INDUSTRY FOCUS

Photonics & Fiber Optics

An exclusive collection featuring top-tier articles, visionary experts, and essential industry insights

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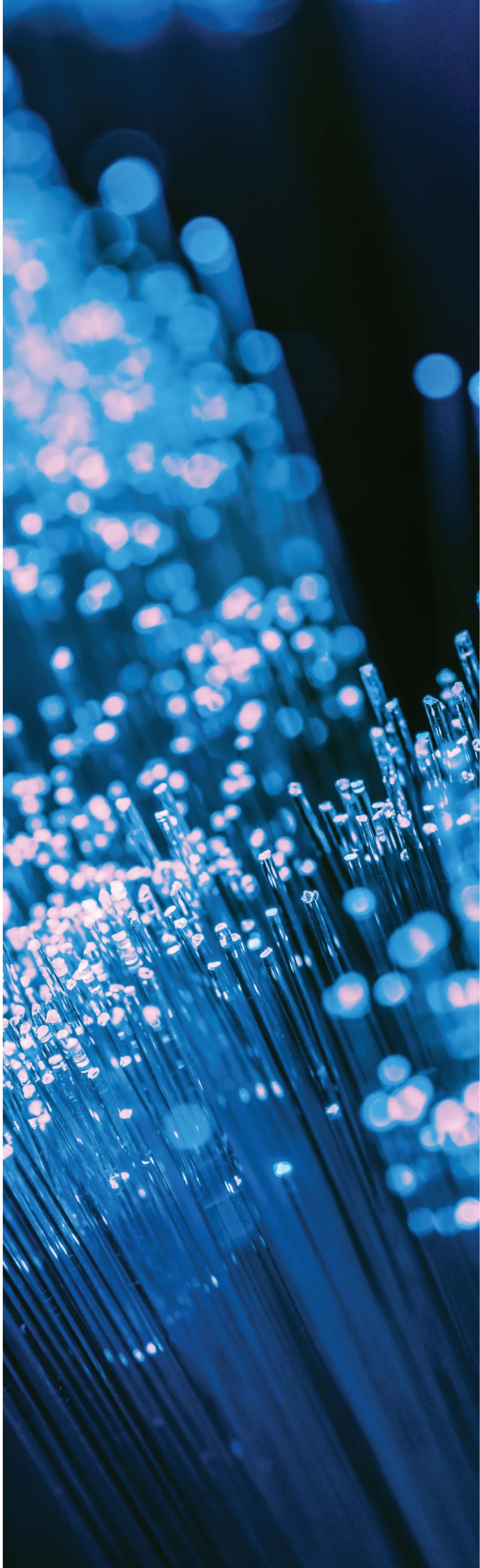
TABLE OF CONTENTS



Foreword

Welcome to the latest edition of our Industry Focus eBook, where we turn our attention to the rapidly evolving world of Photonics & Fiber Optics. As the foundation of countless emerging technologies — from quantum computing to ultra-fast communications — photonics is reshaping our digital and physical realities in profound ways. This collection brings together some of the most exciting developments and discussions in the field, offering insights into its growing influence across industries.

We begin with **An Introduction to Photonics, the Quantum Frontier of Light**, which lays the groundwork for understanding how light manipulation is becoming central to innovation. Moving into the nanoscale, **Introduction to Plasmonics: Harnessing Light at the Nanoscale** explores how scientists are leveraging surface plasmons to enable new optical devices and applications.

Alignment is a critical challenge in photonics, and **A Full Overview of Active Photonics Alignment** provides a deep dive into this essential process, while **Parallel Alignment Strategies for Complex Photonics Devices** outlines how high-throughput solutions are scaling to meet the demands of increasingly sophisticated architectures.

With silicon reaching its physical limits, **Are Photonic Chips Better than Silicon Chips?** takes a comparative look at performance, energy efficiency, and potential for future growth. Pushing further into the frontier, **Exploring the Use of Photonics in Neuromorphic Computing** examines how light-based computing may emulate the human brain more efficiently than traditional methods.

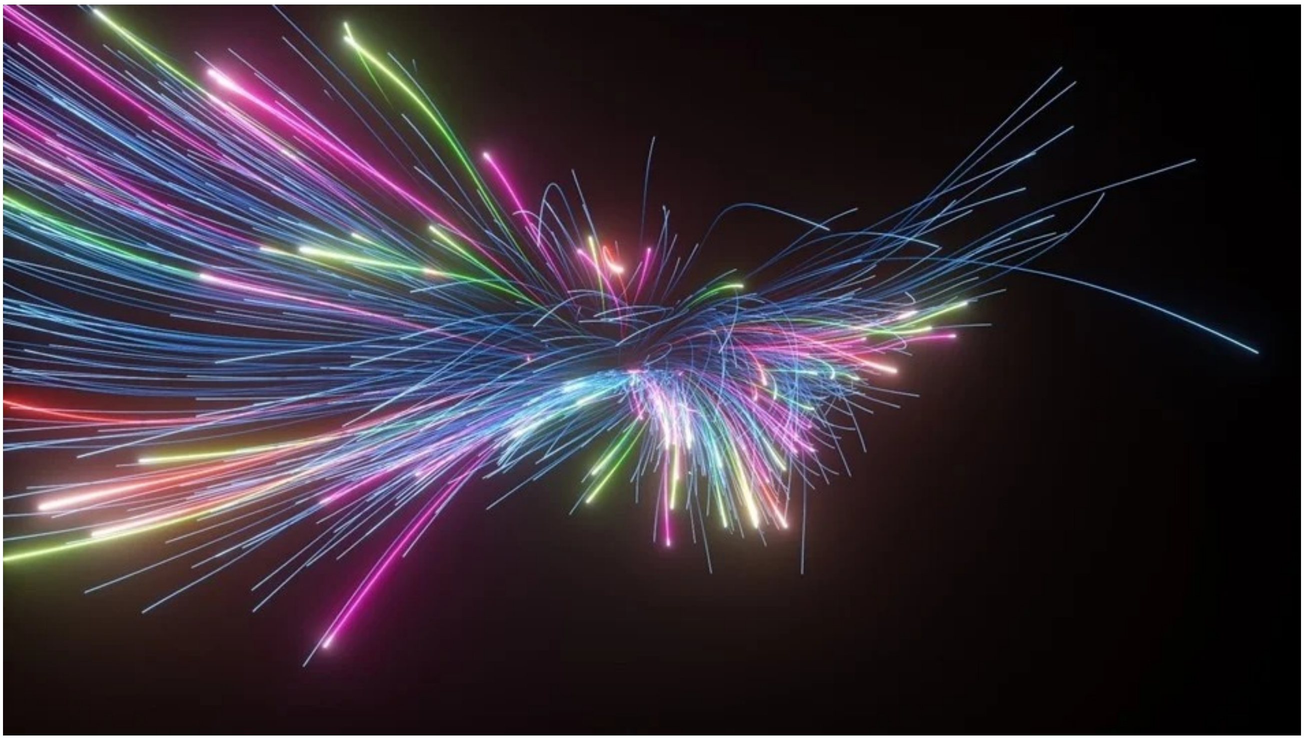
Beyond the technology itself, the industry faces a growing challenge: **The Photonics Skills Gap Threatens Innovation in Quantum and AI** brings attention to a workforce shortfall that could hinder progress in vital sectors.

Finally, we spotlight exciting breakthroughs in optical communications. **New Chip-Based Amplifier Revolutionizes Fiber-Optic Communication** showcases a compact solution with far-reaching implications, while **High-Throughput Alignment System for Photonics Arrays & PICs – Live Demos at SPIE PW, 1/28–30/25** invites readers to witness these innovations firsthand.

We hope this eBook informs and inspires, highlighting the vibrant future photonics is helping to create.

An Introduction to Photonics, the Quantum Frontier of Light

Photonics, the study and development of devices that use photons, has significantly shaped today's technological landscape. Just as J.J. Thomson's discovery of the electron laid the foundation for electronics and, eventually, modern computing, the exploration of photons has opened up a comparable path of innovation and practical applications.



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The theoretical foundation for photonics was laid when Max Planck formulated the quantization of energy, defining them as finite packets. Subsequently in 1905, Albert Einstein's explanation of the photoelectric effect introduced the concept of photons. Several decades of theoretical developments and experimental verifications ultimately led to the invention of the maser and laser between 1958 and 1960[1]. The development of these coherent light sources marked the formal birth of photonics in the 1960s.

Fundamentals of Photonics

At its core, photonics is the study and manipulation of photons, the fundamental building block of all electromagnetic radiation[2]. These elementary light particles are the quantized carriers of energy and momentum, spanning the full electromagnetic spectrum from high-energy gamma rays to low-frequency radio waves.

Within an atom, photons are emitted when an electron transitions from a higher energy level to a lower one, releasing energy in the form of a discrete packet. Because photons are massless and electrically neutral, they travel at the speed of light in a vacuum.

With the invention and commercialization of the laser and subsequently laser diodes, the term "photonics" gained popularity in the 1980s as fiber optic communication became widespread[1]. Coherent laser beams play a critical role in modern telecommunications. Laser pulses are used to encode binary data, representing "1"s and "0"s, which are transmitted through optical fibers. At the source, lasers or LEDs convert electrical signals into optical pulses. On the receiving end, photodetectors translate these optical signals back into electrical form, enabling the high-speed data transmission that constitutes the basis of today's digital communication.

Quantum Nature of Photons

A fundamental principle in quantum mechanics, wave-particle duality, shows that photons exhibit both particle-like and wave-like behavior. This dual nature is key to understanding how light interacts with matter at the quantum level.

The photon is classified as a bosonic particle, carrying an integer spin of 1. This quantized intrinsic angular momentum is closely tied to polarization, a fundamental property in optics. As photons travel through space, they exhibit two transverse circular polarizations, meaning the electric field of circularly polarized light rotates in a circle around the direction of propagation. The polarization of photons was experimentally confirmed in 1931 by C.V. Raman, marking a key moment in deepening our understanding of light and its quantum characteristics.

What Is Quantum Photonics?

Quantum photonics is a field that applies the principles of quantum mechanics to light to build advanced technologies[2,3]. It is an intersection of quantum optics and photonics, focusing on the generation, manipulation, and detection of individual photons and their unique quantum properties. Unlike classical photonics, which deals with large numbers of photons, quantum photonics works at the single-photon level, exploiting phenomena like entanglement, superposition, and non-locality to create groundbreaking technologies such as quantum computers, secure communication networks, and highly sensitive quantum sensors.

Central to quantum photonics is the ability to create entangled photons, whose quantum states are linked regardless of the distance between them. The procedure known as spontaneous parametric down-conversion (SPDC) is usually used to accomplish this[4,5]. SPDC method involves directing a single high-energy photon into a non-linear optical crystal, which causes it to split into two lower-energy photons. The resultant pair of photons are entangled to exhibit essential quantum correlations, including polarization and momentum. This guarantees that the state of a remote partner is immediately affected by a measurement on one photon.

In addition to producing and entangling photons, integrated photonics is essential for handling quantum information. Qubits encoded in photons are transported and manipulated by devices like waveguides, modulators, detectors, filters, amplifiers, and beamsplitters. This integrated approach allows for the miniaturization and scalability of quantum systems, moving them from complex laboratory setups to more practical, real-world applications.

Applications of Quantum Photonics

The unique capabilities of quantum photonics enable a new class of technologies across multiple sectors. One of the most significant applications is in quantum computing, where entangled photons are used to carry out computations based on quantum algorithms. By leveraging the principles of superposition and entanglement, quantum computers have the potential to solve complex problems that are intractable for even the most powerful supercomputers.

Using one of the fundamental ideas of quantum mechanics, quantum key distribution (QKD) is a novel method for securely transferring data over networks. QKD makes good use of the quantum nature of photons, which states that decoherence results from the observation of a state. This ensures that encryption keys are kept secret via an optical network. Any attempt to eavesdrop on the network can be detected, as QKD makes data interception virtually impossible without altering the system in a measurable way. This technology will serve as a pillar for next-generation communication networks designed to be inherently secure and resistant to hacking.

Additionally, quantum photonics provides powerful new instruments for medical and biological study. It makes it possible to use extremely sensitive quantum biosensing to find certain chemicals and biomarkers with previously unattainable accuracy. What's more, quantum imaging allows cellular structures and processes to be observed at a resolution beyond the limits of classical microscopy. This enhanced detail could lead to more accurate diagnoses and improved therapeutic outcomes. To deepen our understanding of biological processes, quantum technologies are also being used to enhance imaging and to study fundamental quantum effects in living systems, such as photosynthesis.

Many companies are actively developing technologies based on quantum photonics, aiming to harness its potential for applications ranging from secure communication to advanced computing and imaging. While established industry leaders like IBM have adopted photonics-based quantum technologies, new spinout companies have emerged offering different services and devices. Some examples include Quandela, Nu Quantum, Xanadu and Qubit Pharmaceuticals.

Challenges and Future of Quantum Photonics

Despite its immense promise, the field of quantum photonics faces several significant challenges. One of the primary hurdles is the efficient and reliable generation of high-quality single photons and entangled pairs. The sources often produce photons at random times, which is a major limitation for building scalable quantum circuits. Additionally, maintaining the fragile quantum states of photons is difficult, as they are susceptible to noise and loss, particularly over long distances. Miniaturizing and integrating these complex optical components onto a single chip is another ongoing challenge that needs to be solved to move from a laboratory setting to a commercial product. As these challenges are addressed, quantum photonics is set to power the next wave of advancements in computing, communications, and sensing, reshaping the technological landscape in profound and lasting ways.

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Introduction to Plasmonics: Harnessing Light at the Nanoscale

Plasmonics is the study of how light interacts with free electrons in metals, creating special waves known as plasmons. Once a curiosity of physics, it has rapidly become a frontier field, capturing global attention for its extraordinary ability to manipulate light at the nanoscale and its promise in revolutionizing technologies from medical diagnostics to renewable energy.[1]

Image Credit: Iryna Palmina/Shutterstock.com

What Is Plasmonics?

In plain terms, plasmonics studies how metals like gold or silver can trap and guide light by coupling it to electron waves on their surfaces. This property makes it possible to bend, concentrate, and even store light at scales thousands of times thinner than a human hair.[2]

Today, plasmonics is increasingly central to optical technologies ranging from sensors and solar cells to ultra-precise microscopes. With its capacity to shrink photonics into the nanoscale regime, plasmonics stands as an interdisciplinary field bridging physics, materials science, and engineering, with rapidly growing industrial and biomedical relevance.[2]

How Do Plasmons Work in Optics?

