Recent advancements in planar optics technology, specifically in the area of optical splitters, switches, modulators, and wavelength-division multiplexers, are driving demand for immediate increases in production throughput, consistency, and yield. Simultaneously, price pressures on these components are forcing drastic reductions in assembly and test costs, which still represent one of the largest portions of the overall packaged component cost.

Furthermore, this class of device (shown schematically in Fig. 1) is typically more difficult to pigtail than are standard optoelectronic devices, making it even harder to achieve robust, low-cost manufacturing methods. These devices are more difficult to assemble because

- they require simultaneous sampling and optimization (active alignment) of multiple input and output channels;
- validation of proper light launching into the device is often necessary before active alignment optimization;
- the fragility of the devices and the necessity of manipulating multiple fibers/fiber arrays increase difficulty in handling.

Automation technology offers the potential to achieve both improved throughput and enhanced yield—by reducing cycle times, eliminating operator dependence, and implementing the statistical process measurement, control, and improvement capabilities required to achieve high-reliability components. These factors provide the highest leverage for reducing device assembly costs.

Until recently, there has been very little academic or commercial research in the area of multichannel component assembly automation. Many of the development efforts funded by the Defense Advanced Research Projects Agency or other defense organizations, e.g., different defense organizations’ Manufacturing Technology (MANTECH) programs, have had a strong military-applications focus, resulting in negligible transfer to the commercial sector. More recently, the National Institute of Standards and Technology has singled out photonics...
manufacturing as a critical area that could benefit from more-explicit government funding under the Advanced Technology Program.

Having identified this lack of basic research into photonics packaging automation, Newport Corp. has teamed with several leading research programs at the University of Maryland to more intensely analyze—and subsequently optimize—automation algorithms and processes for aligning and bonding fibers and fiber arrays to planar optical elements. This work brings together the National Science Foundation-sponsored Center for Opto-Electronic Devices, Interconnects, and Packaging and Newport’s Photonics Packaging Automation Div. in an effort to accelerate the fundamental process research required to develop and deploy successful commercial automation systems.

Recently completed research has resulted in a fully documented alignment and bonding process flow for $1 \times N$ and $M \times N$ waveguide structures (see Fig. 2). Included in the research were the development, testing, and automation of advanced optical alignment algorithms and sequencing software, which resulted in extremely reproducible, operator-independent “align-and-attach” process control. Typical load-to-unload assembly cycle times on a $1 \times 8$ fused silica splitter, using pre-assembled V-groove fiber arrays and ultraviolet (UV) curing epoxy, were under 15 min. Furthermore, these process automation programs have already been implemented on commercially available assembly automation platforms, demonstrating a very rapid product development cycle (see photo).

**The assembly automation process**

The assembly process has been divided into nine discrete steps:

- **Input power measurement**—Before you insert the actual device, you must measure initial power throughput on all input fibers for later reference in quantifying insertion loss, validating optimum alignment, or qualifying component performance. This is typically done using a 90/10 splitter from the reference source to normalize measurements against noise and input source variations.
- **Device loading**—Reproducible, damage-free insertion of the fibers and fiber arrays and waveguide chips can be accomplished through the use of precision device tooling and high-magnification video feedback. Spring-loaded or pneumatically controlled grippers work best in bonding applications because they hold the devices more securely during critical bonding processes.
- **Initial light throughput**—In many planar optic structures, more light will propagate through the substrate layers than through the waveguides themselves if they are misaligned. Therefore, it is often necessary to qualify initial light-launch conditions by end-on viewing of the waveguide outputs to validate proper alignment of the input fiber(s) to the device.
- **Coarse alignment**—Coarse alignment only requires about 50 nW of throughput to start. This process is defined as the optimization of one of the $M$ input channels and one of the $N$ output channels in $x$, $y$, and $z$ directions, to a separation distance of approximately 100 microns between the fibers and the waveguide. (Typically the process begins at about 500-micron separations between components.) This is achieved through a rapid sequence of profiling scans, two-dimensional ($x$-$y$), and three-dimensional ($x$-$y$-$z$) alignment optimization subroutines. This ensures sufficient coupling to perform subsequent fine-adjustment and “roll” ($\Theta_z$) alignment processes.
- **Alignment optimization**—In this sequence, fine alignment is completed for one input and one output fiber, followed by coarse and fine roll alignments, and finally, fine adjustment of the $z$-axis positions. This process typically results in separations of less than 10 microns at fully optimized alignment, depending on the mode-mismatch of the fibers and waveguides. In many cases, index-matching gel or the specified adhesive will be applied during this process to minimize backreflections and Fabry-Perot interference between the mating surfaces. These effects can often be seen, even where the surfaces have been angle-polished to reduce their effects. In addition, the user may choose between having the alignment optimized on one of the channels, or balancing the power among the various channels by seeking a best-fit position that maximizes throughput while minimizing variations.
- **Pre-bonding metrology**—Before bond curing is done, a wide variety of...
metrology tests can be performed using the automation features of the system. For example, the light throughput on each output channel (channel uniformity) can be measured simply by jogging one of the output fibers (which are connected to the power meter) from one channel to the next. This step-and-read measurement sequence is easy to automate and can be programmed for any waveguide separation. All motions and positions are bidirectionally reproducible to less than 50 nm and can be sequenced in any order to avoid damage to the devices. Software compensation can also be used to adjust for angled edges or tilted components.

