor Ortel used spools previously in their production lines, so the spools needed to be designed to minimize any adverse impacts in productivity. The spools were kept as small as possible (3.25" diameter by 3/16" thick) and were molded from plastic for light weight. Putting the fiber onto and taking the fiber off of the spools could present bottlenecks in productivity. Winders were built which are capable of winding fiber onto 50 spools at a time. The spools are built from two halves which can be separated to remove the fiber from the spools after the pigtailing process. Other features of the spool design accommodate other steps in the fiber preparation processes of UTP and Ortel.

Cost

The AFPMs were designed to satisfy all criteria for pigtailing the UTP and Ortel OE devices and yet be low in cost. At the beginning of this project, the UTP and Ortel processes were carefully studied to determine the required capabilities of the AFPM. The final design of the AFPM incorporates high precision tolerances only where absolutely necessary. Standardization of the various modules minimized costs as well. The total costs for parts for the 3 AFPMs were:

<table>
<thead>
<tr>
<th>Material</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTP</td>
<td>$65K</td>
</tr>
<tr>
<td>Ortel</td>
<td>$50K</td>
</tr>
<tr>
<td>LLNL</td>
<td>$60K</td>
</tr>
</tbody>
</table>

These amounts include only the costs for materials, machine shop work, and commercially-available products. These totals do not include such efforts as mechanical and electrical design, software development, assembly, and testing. (The Ortel AFPM is less expensive because it has only one high-precision stage while the other two machines have 2 high-precision stages each.) Obviously, commercially-available versions of the AFPM will be perhaps 2 to 3 times more expensive than the cost for just parts. Nevertheless, this basic design for an automated fiber pigtailing machine is quite low in cost considering the capabilities and flexibility that are available.

Technology Transfer

An important aspect of this project is the eventual transfer of the design of the AFPM to US industry. There are several mechanisms by which the technology transfer will take place. Representatives of US industry will be invited to the Final Design Review for a presentation of the AFPM design and a pigtailing demonstration. Drawings of the design concepts will be made available to US industry at the conclusion of this project (no details compromising UTP or Ortel proprietary information will be revealed). Finally, the 3rd AFPM, which pigtails a non-proprietary waveguide device, will reside at LLNL for viewing by representatives of US industry. This 3rd AFPM will also be used for development of additional capabilities not incorporated into these 1st generation AFPMs.

Summary

Three Automated Fiber Pigtailing Machines (AFPMs) have been designed and built under this ARPA-funded project. The AFPM enables many of the critical technologies to perform automated sub-micron fiber pigtailing compatible with a low-cost manufacturing environment. These technologies include low-cost high-precision stages, computer vision to replace the labor-intensive coarse alignment, and many details of parts handling and feeding. Subsequent generations of the AFPM may build upon the design concepts developed here to pigtail fibers to OE devices in more complicated geometries. For example, all applications for this project use epoxy to attach the fibers, so no applications using solder or laser welding have been considered. Also, the stages to manipulate the fibers provide only 3 axes of translation, so no rotational degrees of freedom are available, including the very important roll axis for polarization-dependent applications. The third AFPM at LLNL will be used to develop some of these capabilities.

Acknowledgments

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Figure 3. The kit tray measures 15" long by 3.5" high by 1" thick. The tray body is standard for all applications while only the device cartridge in the center is customized for each OE device. The fiber spools can hold at least 2 meters of fiber.
UTP; Randy Heyler and Soon Jang at Newport/Klinger; Ron Moeller and Huey Lu at Ortel; and Eric Breitfeller, Henry Garrett, Robert Johnson, Kirk Kleint, Joe Lown, Mark Lowry, Shin-yee Lu, and Ron Tilley at LLNL. At Lawrence Livermore National Laboratory, this work was performed in part under the auspices of the U.S. Department of Energy under contract No. W-7405-Eng-48.

References


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