Plasmons come in two main varieties: Surface plasmon resonance (SPR) and localized surface plasmon resonances (LSPRs).

- **SPR** occurs when incident light excites collective oscillations of electrons along a flat metal–dielectric interface, such as a thin gold or silver film on glass. At resonance, the light energy couples into a surface-bound wave, called a surface plasmon polariton (SPP), which travels along the surface like ripples gliding across water. These waves are extremely sensitive to changes in the surrounding refractive index, making them powerful for sensing applications. Even tiny molecular interactions on the surface can shift the resonance, allowing precise detection.[3]

- **LSPR**, on the other hand, happens in metallic nanoparticles, such as gold or silver spheres and rods. Here, the electrons oscillate locally in response to light, confining electromagnetic energy into nanoscopic "hot spots." Unlike propagating SPPs, these resonances are spatially confined, enhancing fields in volumes far smaller than the wavelength of light.[3]

The materials of choice are typically gold and silver, valued for their stability and strong plasmonic response in the visible and near infrared ranges. These metals enable confinement of light well beyond the diffraction limit, which in conventional optics is the boundary that prevents focusing below roughly half a wavelength. By overcoming this limit, plasmonics makes it possible to trap, guide, and manipulate light in spaces only a few nanometers wide.[1, 3]

A helpful analogy is to imagine tossing a stone into a pond. The ripples spread across the surface, just as plasmons propagate along a metal film. Now imagine those ripples confined inside a droplet instead of a pond. That is the essence of LSPR, where the waves are trapped and intensified in a tiny nanoparticle. This ability to compress light into the nanoscale is what makes plasmonics so powerful for optics, sensing, imaging, and medicine.[2]

Optical Applications of Plasmonics

Sensing Technologies

Plasmonic sensing leverages LSPR for detecting minuscule changes in the local refractive index. When molecules bind to a plasmonic nanoparticle, they alter the resonance condition, shifting the wavelength of light absorbed or scattered. This shift provides a highly sensitive and label-free detection method.[1]

Such sensors already underpin biosensing and environmental monitoring. For example, SPR-based biosensors have been applied in diagnostics for viruses, including rapid COVID-19 detection systems, offering real-time, non-invasive monitoring. Beyond healthcare, LSPR platforms are advancing food safety, water quality testing, and chemical hazard detection.[4]

Plasmonic Photovoltaics and Light Harvesting

Solar energy conversion is another arena transformed by plasmonics. Plasmonic enhancement occurs in multiple ways. First, far-field scattering by metallic nanoparticles increases the trapping of sunlight within the absorbing layer. This boosts the optical path length and allows thinner films to achieve full absorption. Second, near-field effects enable nanostructures to act as nanoantennas, intensifying the local electromagnetic fields and effectively increasing the absorption cross section of the photovoltaic material. Third, plasmonic hot charge carrier injection contributes additional energetic electrons and holes, improving photocurrent generation. Finally, plasmon-enhanced resonance energy transfer (PRET) extends light harvesting across a broader range of the solar spectrum, capturing more of the sun's energy for conversion.[5]

While silicon remains the most widely used photovoltaic material, its indirect band gap requires thick wafers to absorb sufficient light, which increases costs and leads to losses from carrier recombination. Incorporating plasmonic nanostructures addresses this limitation by boosting absorption in thinner films and reducing recombination.[5]

For example, A study by Zhang et al. have shown that plasmonically enhanced thin silicon solar cells, only 20 µm thick, can achieve efficiencies of 18.2%, comparable to conventional 180 µm cells, but with only a tenth of the material requirement.[6]

Imaging and Microscopy

Traditional optical microscopes are limited by the diffraction barrier, but plasmonics overcomes this through near field techniques such as scanning near field optical microscopy (SNOM) and stimulated emission depletion microscopy (STED). Metallic nanostructures, like gold-coated tips, act as nanoantennas that concentrate light into nanoscale hot spots, enabling imaging with far greater precision than conventional optics. This has allowed researchers to visualize viruses, protein fibrils, and even single molecules with nanometer resolution, transforming microscopy into a tool capable of probing biological and material processes at the molecular scale.[7]

Commercialization and Industry Impact

Plasmonics is no longer confined to laboratories as it has entered the commercial domain. Companies such as HORIBA Scientific and Thermo Fisher Scientific offer SPR spectrometers and plasmonic optical devices that are widely used in research and diagnostics. Plasmonic nanoantennas are also being integrated into optical communication systems to enable faster data transfer.[8]

In medicine, plasmonic biosensors are finding applications in point-of-care diagnostics, while in consumer technology, plasmonic coatings are explored for improving display brightness and energy efficiency. Environmental monitoring devices equipped with plasmonic chips can now detect pollutants at parts-per-billion concentrations. The growing industrial adoption of plasmonics demonstrates its transition from a purely academic field into a driver of next-generation healthcare, electronics, and green technologies.[8]

Challenges and Limitations

Despite its enormous potential, plasmonics faces several significant challenges. One of the major hurdles is material loss, since metals such as gold and silver experience high ohmic losses that shorten the propagation length of plasmons and reduce device efficiency. Another challenge lies in fabrication, as creating nanoscale structures demands extremely precise lithography or chemical synthesis methods, which are both costly and time-consuming.[9]

Scalability and cost also remain pressing concerns, as moving from laboratory research to industrial deployment requires more affordable materials. To address this, researchers are exploring alternatives such as aluminum, which is abundant and inexpensive, as well as graphene and transition metal nitrides.[9]

These efforts highlight the crucial role of materials science in advancing the field, with the ongoing goal of achieving low-loss, scalable plasmonic platforms for real-world applications.

Future Developments in Plasmonics for Optics

The future of plasmonics lies in pushing boundaries even further, with several exciting directions already taking shape. At the intersection of quantum mechanics and nanophotonics, quantum plasmonics explores how single plasmons can carry quantum information, opening possibilities for advanced communication and computing systems.[5]

Plasmonic metasurfaces, built from engineered nanoscale arrays, offer the ability to sculpt wavefronts of light, enabling ultrathin devices such as flat lenses and holographic displays. On-chip integration is another promising avenue, where combining plasmonics with CMOS-compatible materials could yield ultrafast and compact circuits for all-optical data processing.[1, 5]

Meanwhile, artificial intelligence is being harnessed to optimize the design of nanostructures for tailored plasmonic responses, and research into hot-carrier dynamics suggests the potential for femtosecond optical switches critical to next-generation communication technologies.[1]

Looking ahead to the next five to ten years, breakthroughs in plasmon-enhanced solar cells, portable diagnostic devices, and optical computing components appear highly plausible. With continued interdisciplinary research, plasmonics is poised to play a transformative role in the future of optics and beyond.

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A Full Overview of Active Photonics Alignment

Global data demand continues to grow at an exponential rate, driven by emerging applications in cloud computing, artificial intelligence, autonomous systems, and high-bandwidth communications. Even during the 2020 COVID-19 pandemic, global network traffic rose by more than 20 %, underscoring the critical importance of scalable, energy-efficient data transmission and routing infrastructure.

The photonics chip industry continues to expand rapidly, with its technologies now integrated into a broad spectrum of mainstream applications. These include advanced light detection and ranging (LiDAR) systems, compact sensor modules in wearables and automotive vision systems, and emerging fields such as quantum information processing, high-speed optical interconnects, and photonic computing, where photons replace electrons as information carriers for logic operations.

At the core of this technological transformation lies silicon photonics (SiPh) - a platform that monolithically integrates optical and electronic functionality on a single silicon substrate. This integration provides substantial benefits in bandwidth density, energy efficiency, and form factor reduction.

Given the rapid diversification of SiPh applications and the accelerating adoption in consumer and data-communications markets, production volumes are projected to increase by several orders of magnitude - potentially up to a thousand-fold - in the coming years. Achieving this scalability will require equally transformative advances in automated optical alignment and packaging technologies, which are the focus of this discussion.

The Difference Between Optical and Electronic Alignment

Compared to electronic ones, optical circuits require more time-consuming verification and characterization steps at multiple stages - from wafer-level testing through subsequent packaging and assembly processes. Each stage demands positional accuracies that are typically two to three orders of magnitude tighter than those required for conventional electronic probing and often involve additional mechanical degrees of freedom (DOF).

In electronic testing, probe needles can readily contact electrical test pads, with feature sizes on the order of tens of micrometers. In contrast, silicon photonics (SiPh) test structures and coupling interfaces present optical features with alignment tolerances in the 20–50 nm range. Achieving and maintaining this level of precision necessitates advanced motion systems at the nanometer level and closed-loop control architectures far beyond those used in traditional semiconductor probing.

Such precision cannot be realized through passive visual feedback - microscope- or camera-based alignment methods, which lack the necessary spatial resolution and dynamic feedback speed. Consequently, optical alignment must be active, relying on real-time optimization of coupled optical power to determine true alignment. This approach ensures maximum transmission efficiency despite mechanical, thermal, or process-induced variations.

The Challenge of Upscaling SiPh Production

Fabricating photonic integrated circuits requires challenging nanopositioning tasks, and vision- or fixturing-based techniques are insufficient, especially given device variances.

The requirement for repetitive alignment throughout all manufacturing stages, from initial probing and grading on the wafer to final assembly and packaging, which includes multiple steps of placing and bonding functional elements interspersed with additional testing, has long been regarded as a barrier to scaling up production, accounting for up to 80% of total costs.

The historically high expense of active alignment methods has been a primary motivator for the multi-decade hunt for passive alignment technology. Precision active alignment is now available, eliminating numerous associated expenses and allowing for a cascade of savings throughout the manufacturing workflow.

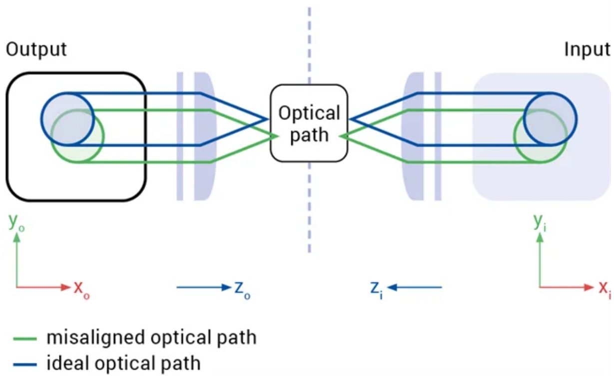


Figure 1. *Testing and packaging today's photonic devices can be challenging across multiple DOF. The alignment of multi-channel devices, such as fiber-optical arrays, used to be a slow, repetitive process before modern parallel algorithms were developed. Image Credit: PI (Physik Instrumente) LP*

Passive or Active Alignment?

An active or passive technique can accomplish precision alignment in non-photonics manufacturing. A dovetail joins two boards at right angles, aligning the edges.

Passive positioning, however, is often ineffective for applications needing higher accuracy, such as aligning optical fibers to chips or other components, because the tolerances are too tight, making manufacturing processes unstable.

When the design becomes more sophisticated, the machine tools and procedures needed to meet the requisite tolerances become more expensive, and the number of rejects increases, resulting in additional expenditures.

Some device tolerances, such as fiber-core centration, cannot be addressed with improved fabrication techniques, and machining the world's finest V-groove is of little use when device-to-device variability exceeds the required alignment tolerances.

Ingenious passive alignment solutions have arisen that show great promise for specialized applications, such as the Photonic-Plug (Teramount), although active alignment will remain necessary.

In comparison, active alignment enhances performance by using robots to autonomously align devices, and given the cost savings, flexibility, and speed indicated below, it will continue to be the favored choice for photonic device manufacturing in the future.

Active alignment works by maximizing coupling performance, and the latest breakthrough detailed in this research does so cost-effectively across multiple channels in different DOF, which is necessary because SiPh can print several circuits with multiple inputs and outputs on a single chip.

Active Alignment: What is Necessary?

Active alignment necessitates advanced control electronics and high-precision mechanics. During manufacturing, the photonic device's components are autonomously controlled to maintain their mutual position.

Traditionally, this was a time-consuming operation since optimizing several channels, inputs, and outputs in multiple DOF needed numerous iterations to achieve the desired result. Using old methodologies, this time will only increase as devices become smaller and more complex, raising the cost even higher.

For example, alignment in a multi-lens assembly is significantly more difficult than for a single element, as is a SiPh chip with several channels instead of the single fibers used in the late 1990s.

Fortunately, revolutionary control algorithms can now simultaneously complete all of the necessary sub-alignments across various DOF, channels, and operating systems, completing the entire operation in a single rapid step. This eliminates repetitive looping and often lowers alignment time by 99%.

Precision Positioning of Signal-Carrying Elements

The primary problem in active alignment is precisely arranging signal-carrying devices, such as single fiber or fiber arrays, lenses, interposers, or other chips, in relation to coupling points like grating couplers or edge facets.

These couplings can occur within or outside passive and active photonic structures such as waveguides, vertical cavity surface-emitting lasers, and photodiodes. When linking photonic components, alignment accuracy of tens of nanometers is typically required to achieve the maximum optical power transmission and lowest attenuation.

Precision Automation: Finding the Main Peak

In almost all photonic component alignments, the signal, such as linked optical power, reaches a global peak when optimally aligned and declines when out of place.

This is a global pattern, and spurious lower or local peaks are frequently observed, which should not be chosen for optimization. However, finding that global peak has typically been time-consuming, especially when it involves many DOF.