• Bonding—If adhesive has not already been applied, it is injected via a time-pulsed or positive-displacement adhesive dispenser. Adjustable hard-stops control the position of the epoxy syringe. Calibrated UV radiation is delivered via dual fiber-optic illuminators; the delivery of radiation can be programmed for variable intensity during the curing cycle. Both commercial-grade and user-proprietary optical adhesives can be accommodated. For example, Newport has developed bonding process sequences for fused silica waveguides (using commercial-grade UV adhesives) that reproducibly achieve extremely small (less than 0.1-dB) curing shifts. Thermally activated device tooling can also be incorporated; however, thermal curing adds substantial time to the overall process cycle. Alignment re-optimization during the curing cycle is an available feature, although this process typically only required during prolonged thermal curing cycles.

• Post-bonding metrology—After the bond has cured and cooled (about 2 to 5 min for many UV adhesives), final throughput measurements are made to quantify bond shift and validate device quality. All measurements and process results are automatically logged and can be transferred to user databases via an Ethernet connection.

• Unloading—One of the most expensive yield points is device unloading. Breaking a device or fiber at this point consumes about 90% of all the added value. Proper tooling and ergonomics (e.g., large access areas for the operator) can facilitate damage-free removal of the assembly.

**Key research factors**

Although at first glance this assembly process may seem fairly straightforward, many critical elements were investigated to arrive at a widely applicable process that could be commercially deployed.

First, the alignment optimization sequence comprises many parameters and process choices. Developing an optimum formula of scanning, profiling, gradient search, and other numeric alignment methods, along with understanding the basic trade-off between process parameter selection, cycle time, and reliability, was no trivial task. The software platform used in this research (see Fig. 3) enabled fast testing and validation of different techniques, and also permitted easy programming and assembling of process subroutines to facilitate test program development.

Second, several completely new alignment techniques were developed from the insights gained during the research. Among these are multiple approaches to optimizing Ω roll alignment (multiple scanning techniques and adaptive algorithm optimization), and channel-balance methods for minimizing throughput variations between channels.

Finally, the company had to develop a comprehensive nomenclature for all device components, channel designations, process variables, and pre-set automation sequence positions. Using these, any new user can fully understand the process automation sequence and easily manipulate it to suit new applications or device technologies.

**Future work**

In addition to researching alignment and bonding processes, we continue to study several other key areas of hardware and software development that are also critical to a successful automation system solution. These areas include:

• vision-aided positioning and gauging (onboard calibrated optical measurement),
• implementation of onboard wavelength testing metrology,
Enhanced tooling/fixturing/parts handling systems,
adhesive dispensing/curing process development for various materials,
automated alignment techniques and algorithms.

Research will continue to achieve a more fundamental understanding of these critical assembly and test process requirements. New techniques should continue to remove the uncertainties in photonics manufacturing and lead to the deployment of cost-effective automation solutions in the photonics industry.

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Fig. 3. Software-based process control systems offer comprehensive process automation and sequencing control, enabling fast process optimization and reproducible automation results.

*Enhanced tooling/fixturing/parts handling systems,*
*adhesive dispensing/curing process development for various materials,*
*automated alignment techniques and algorithms.*