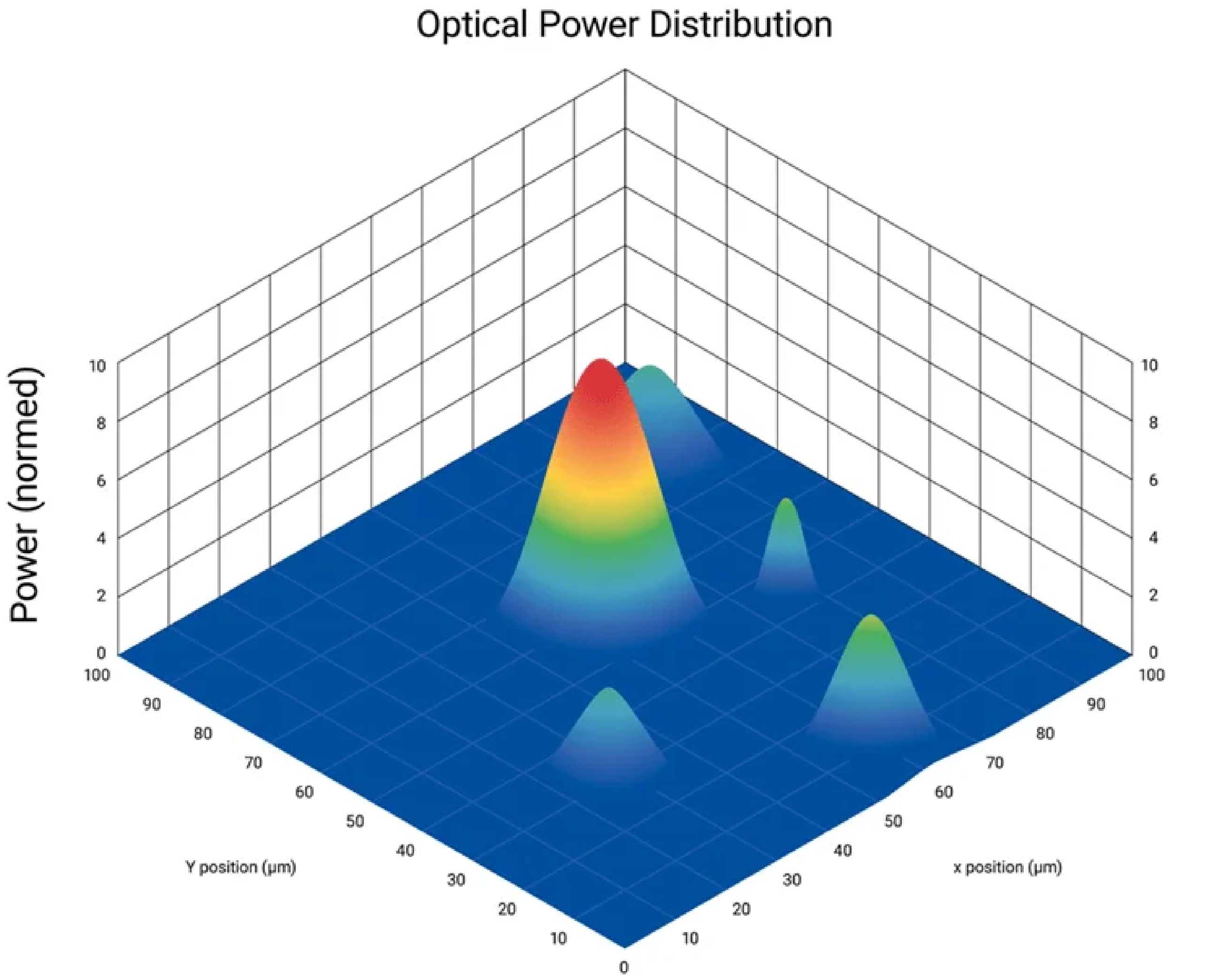


Figure 2. *Power distribution of an optical component shows multiple peaks. Modern algorithms and precision mechanics can help determine the main mode and find the exact peak quickly. Image Credit: PI (Physik Instrumente) LP*

Advanced Algorithms and Fast Mechanics

A revolutionary combination of advanced algorithms and quick mechanisms, such as PI's award-winning Fast Multichannel Photonics Alignment solutions (FMPA), has significantly increased throughput.

FMPA optimises coupling between photonic elements across channels, inputs and outputs, and DOF, even when these independent variables influence each other, using novel functionalities such as rapid first light detection, a vibrationless areal scan, and an innovative parallel gradient search capable of real-time, multivariate tracking optimization.

Previous approaches required coupling to be tuned sequentially, looping back and forth, and readjusting at each axis to gradually establish a consensus.

This took a long time, sometimes several minutes, and had a substantial influence on costs, efficiency, and scalability. In comparison, FMPA can make all of these changes in a single step using a simple set of commands that take only seconds to execute.

Because the alignments are executed concurrently, the optimization time is substantially independent of the number of alignments. This considerable reduction in alignment time, generally two orders of magnitude, dramatically lowers costs, making operations like probing SiPh wafers commercially viable.

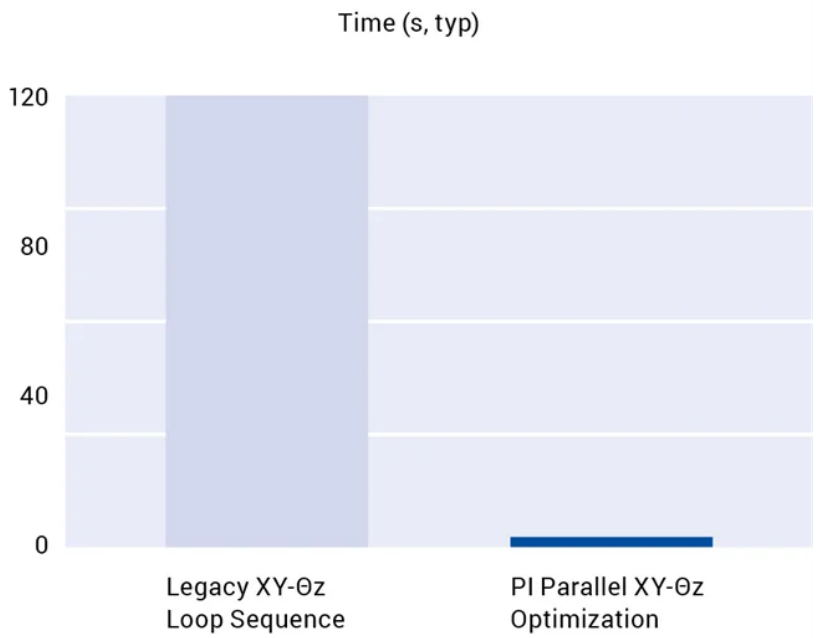


Figure 3. *Alignment speed is crucial in reducing production costs. Image Credit: PI (Physik Instrumente) LP*

Active Alignment: Different Processes

There are two types of alignment methods for photonic components: area scans and gradient searches.

Areal scans identify the peak of a measured figure of merit, such as optical power, modulation transfer function (MTF), or modal purity, within a specific region. They can be used to precisely characterize a component's optical fingerprint and differentiate global and local maxima.

Gradient searches allow for quick final optimization and tracking, and FMPA's unique implementation may optimize and track one or more couplings in several DOF at the same time, reducing drift processes, disturbances, and so on. These steps are covered in greater depth below.

Area Scans

Areal scans, which scan an area to discover the approximate location of the highest coupling peak, are used for a variety of purposes, including:

- Detecting the earliest light
- Profiling a coupling for effective process control
- Localizing a coupling's principal mode for optimization using gradient search. This sequence creates a powerful hybrid strategy that helps prevent locking upon a local maximum.

FMPA's area scans include unique single-frequency sinusoid and spiral scans. These are substantially faster than raster or serpentine scans because they are continuous and do not require the stop-and-start actions that traditional scans do.

In addition, the frequency is adjustable to avoid generating structural resonances. It is also possible to pick a constant velocity spiral scan, which allows data to be acquired with a constant density throughout the spiral.

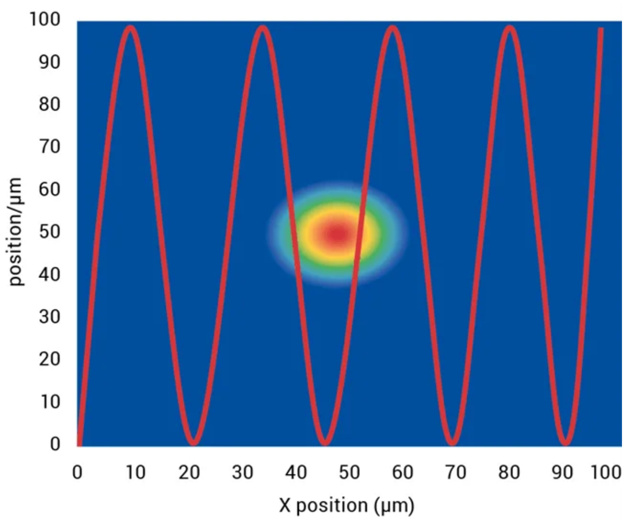


Figure 4a. *Sinusoidal areal scan for detecting first light. Image Credit: PI (Physik Instrumente) LP*

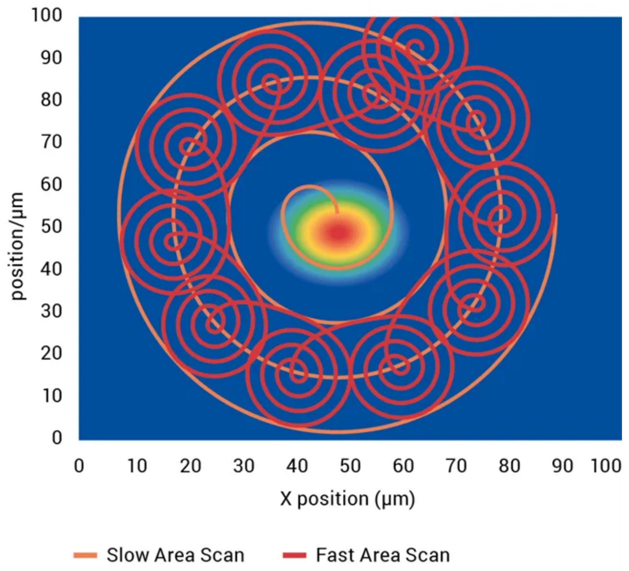


Figure 4b. *Spiral scan using a hexapod/piezo approach. A fine and coarse scan can be executed simultaneously. Image Credit: PI (Physik Instrumente) LP*

Gradient Searches

Gradient searches use a modest, roughly circular dither motion between devices to vary the coupling. This variation in the figure of merit enables the local gradient of the coupling to be determined in real time. The controller automatically detects modulation and directs the alignment to minimize it until it reaches zero, signaling complete optimization.

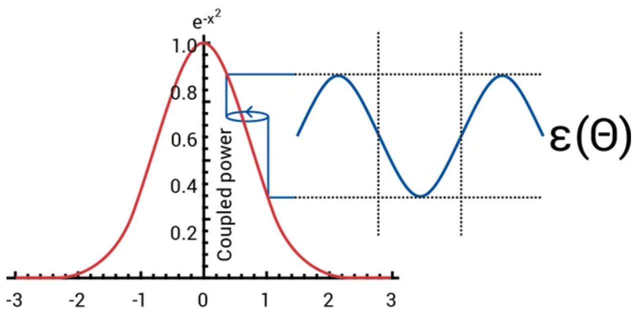


Figure 5. *Graphical depiction of gradient determination via a circular dither, which modulates the observed coupled power (or other parameters). The modulation phase with respect to the dither indicates the direction towards maximum while its amplitude falls to zero when optimized. Image Credit: PI (Physik Instrumente) LP*

$$|\varepsilon(\Theta)| = \nabla I = (I_{min} - I_{max})/I_{min}$$

Figure 6. *The observed gradient can be expressed by the above equation and serves as a measure of alignment error. Image Credit: PI (Physik Instrumente) LP*

The controller can automatically calculate the local gradient based on the observed modulation (Figure 6).

The gradient (∇I) decreases to zero when optimized. Any axes in an FMPA system can execute various types of alignments, depending on their physical capabilities. Gradient searches are fast and precise methods for transverse optimization, but they can also be used for other purposes, such as:

- In a single linear axis, which is ideal for localizing the beam waist in a lens coupling
- In a gimbaling or swivelling fashion to optimize an angular orientation
- In a rotation about one channel axis of a multichannel device, to bring all elements of the device's arrayed input/output (I/O) channels into correspondence

These techniques are suited for a wide range of optimizations, including bulk optic, cavity, and pinhole alignments.

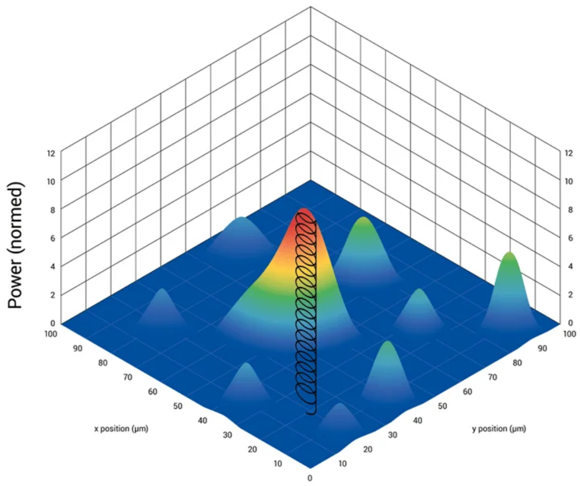


Figure 7. *A graphical depiction of a digital gradient search (hill-climb algorithm). Once the main mode has been identified through an area scan, the algorithm will reach the peak quickly. The main peak is automatically fine-tuned in all DOF the application requires. All of this is achieved in parallel with one command by the user. With today's photonic devices, it cannot be assumed that the peak is symmetrical, follows a Gaussian distribution, or has a circular cross-section. Furthermore, both edge and diffractive-coupler scenarios must be met. Image Credit: PI (Physik Instrumente) LP*

Compensating for Position Changes

Photonic devices in packaging must be permanently bonded and attached to fibers to transfer signals, which is commonly accomplished with a UV-curing epoxy glue. However, polymerization happens during the curing process, which increases stress and causes component displacement.

As a result, a tracking mode within the FMPA algorithm is useful for correcting for positional changes in the optical elements in real time, during the early phases of polymerization, making the necessary corrections, and fine-tuning the alignment to maintain optimal orientation.

Solving the First Light Problem

Before the optimization steps can begin, an optical signal above the noise level must be detectable.

This procedure is known as first light detection. Finding first light has been time-consuming in all industrial photonics alignment applications, including wafer probing and device packing. It is especially difficult in devices with inputs and outputs since both sides must be aligned to provide even a minimal level of coupling.

Traditional First Light Search Algorithms

At the micron to submicron scale, cyclic patterns such as Archimedean spirals or sinusoidal raster scans are commonly used to detect signals (see Figures 4a and 4b).

In the case of considerable device-to-device variances or indeterminate fixturing, these repetitive, narrowly spaced scans might take a long time to complete, depending on parameters such as the area to be scanned, whether inputs and outputs must be aligned at the same time, and so on.

New First Light Capture Process

A unique, embedded search and alignment algorithm (patent pending) has been developed, potentially revolutionizing the area. The algorithm, known as PILightning, is integrated in PI's advanced controllers.

It enables highly dynamic mechanics, such as piezo scanners or direct-drive air bearing stages, to realize significant cost benefits over earlier first light search algorithms. This new procedure is completely automated and almost instantaneous, eliminating the need for extensive calibration or operator involvement.

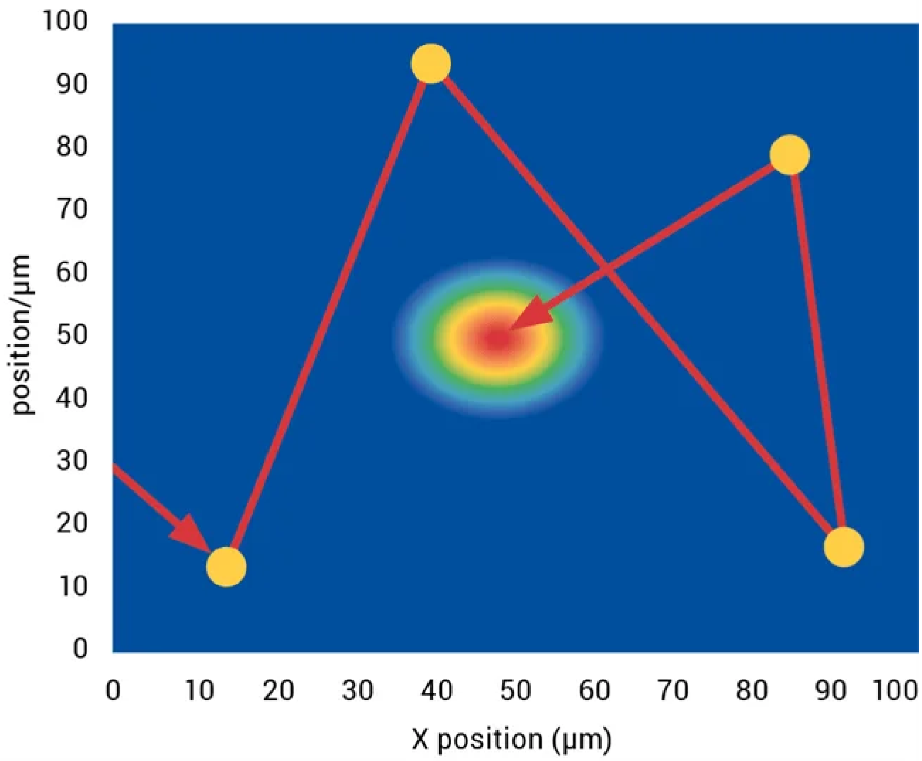


Figure 8. *First light detection with PILightning. Learn more here. Image Credit: PI (Physik Instrumente) LP*

PILightning is based on a novel search strategy that incorporates an AI-powered real-time executive function (Figure 8). It significantly decreases the time required to locate first light in single and double-sided couplings, as well as loopback (omega) waveguide arrangements.

Once the first light is detected, the FMPA (Fast Multi-Channel Photonics Alignment) fast gradient search method is activated, which uses real-time feedback control to rapidly optimize the alignment across degrees of freedom and channels.

Depending on the application, a tracking algorithm can be enabled to preserve optimal coupling efficiency, which is critical in curing circumstances.

Orders of Magnitude Improvement

PILightning has been shown in tests to minimize first light capture by an order of magnitude or more in single-sided alignment applications.

Double-sided applications yield gains that exceed two orders of magnitude. The broader the search area and (as with the FMPA parallel optimization functionality) the more complicated the alignment, the greater the benefit.

Figure 9. The F-141, dual-sided, PILightning-enabled fiber alignment system - dubbed PINovAlign - is designed to provide highest performance with the most compact footprint. It is available in 3-, 4-, and 6-axis configurations and provides exceptional throughput advantages in in fiber-array applications. Image Credit: PI (Physik Instrumente) LP

Mechanisms for Different Requirements

While the techniques outlined above apply to all types of mechanical alignment devices, differing requirements for alignment mechanisms, such as size, travel range, DOF, and so on, necessitate distinct configurations and technologies.

Optical Power Meters: Bandwidth and Dynamic Range Rule

A very sensitive power meter with a broad dynamic range and high bandwidth is also required to ensure the correct alignment of SiPh components. To fully utilize the FMPA algorithms, a signal bandwidth of 20 kHz and a dynamic range of six orders of magnitude with logarithmic output are typically used.

Figure 10. *High-speed optical alignments require optical power meters with high bandwidths. Image Credit: PI (Physik Instrumente) LP*

Gantry Platforms for Large Format Applications

Processing densely packed nanoscale structures over wide areas for a variety of applications, including semiconductor and SiPh testing and manufacture on circuit boards, trays, carriers, and other large substrates, necessitates high-accuracy, high-throughput solutions offered on dependable platforms.

Novel gantry systems are ideal for these applications since they greatly boost throughput while also delivering repeatable and resilient outcomes in a compact form factor.

Some current gantry systems, such as those offered by PI, employ power-dense ironless linear motors to handle the high dynamics necessary in photonics applications.

These efficient direct drive motors can include two high-resolution linear encoders on each gantry axis, with nanoscale or sub-nanometer resolutions, allowing for repeatable positioning even during the most demanding duty cycles.

Mechanical or air bearings are available, with the latter offering numerous benefits, including cleaner operation with no chance of contamination that could harm the delicate optical circuits. Controllers with and without built-in FMPA capabilities are available.

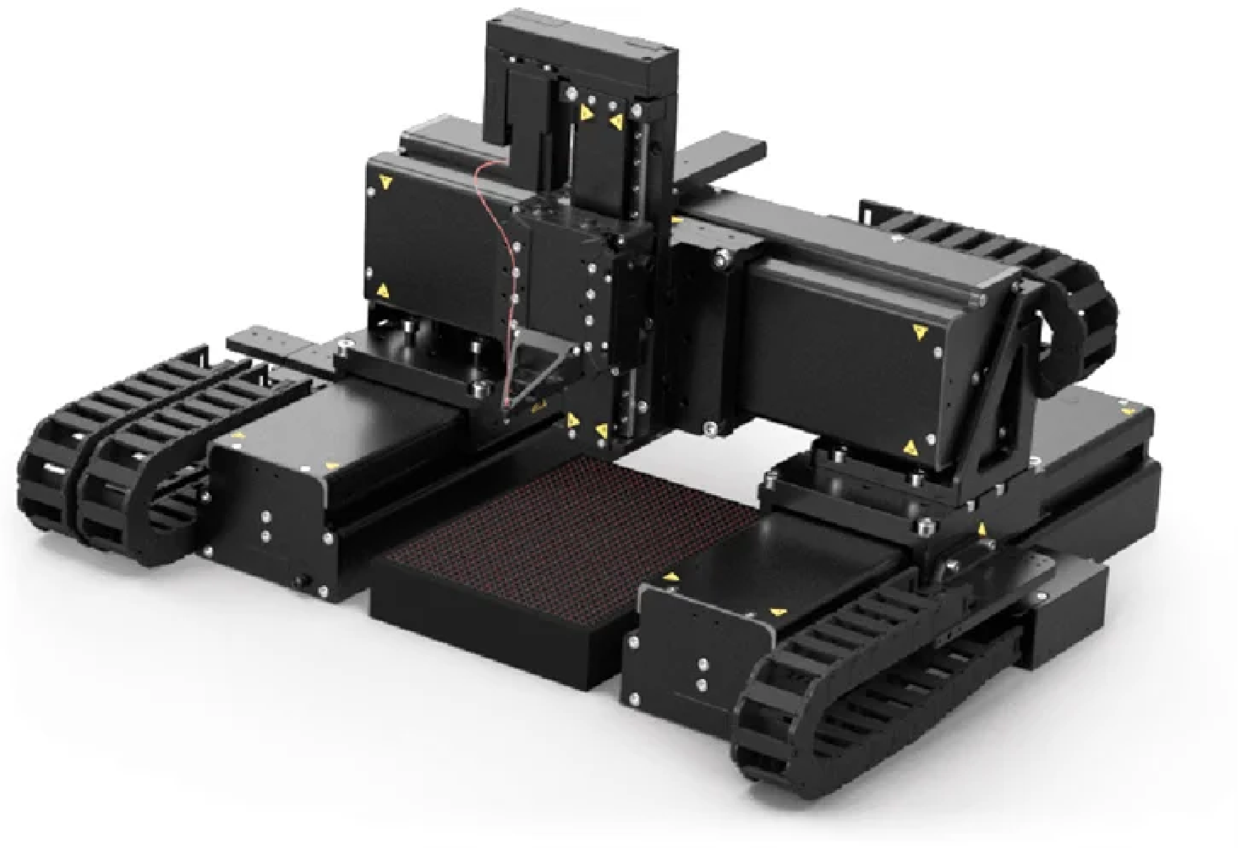


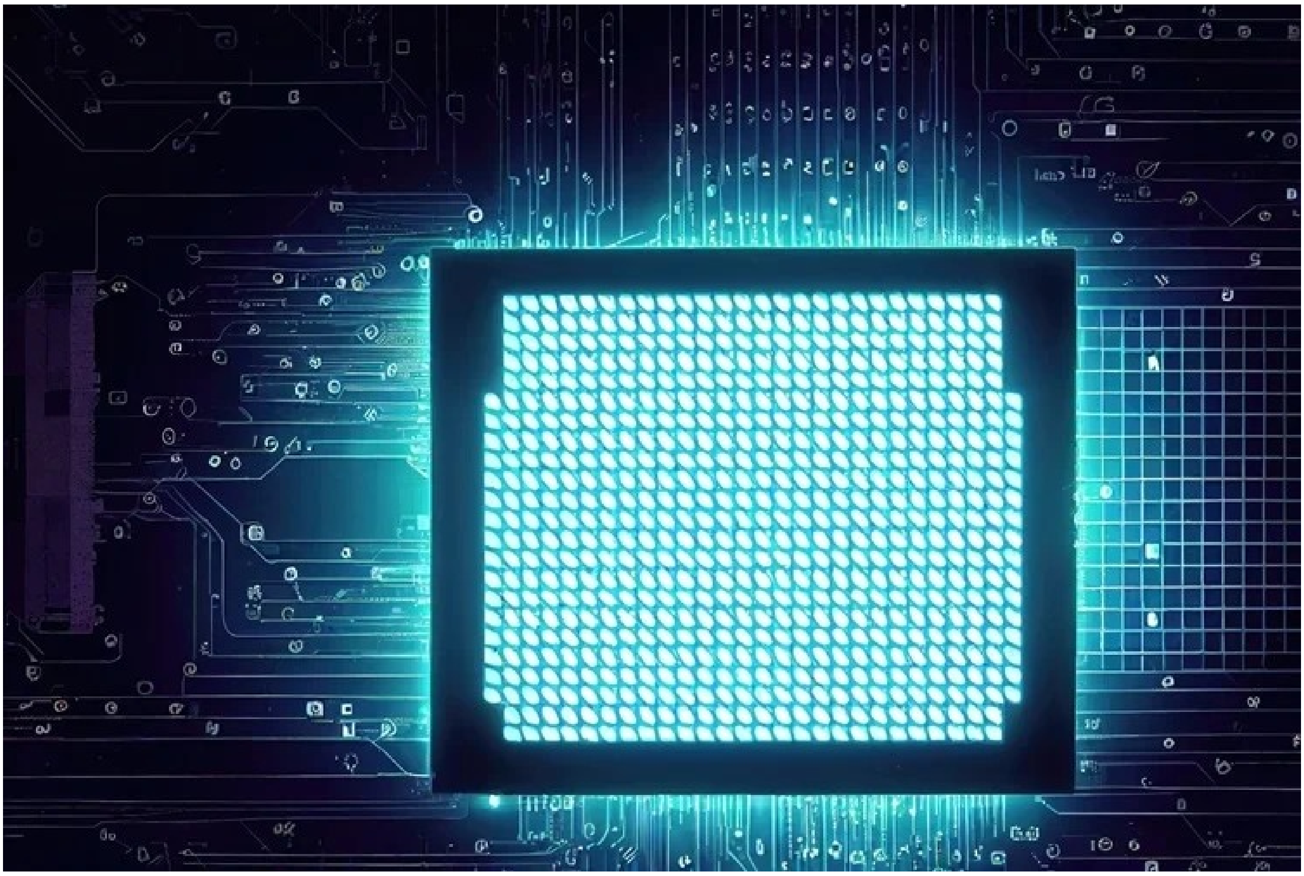
Figure 11. *Mini Gantry. Image Credit: PI (Physik Instrumente) LP*

This information has been sourced, reviewed and adapted from materials provided by PI (Physik Instrumente) LP.

For more information on this source, please visit PI (Physik Instrumente) LP.

Are Photonic Chips Better than Silicon Chips?

For decades, silicon chips have powered modern electronics, from computers and smartphones to industrial computing and artificial intelligence. As computing demands continue to grow, however, the limitations of silicon-based chips are becoming more apparent.



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Processing speeds, power efficiency, and scalability are all reaching physical and technological limits. Researchers are now exploring photonic chips, which use light instead of electrical signals to process information.

The key question is whether photonic chips can replace silicon chips, or if they will serve as a complementary technology in future computing systems.

How Photonic Chips Work

Traditional silicon chips rely on electrical signals to transfer data. Electrons move through circuits, enabling information processing and storage. In contrast, photonic chips use photons

—particles of light—to transmit data, significantly increasing speed and efficiency.

A photonic integrated circuit (PIC) consists of optical components such as waveguides, modulators, and photodetectors, which control and direct light instead of electrical currents. This approach allows for faster data transfer and reduces energy losses caused by electrical resistance and heat generation.

Photonic chips are already used in high-speed optical communication, AI processing, and quantum computing, where fast data transmission is essential.[1] They are also becoming important in biosensing and medical technology, improving real-time monitoring, medical imaging, and diagnostics.[2]

How Photonic Chips Compare to Silicon Chips

Speed

Photonic chips process information at the speed of light, making them 10 to 100 times faster than conventional silicon chips. Electrons move significantly slower than photons, which limits the speed of traditional microprocessors.

One example of this advantage is the lithium niobate (LN) photonic chip, developed by Feng *et al.*, which demonstrated high-speed processing and low power consumption. The chip was fabricated on a 4-inch LN wafer and achieved processing speeds of 256 G samples per second (GSa/s).

Researchers integrated a high-speed modulation component, enabling the chip to perform first- and second-order temporal integration and differentiation computations with 98 % accuracy at bandwidths exceeding 67 GHz.

This high fidelity and computational efficiency were tested in image segmentation applications, where the chip was used to outline cancer cell boundaries. It processed images 50 to 100 times faster than conventional microprocessors, all while consuming less power.[3]

Energy Efficiency

Silicon chips generate heat during operation, requiring cooling systems that consume additional power. In high-performance computing, data centers, and AI processing, managing heat output is a growing challenge.

Photonic chips reduce energy consumption because they do not rely on electrical resistance. They also include thermal heaters, which optimize their performance while using only a few milliwatts of power.[4]

Researchers from Oregon State University, in collaboration with Intel and NASA, have developed on-chip wavelength division multiplexing (WDM) to regulate temperature in photonic chips. Their prototype consisted of four tunable silicon micro-ring resonators (Si-MRRs), which allowed for continuous tuning using gate voltage.

This approach enabled precise temperature regulation without consuming additional power, leading to considerable power savings, and keeping the temperature of photonic chips within safe limits.[5]

Scalability and Future Growth

Silicon-based microprocessors are approaching their physical limits in terms of size and performance improvements. Advances in nanotechnology and additive manufacturing have helped extend their usefulness, but breakthroughs in silicon chips are becoming harder to achieve.

Photonic chips, however, have room for further development and miniaturization. Researchers are integrating quantum photonic components and improving fabrication techniques to increase their capabilities.

3D printing and lithography techniques allow for the mass production of compact photonic chips, avoiding the costly and time-consuming process of manufacturing individual components, which is required for traditional silicon chips.

Quantum photonic chips, in particular, offer new possibilities for secure communication and high-speed computing, with researchers actively working on improving their stability and efficiency.[6]

Compatibility with Existing Technology

Silicon chips are used in nearly all modern electronics and can be easily integrated into new systems. Photonic chips, however, require specialized infrastructure, including light modulators, waveguides, and optical stabilization equipment.

These additional components add complexity and cost to system integration, making it difficult to transition entirely from silicon to photonic-based computing.

Are Photonic Chips the Future? The Rise of Silicon Photonics

Despite the advantages of photonic chips, they are unlikely to replace silicon chips entirely in the near future.

Fabricating photonic chips is highly complex and expensive, requiring precise materials and manufacturing techniques. Many experts question whether companies will transition to a completely photonic-based infrastructure, given that silicon chips remain cheaper and easier to produce.[7]

To address these challenges, researchers have developed silicon photonics, a hybrid approach that integrates photonic components into traditional silicon chips. This combines the manufacturing advantages of silicon with the speed and efficiency of photonics.

Advances in optical communication and AI computing have made silicon photonics the preferred solution for improving computational performance without entirely replacing existing semiconductor technology.[8]

Silicon photonics has enabled large-scale integration, with researchers successfully incorporating over 10,000 components onto a single chip. Existing CMOS (complementary metal-oxide-semiconductor) manufacturing processes can be used to mass-produce these hybrid chips, avoiding the need for entirely new production techniques.

While photonic chips continue to improve, silicon photonics remains the more practical and economically viable solution. The development of new materials, such as graphene and other 2D substances, has enhanced photonic chip efficiency, but widespread adoption is still a long way off.

For photonic chips to become mainstream, further advancements in fabrication, cost reduction, and system integration are needed. Until then, silicon remains the foundation of modern computing, with photonics enhancing rather than replacing it.

To learn more about the latest advancements in semiconductor and photonic chip technology:

- Controlling Light Color and Frequency for Advanced Technologies
- Light-Based Lithography in Microchip Miniaturization
- New Path to Uniform Perovskite Nanocrystals for Advanced Devices
- Semiconductor Manufacturing By Country: The Industry's Biggest Players
- What to Know About Optically Active Semiconductor Quantum Dots
- Miniaturized Photonic TWPA for High-Capacity Data Transmission

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Exploring the Use of Photonics in Neuromorphic Computing

The human brain processes information through synapses and neurons. It performs complex tasks with high efficiency while using minimal energy. Neuromorphic computing mimics this biological system, using artificial neurons and synapses to enhance computational speed and reduce power consumption.

As computing demands grow, photonics is becoming an essential component in neuromorphic architectures. But how is light being integrated into these systems, and what advantages does it offer over traditional electronics?

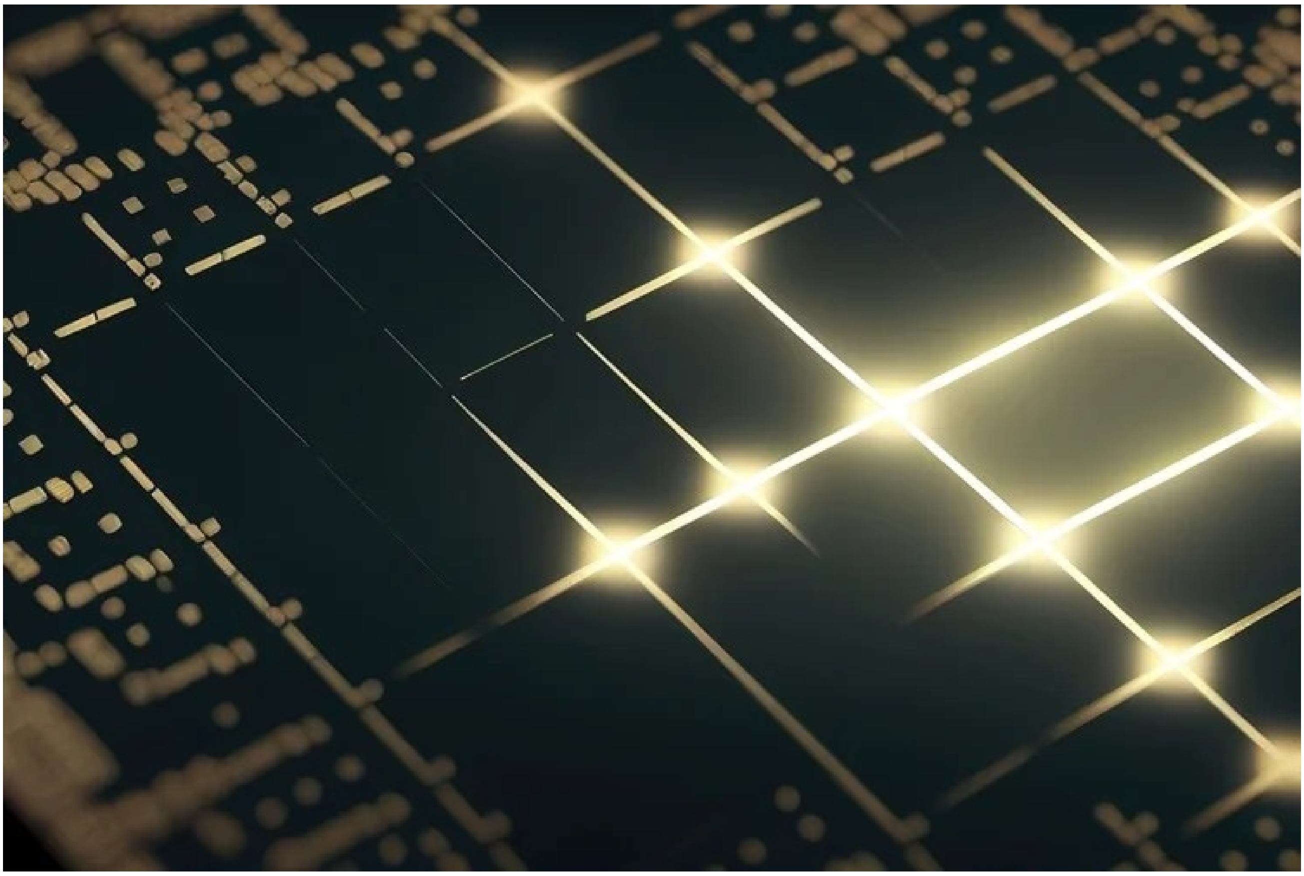

Image Credit: Alexander_Evgenyevich/Shutterstock.com

What is a Photonic Neuromorphic Computing System?

A photonic neuromorphic computing system is a computational framework that uses light to process information, rather than electricity.

Photonic systems manipulate light through waveguides, modulators, and integrated circuits, enabling parallel processing and ultra-fast signal transmission. Photonic systems are faster and more energy-efficient than traditional electronic computers, as they don't suffer from electrical resistance and heat generation.

These benefits make photonic neuromorphic computing a promising solution for artificial intelligence (AI), deep learning, and real-time data processing.

How Do Photonic Neuromorphic Computing Systems Work?

Neuromorphic computing systems rely on Photonic Integrated Circuits (PICs). These circuits consist of optical neurons, modulators, memories, and photodetectors, all compactly integrated onto a single chip. Unlike electronic circuits, PICs use photons instead of electrons, allowing for higher-speed computation with minimal energy loss.

Light propagates through these circuits at nearly the speed of light, transmitting and processing information with sub-nanosecond latency. A key advantage of PICs is their ability to operate in parallel, meaning multiple signals can travel independently through different wavelengths and polarizations without interference.

Recent research has demonstrated that photonic neuromorphic processors can achieve 16 peta operations per second (POPS/s) while consuming less than 2 watts of power. This performance far surpasses traditional computing hardware.

Applications of Photonic Neuromorphic Computing

Optical Communication

Photonic neuromorphic computing is playing an increasing role in optical communication systems. Beyond signal transmission and channel equalization, these systems enhance optical header recognition and data recovery, enabling faster and more efficient processing of high-bandwidth optical signals.

AI Systems and Deep Learning

The increasing complexity of AI and deep learning requires hardware capable of processing large datasets efficiently. Neuromorphic computing is helping accelerate AI workloads. These systems achieve high computational rates per neuron synapse and optimize NxN weight matrix deployments, making them well-suited for deep learning applications.

In 2023, researchers from Greece and California-based startup Celestial AI developed a neuromorphic silicon photonics chip designed to enhance AI frameworks. Their approach introduced a hybrid architecture that combined a linear optical framework with SiGe electro-absorption modulator (EAM) technology to improve performance.

This photonic Xbar architecture reduced power losses and improved matrix-vector multiplication accuracy. Tests showed that an EAM-based silicon photonic neuromorphic chip built on Xbar technology supported 4-bit resolution artificial neural networks (ANNs). It achieved a 50 GHz computational rate with over 95 % accuracy.

Ultra-Fast Image Processing

Neuromorphic computing systems, like classical ANNs, are highly efficient in image classification and pattern recognition.

Spiking Neural Networks (SNNs) have demonstrated exceptional image processing capabilities. These systems use convolution and pooling techniques for feature extraction. They can be integrated with photon avalanche detectors and dynamic vision sensor (DVS) cameras to process images much faster than conventional methods.

Vertical Cavity Surface Emitting Lasers (VCSELs) are a type of semiconductor laser that operates with low energy and integrates easily into modern technology. Researchers have explored the potential of VCSEL neurons for image processing by combining photonic neuromorphic computing with VCSEL-based systems. This led to the development of an all-optical spiking platform designed for high-speed image processing.

The new platform uses a single VCSEL as an artificial optical spiking neuron. It is integrated with a multiplexing mechanism to improve system efficiency. Researchers tested the platform in neuromorphic edge-feature detection experiments, where streams of optical input pulses were processed using a single VCSEL. The system successfully applied consecutive 2×2 kernel operators to images, enabling fast neuromorphic spiking events for edge detection.

In testing, the platform processed 5,000 images from the MNIST handwritten digit database in a single experimental run. It handled 500 images per digit within 6.56 milliseconds, achieving a mean classification accuracy of 96.1 %. The system used commercially available devices and telecom-wavelength components, requiring no specialized VCSEL optimization.

These results demonstrate the potential of photonic neuromorphic computing for fast, energy-efficient, and hardware-friendly image processing. VCSEL-based spiking neurons could lead to high-speed, telecom-compatible neuromorphic platforms for real-time vision applications.[9]

Challenges in the Adoption of Photonic Neuromorphic Computing

Despite its advantages, photonic neuromorphic computing faces several challenges. Current PICs require significant energy to maintain optical stability. This challenge becomes even more pressing for portable and large-scale systems, where energy efficiency is critical.

Researchers are investigating high-mobility materials like Indium Gallium Arsenide (InGaAs) to develop more efficient photonic platforms with lower power requirements.

Material limitations are also a concern. No single material possesses all the properties needed for an ideal photonic neuromorphic circuit. To overcome this, hybrid approaches are being explored, integrating phase-change materials and modulators to enhance computational flexibility and non-linearity. These advancements aim to improve signal processing efficiency and operational reliability.

To improve scalability, researchers are exploring meta-surfaces, which are being tested for their ability to create compact, high-performance photonic devices. These advancements could enable widespread industrial adoption in the near future.

Another approach involves integrating Complementary Metal-Oxide-Semiconductor (CMOS) technology with silicon photonics, enhancing tuning modulation, stability, and overall system efficiency.

Sustainability is also becoming a key focus, as regulations on eco-friendly material sourcing become stricter. The development of environmentally sustainable photonic components will be essential for long-term adoption. At the same time, the rise of photonic neuromorphic computing introduces privacy and security concerns, as its high processing speed and connectivity introduce potential data vulnerabilities.

Despite these challenges, research is advancing to make photonic neuromorphic systems more efficient, scalable, and ready for real-world applications. With improvements in materials, power efficiency, and integration, these technologies could reshape AI, computing, and next-generation digital systems.

To learn more about the latest advancements in photonic computing, AI hardware, and semiconductor technology, please visit:

- Advances in Photonic Devices for Optical Computing
- Semiconductor Manufacturing By Country: The Industry's Biggest Players
- How Quickly Can AI Process Data?
- What to Know About Photonic Quantum Computers
- Are There Alternatives to Semiconductor Chips?

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Parallel Alignment Strategies for Complex Photonics Devices

Physik Instrumente's Parallel photonics alignment technology comprises a suite of advanced firmware-level algorithms integrated into the company's highest-performance motion controllers for 6DOF hexapods and nanopositioning multi-axis scanners.

These algorithms optimize fast optical coupling between photonic and other optical components and assemblies across multiple degrees of freedom, inputs, outputs, elements, and channels. Many of these optimizations can run concurrently, even when the parameters interact.

The result is a significant reduction in process time in applications such as testing and assembly of LiDAR sensors, smartphone camera modules, and advanced silicon photonics devices.

Serial Versus Parallel Alignment Strategies

In silicon photonics (SiP) devices, short waveguides' input and output couplings are often interdependent; adjusting one side can perturb the other, necessitating re-optimization.

Traditionally, achieving optimal coupling required an iterative, serial alignment process: repeated adjustments of the input and output channels in alternating sequence until a global alignment "consensus" was reached. A similar issue arises when optimizing angular alignment, where any improvement in pitch, yaw, or roll affects the transverse position, triggering yet another optimization loop. These nested, serial iterations result in extended process times and reduced throughput.

PI's Fast Multi-Channel Photonics Alignment (FMPA) technology eliminates this bottleneck by enabling concurrent, parallel optimization of all interacting degrees of freedom. The system can simultaneously adjust input, output, angular, and lateral parameters, rapidly converging toward a true global optimum.

This approach allows global consensus alignment to be established in a single step. Moreover, FMPA can maintain active tracking and continuous correction during production, compensating for drift, curing stresses, and other dynamic effects.

The outcome is a substantial increase in manufacturing throughput and process stability, along with a measurable reduction in cost per device. As photonic components grow more complex and alignment tolerances tighten, the benefits of true parallel optimization become increasingly critical to competitive process economics.

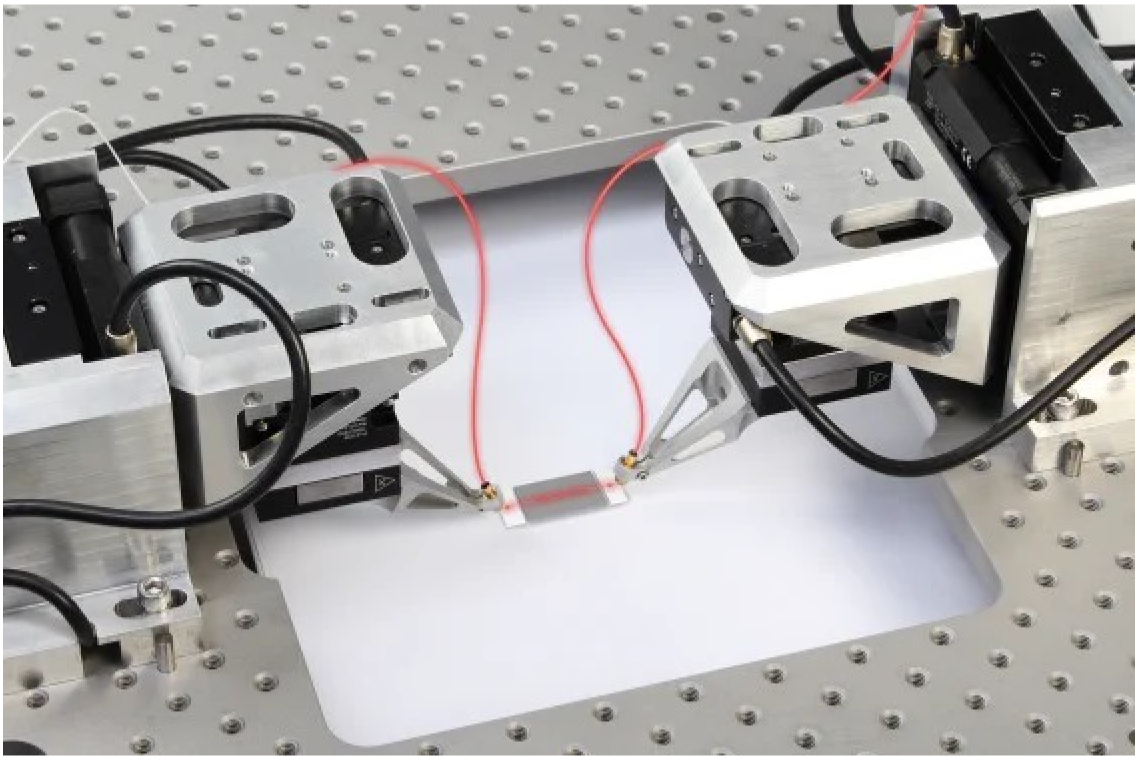

Fig 1. *Aligning the inputs and outputs of waveguide devices at an industrial pace requires parallel optimization and nanoscale accuracy. Image Credit: PI (Physik Instrumente) LP*

Look for the Loops

To fully utilize this capacity for maximum overall cost reductions, some different thinking may be required than what is typical of classical alignment hardware.

Generally, one looks for sequential alignment loops that can be replaced with simultaneous improvements. This article examines a few sample applications and addresses implementation challenges to demonstrate how this astonishing new capability may boost productivity in testing and packaging.

Background of FMPA Operation

The device alignment should be divided into discrete alignment operations. For example, probing a waveguide with one input and one output using a lensed fiber usually requires four alignment processes:

1. Transverse optimization routine, input

2. Transverse optimization routine, output
3. Z optimization routine, input (beam waist seek)
4. Z optimization routine, output (beam waist seek)

If the device has one or more extra inputs or outputs, add as follows:

5. Theta-Z optimization routine, input
6. Theta-Z optimization routine, output

If the device needs optimization in theta-X and theta-Y, include:

7. Gimbaling optimization routine, input
8. Gimbaling optimization routine, output

Breaking down the overall alignment task into subprocesses is essential for identifying which steps can run simultaneously.

With FMPA, users start by listing their alignment routines and defining them directly in the controller. This setup only needs to occur once - though you can update or modify it anytime. Once a routine is defined, it becomes repeatable. Better yet, multiple routines can run simultaneously, and this is where parallelism comes in.

Defining a process involves telling the controller which axes are involved, specifying which analog input reflects the quantity to be optimized (such as optical power or MTF), and selecting various process options. Users should name each process.

Users can run routines using the Fast Routine Start (FRS) command. For example, FRS 1 starts the transverse optimization on the input, FRS 2 starts the transverse optimization on the output, and FRS 1 2 runs both simultaneously.

Types of Alignment Routines

Independent alignment engine hardware is required on each side of the device. Any number of alignment engines can be employed; the most frequent configurations use one or two, but three or more will become more popular as SiP technology advances.

Typically, each alignment engine consists of a multi-axis long-travel assembly and a shorter-travel, high-speed, high-resolution piezoelectric multi-axis nanopositioning stage.

The technique's modularity is a significant advantage. Some applications do not require the lengthy trip mechanism or the nanopositioning stage's speed, precision, or continuous tracking capability.

In each event, regardless of the type of motion system used, all FMPA algorithms and processes are nearly the same; the only difference is the capability.

Fig 2. *F-712.MA2 high-precision fiber alignment system. Image Credit: PI (Physik Instrumente) LP*

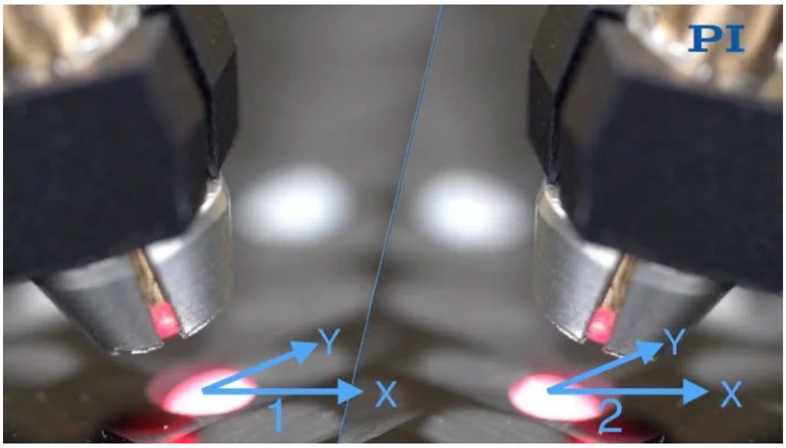

Fig 3. *Video explaining parallel alignment: Dividing a task like waveguide I/O coupling into sub-tasks like "1" and "2", as shown, will illuminate opportunities for parallel execution. Here, the two processes can proceed in parallel even though they interact, especially in the case of short waveguides where inputs and outputs steer each other. Similarly, processes related geometrically (such as a transverse and Z optimization in situations such as those shown with an angled beam) can be performed in parallel. Image Credit: PI (Physik Instrumente) LP*

Fig 4. *NanoCube®, piezo-based, high dynamic, 3-axis scanner with 100 μm travel range. Besides its nanoscale resolution and blazing speeds, this flexure-based subsystem can perform continuous tracking without wear. Image Credit: PI (Physik Instrumente) LP*

Long Travel Options

A stack of linear stages is sufficient for scenarios without angular optimizations or array alignment.

A hexapod is required otherwise, not only in situations requiring full six-degree-of-freedom positioning and optimization, but also in simpler situations, because the hexapod allows the rotational center point of even a single angular optimization to be placed on the optical axis, at the beam waist, and so on.

This is critical for eliminating parasitic geometric errors, which are another key to increasing overall productivity.

Sometimes, very long travel in one or two axes is required for loading operations, in which case the hexapod can be installed on a long-travel motorized stage. The hexapod controller can accommodate two extra DC servomotor axes. Alternatively, force sensor components can be included.

Fig 5. Single-sided fiber alignment system. Image Credit: PI (Physik Instrumente) LP

The Alignment Processes

There are two sorts of processes: areal scans, which aim to pinpoint a peak within a specific region, and gradient searches, which aim to efficiently improve coupling (and optionally follow it to reduce drift processes, disturbances, and so on).

Gradient Searches

Gradient searches cause a slight circular dither motion of one device versus the other, modulating the coupling. The amount of modulation of the figure-of-merit being optimized (for example, optical power or MTF) represents the local gradient of the coupling. At optimal, the modulation is zero (Fig. 6).

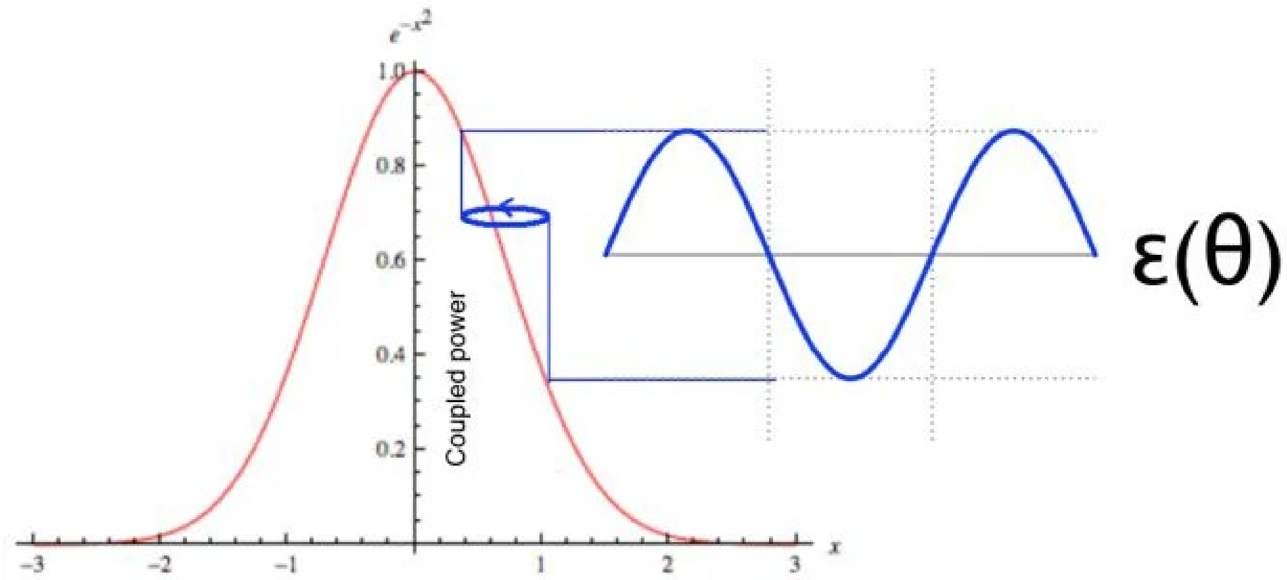

Fig 6. *Graphical depiction of gradient determination via a circular dither, which modulates the coupled power (or other quantity) observed. The phase of the modulation with respect to the dither indicates the direction towards maximum, while its amplitude falls to 0 at optimum. Image Credit: PI (Physik Instrumente) LP*

$$|\varepsilon(\theta)|=\nabla I=(I_{min}-I_{max})/I_{min}$$

Equation 1. *The observed gradient serves as a measure of alignment error.*

The local gradient can be quantitatively deduced from the observed modulation using a simple computation, such as Equation 1. At optimal, the gradient ∇I equals zero. Any axes in an FMPA system can accomplish any of these alignments (according to their physical limitations, of course).

As a result, areal scans can be performed using motorized stage axes, which can be quite useful for detecting first light.

Gradient searches are most commonly associated with transverse optimization, although they can also be performed (for example) in a single linear axis, which is perfect for localizing the beam waist in a lensed coupling, or in a gimbaling fashion to optimize an angle.

Numerous possibilities exist. These are extremely versatile algorithms that can be used for a wide range of optimization tasks, including bulk optic, cavity, and pinhole alignments.

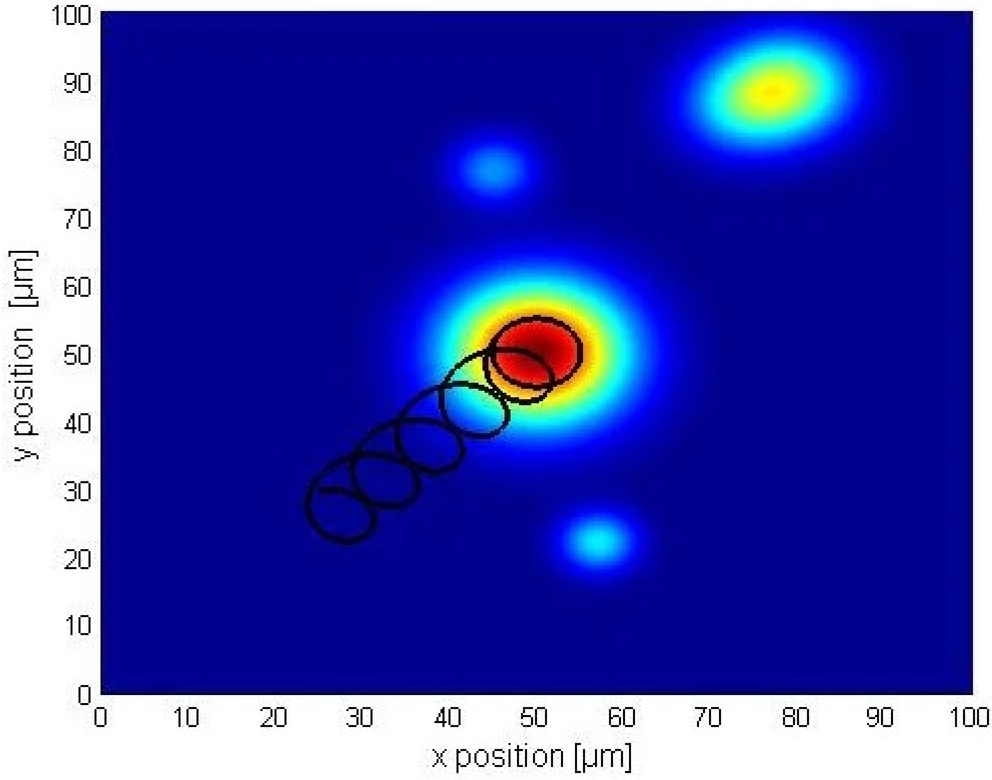

***Fig 7.** Optical power distribution. Image Credit: PI (Physik Instrumente) LP*

FMPA is distinguished by the ability to run several gradient searches simultaneously. Transverse optimizations are typically the most delicate and impacted by other alignments. As a result, transverse routines are usually restricted to high-speed, high-resolution piezoelectric stages like PI's P-616 nanoCube.

The NanoCube's fast speed and continuous tracking capacity maintain transverse optimization during Z and angular optimizations, which would otherwise necessitate a time-consuming, looping sequential approach.

Areal Scans

Scanning an area to discover the approximate location of the highest coupling peak is beneficial for a variety of purposes:

- Seeking the first light
- Profiling a coupling to determine its dimensions. This could be a critical process control step.
- Localizing the principal mode of a coupling for optimization via gradient search. This hybrid technique is particularly effective in preventing locking-on to a local maximum.

In addition to reducing the areal scan to a single command, FMPA controllers provide automatic curve-fitting capabilities and a data recorder that can capture the profile on the fly for subsequent retrieval, analysis, or databasing.

FMPA areal scans are very quick, taking about 300 msec for common NanoCube applications and loads. The curve-fitting capacity can fit a Gaussian to a relatively sparse scan (i.e., a quick scan), allowing for good localization of the optimal coupling point without spending a long time to do a very fine scan.

Another capacity is determining the centroid of a flat-top ("top-hat") coupling, such as when probing a deposited photodetector with a single-mode fiber. This permits the scan to end with the fiber at the geometric center of a flat or inclined top-hat coupling.

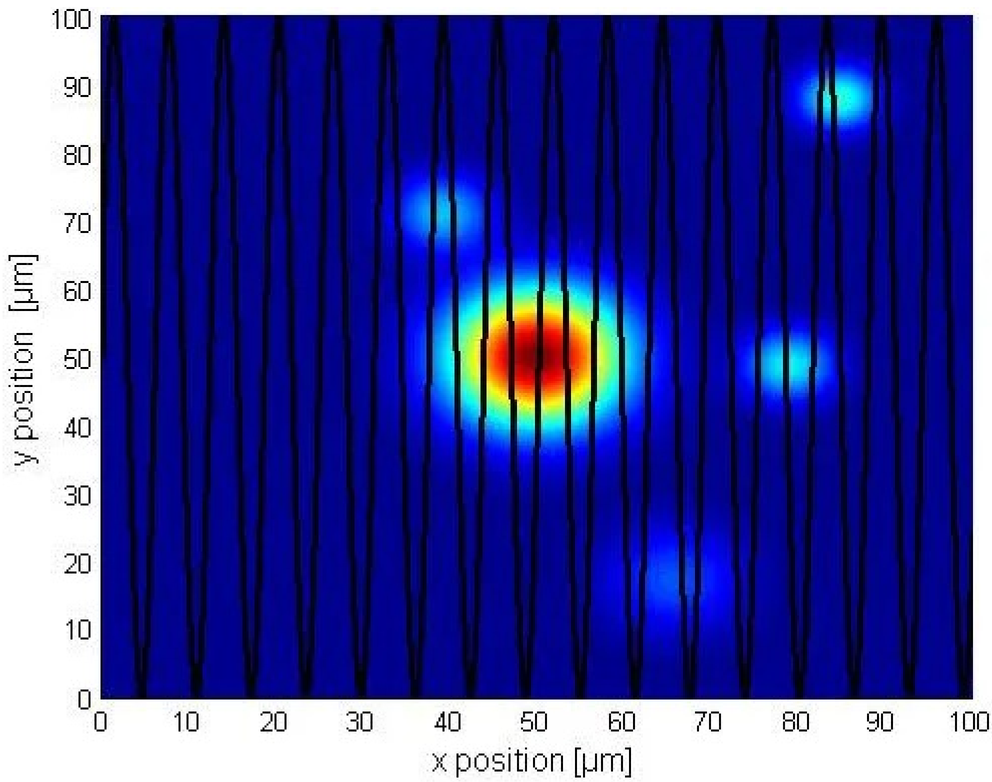

Fig 8. *Optical power distribution. Image Credit: PI (Physik Instrumente) LP*

FMPA offers unique areal scan possibilities, including single-frequency sinusoid and spiral scans. These are far faster than typical raster or serpentine scans because they are really continuous, eliminating the settling requirements of traditional scans' stop-and-start motions. The frequency can be adjusted to prevent triggering structural resonances.

A constant-velocity spiral scan may also be chosen, allowing data to be collected with a consistent density over the spiral.

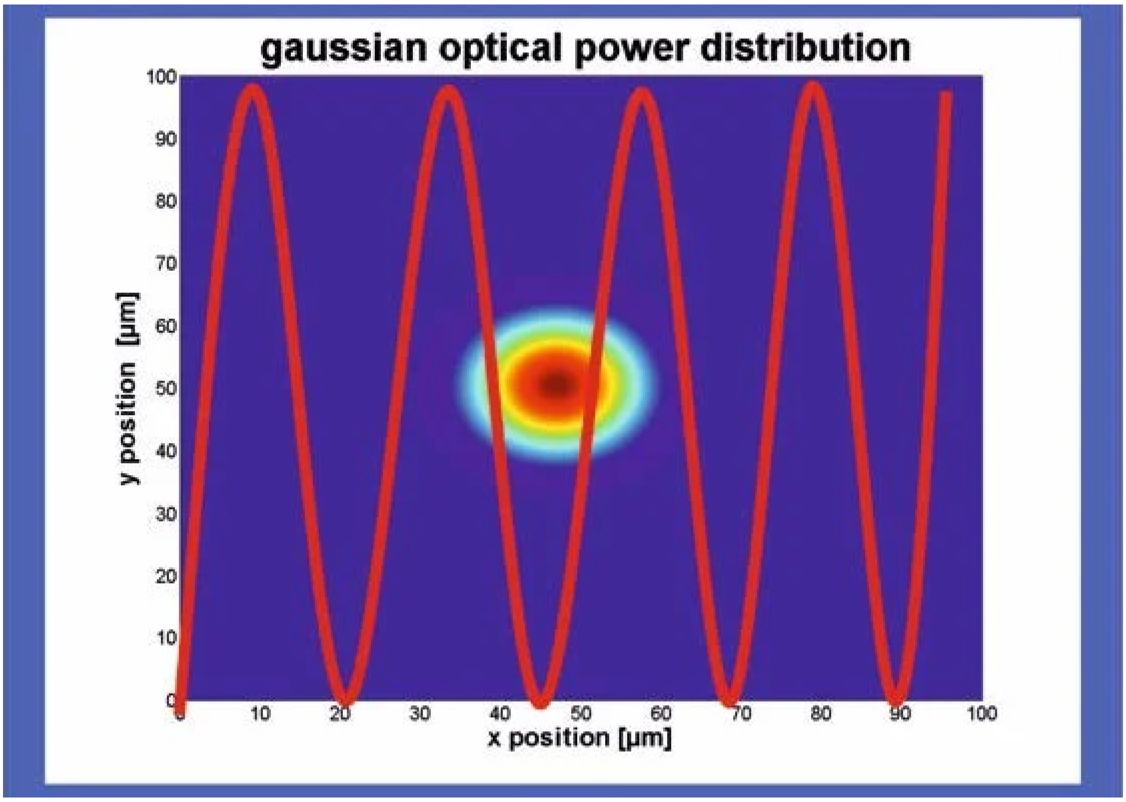

Fig 9. *Sinusoidal area scan. Image Credit: PI (Physik Instrumente) LP*

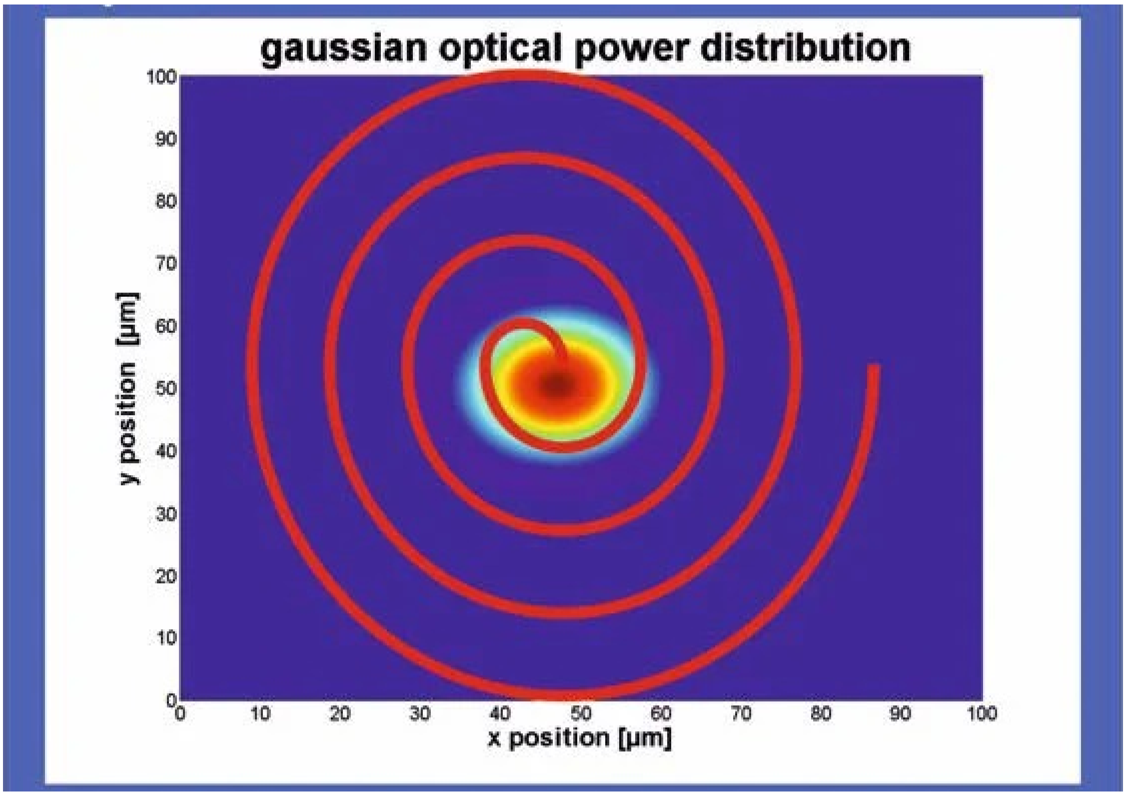

Fig 10. *Spiral area scan. Image Credit: PI (Physik Instrumente) LP*

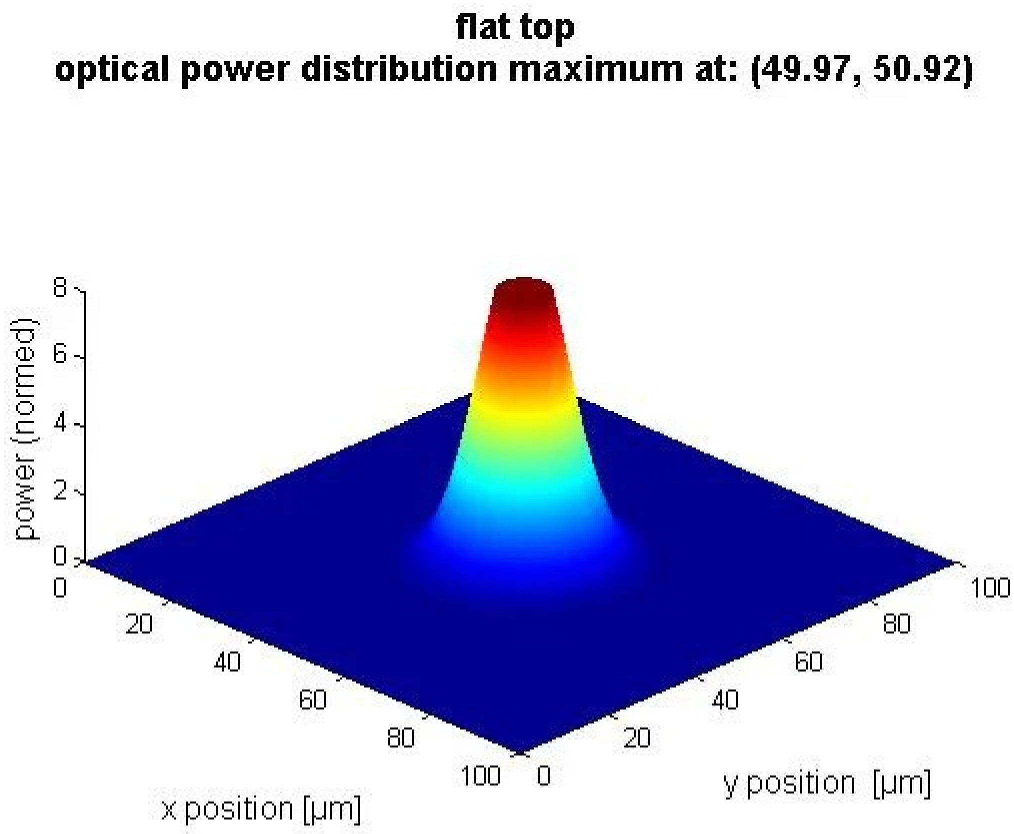

Fig 11. *Uniquely, PI FMPA controllers can perform a fast areal scan and automatically calculate and align robustly to the centroid position of upright and tilted top-hat couplings. Image Credit: PI (Physik Instrumente) LP*

Wafer Probing of Angle-Insensitive Devices

Even in the most basic scenario of a short waveguide device with only one input and output, the steering interaction described above can be a bothersome process bottleneck. Add the additional alignments required for angle-sensitive couplings and array devices, and the issue soon becomes complex and time-consuming.

Parallelism mitigates all of this and speeds up the process. For this example, consider a planar waveguide with a single input and output, both of which can be probed using diffractive couplers. Many thousands of such devices are typically manufactured on big wafers, so throughput is critical.

The diffractive couplers typically project the waveguide's input and output out of the wafer at an angle of 10-25° from vertical. Lensed probe fibers are frequently employed, resulting in a clear optimal separation along the optical axis.

High-quality wafer probers have lower placement accuracies than the NanoCube's 100 µm ×

100 µm × 100 µm field of vision, eliminating the requirement for first light seeks per device in probing applications. Note that the optical Z axis is at an angle to the mechanical Z axis for conventional stage stack placement.

$$Z_{optical} \nparallel Z_{mechanical}$$

To minimize collisions, the mechanical XY plane should stay parallel to the wafer, so tilting the motion assembly to accommodate the tilted optical beam is typically not ideal. As a result, optimization motions in mechanical Z must be followed by compensating motions in X and Y to maintain alignment.

This is a perfect example of parallelism. The first four alignment routines in the generic list compiled above apply:

1. Transverse optimization routine, input
2. Transverse optimization routine, output
3. Z optimization routine, input (beam waist seek)
4. Z optimization routine, output (beam waist seek)

Using non-parallel alignment technology, the normal approach would be:

1. To accommodate $Z_{optical} \nparallel Z_{mechanical}$, loop:

    a. To accommodate steering effects, loop:

        I. Align one side to maximize throughput
        II. Align the other side to maximize throughput

    b. Move in Z and evaluate if the move direction improved coupling

2. Repeat the above loops until optimized.

The total time required is often many tens of seconds! FMPA makes the procedure significantly easier and can be two or more orders of magnitude faster. Fundamentally, one defines gradient searches 1-4 from the list (again, this only needs to be done once, but any process may be tweaked or re-defined arbitrarily), and then for each device:

- Issue the Fast Routine Start command: FRS 1 2 3 4

Execution is normally completed in a few hundred milliseconds. A single E-712 controller can support up to four P-616 NanoCubes, which can be put on various workstations and do not have to process the same device.

Fig 12. *E-712 digital piezo controller. Image Credit: PI (Physik Instrumente) LP*

Tracking and the Completion Criterion

The gradient search has the unique advantage of optimizing and tracking its optimum. If you run many gradient searches on a device, they might all track simultaneously.

Alternatively, you may want to align first, then stop and hold in the optimal position for your application. This criterion - whether to align and stop or continue tracking - is an example of a parameter you may change in the process description to fine-tune the process's behavior to fit your application's requirements; there are other such alternatives.

Because the process is dependent on the instantaneous gradient of the coupling, it is logical to describe its endpoint in terms of the gradient.

This is called the Minimum Level, or ML. Setting the process's ML parameter to 0 indicates that it should never be satisfied and should continue to track until instructed to quit. This is important for handling drift processes, such as elevated temperature testing.

Setting ML to a small but non-zero value causes the gradient search to end at the observed optimal point. Due to the possibility of mechanical wear, ML=0 tracking should only be used with flexure-guided systems.

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The Photonics Skills Gap Threatens Innovation in Quantum and AI

The photonics industry sits at the heart of modern technological progress, powering innovation across sectors like telecommunications, data processing, information technology, healthcare, quantum science, and defense.[1] While the photonics industry is driving progress across multiple fields, it faces a growing challenge: a shortage of talented, highly skilled professionals. Demand for the next generation of young leaders, those who will shape the future of photonic devices, is steadily rising. Yet, the industry is struggling to keep pace due to a limited pipeline of qualified experts.

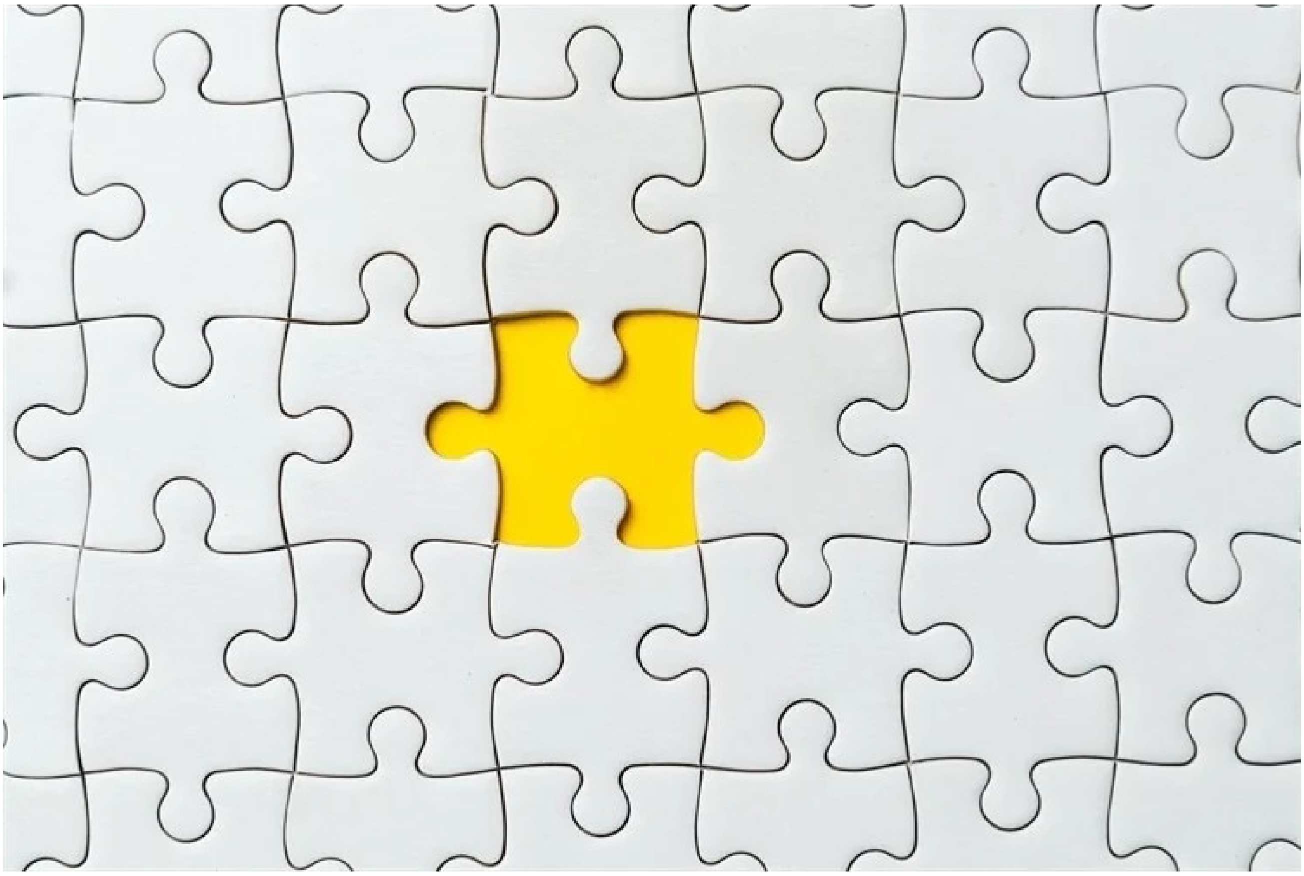

Image Credit: Gumbariya/Shutterstock.com

Why Is There a Skills Gap in Photonics?

The photonics industry is facing a serious shortage of qualified labor, driven by an aging workforce, a growing skills gap, limited training infrastructure, and the need for a diverse, modern skill set. As the industry expands rapidly, there's a critical need for technicians equipped with up-to-date expertise to support large-scale industrial success. To meet this demand, training programs and educational curricula must evolve, integrating core concepts in both linear and nonlinear photonics, along with practical, hands-on components aligned with the needs of today's digital landscape.[2]

A deep understanding of the light-matter interactions is essential for various sectors, including the photonics sector, fiber optics industry, high-speed data telecommunication industry, and quantum sciences. However, the industry-related knowledge is only being delivered at the graduate level. Fresh graduates are falling behind when it comes to technical advancements, which is causing a serious shortage of individuals for the photonics industry. In this regard, hands-on training in linear and non-linear photonics during the undergraduate studies will play a crucial role in bridging the skill gap and maintaining a constant supply of a qualified workforce.[3]

Industry Impact: Delayed Projects and Innovation Stalls

Industrial Experts on the Effects of Lack of Skilled Workforce

The lack of workers skilled in manufacturing photonics systems, assembling photonics components, performing rigorous industrial testing, and resolving issues is seriously affecting progress in the industry. Elizabeth Moore of MIT's Materials Systems Laboratory emphasized that the shortage of mid-level skilled workers poses a significant risk. Without enough talent to support scaling efforts, the industry could face project delays and serious setbacks in advancing innovation.

Emerging fields like integrated photonics are advancing quickly, but the shortage of skilled professionals is becoming the leading obstacle to continued growth. Even the Vice President and CTO of Optical Engineering at Marvell Technologies has underscored the urgent need for technicians and experts with strong competencies in integrated photonics and high-speed optical communication systems.[4]

Other Critical Sectors Affected

The convergence of photonics technology with smart semiconductor manufacturing is leading to on-chip photonics manufacturing, novel IoT infrastructure development, efficient on-chip semiconductor devices, and ultra-fast data transfer. The skilled workforce of the photonics industry is crucial for semiconductor manufacturing, quantum computing, and intelligent decision-making system development.

The convergence of photonics technology with advanced semiconductor manufacturing is driving breakthroughs in on-chip photonics, next-generation IoT infrastructure, high-efficiency semiconductor devices, and ultra-fast data transmission. A skilled photonics workforce is essential not only for semiconductor manufacturing but also for advancing quantum computing and intelligent decision-making systems.

However, the shortage of specialized talent is slowing progress in these areas. This talent gap is particularly impactful in the development of smart quantum computers and in maintaining the efficiency of high-speed data centers, where photonics plays a central role in cloud computing performance. Quantum computing chips and neuromorphic chips increasingly rely on the design, packaging, and processing methods of silicon-integrated photonic chips. When the photonics sector lacks the skilled professionals needed for research and development, it creates ripple effects, delaying innovation and disrupting product development across these closely connected industries

Major Challenges in Training

One of the primary drivers of the skills gap in the photonics industry is the lack of specialized undergraduate programs. Existing STEM curricula are falling short of meeting the specific demands of the photonics sector. This disconnect between academic training and industry needs continues to limit the pipeline of qualified professionals entering the field.

Lack of Programs at the Undergraduate Level

Josanne DeNatale, Marketing Manager for the American Center for Optics Manufacturing (AmeriCOM), has pointed out that the U.S. community college system is significantly lagging in equipping students with the skills needed to replace the retiring workforce in the optics and photonics industry. Currently, around two-thirds of degree programs in photonics, laser, and optical technologies are offered at the graduate level, leaving a major gap at the foundational stages of education. Indian River College stands out as the only institution offering an electronics engineering degree with a dedicated focus on photonics technology, highlighting just how limited undergraduate options are in this critical field.[5] This underscores a broader issue: there is a clear lack of focus on the photonics industry within major educational institution. In other countries, the challenge is even greater, as many institutions lack access to cutting-edge technology and the resources necessary to offer students the hands-on training and experience required to enter the photonics workforce with confidence.

Need for Industry-Focused Photonics Training Program

Experts from MIT recently published a comprehensive report analyzing the skills gap and evolving needs within the photonics industry. After conducting an in-depth survey and interviewing leading photonics manufacturers, the report revealed a sharp rise in demand for roles such as photonics technicians and optical equipment operators. Meanwhile, positions like CNC machine operators, electronic equipment assemblers, maintenance technicians, and electronics technicians are also growing, though at a more moderate pace. These findings highlight the shifting workforce priorities as the industry continues to expand and evolve.

The number of technically skilled middle-level and lower-level technicians in the U.S was estimated to be around 58,000, with estimates forecasting the number to reach around 85,000 by the end of 2031. Keeping these numbers in mind, the U.S. needs around 140 more industry-oriented training programs to meet the needs of the photonics industry regarding engineering technicians.

If the focus is on short-term photonics industry-focused vocational training programs, at least 185 national-level programs need to be instigated to provide the required number of lower-skill level technicians for the optics and photonics manufacturing industry. With these specially designed training programs and short vocational courses, it is possible to bridge the skill gap and provide the workforce with the relevant skills needed for the future.[6]

Bridging the Gap: Solutions and Innovations

Governments, companies, and educational institutes have recognized the need for specialized programs focused on the photonic industry, and investments are being made to ensure that a qualified workforce is available to ensure future progress.

AIM Photonics: Ensuring the Photonics Industry Skill Set Development in the U.S.

In response to these challenges, AIM Photonics represents a significant initiative led by the U.S. Department of Defense to strengthen the connection between industry and academia, support photonics manufacturing, and address the sector's growing skills gap. One of its key goals is to develop and train top-tier talent across the country. AIM Photonics offers a range of online courses covering essential topics such as the Integrated Photonics Simulation Library, PIC sensor design, photodetectors, and silicon photonics, helping to build a more prepared and technically proficient workforce.

They also offer one week of AIM Photonics Summer Academy, providing participants with an intensive study of chip fabrication principles, packaging strategies, materials, and an introduction to electronic-photonic design automation (EPDA) software. Additionally, they have partnered with educational institutes to offer Bachelor's degrees, certificates, and associate programs aimed at providing students with the cutting-edge knowledge of the photonics industry and giving them hands-on experience to excel in the present-day industry.

EU's Photonics Education Network for Next-Gen Innovation and Digital Skills Excellence for Industry and Society (Phortify)

Phortify is the European Union's education network for providing students with the required next-gen manufacturing technology skills, aiming to train graduates and young professionals utilizing cutting-edge modern tools, technology, and photonics knowledge. Already, 5 million

Euros have been strategically invested in this innovative program, which is focused on developing a common photonics curriculum by industrial experts for seven Master's programs across Europe. Apart from the Master's program, meticulously designed modules for developing cutting-edge photonics competencies without an extended career break shall also be offered to ensure that high-quality photonics training and education are accessible to all levels of workers.[7]

The governments of countries like Finland are also investing in promoting photonics education. Through its flagship program, the Photonics Research and Innovation Platform (PREIN), Finland is taking a focused approach to tackling the key challenges facing the photonics industry. Led by a consortium of four top educational institutions, PREIN aims to strengthen collaboration between research, education, and industry. The program supports innovation, talent development, and applied research to ensure Finland remains competitive in the rapidly evolving field of photonics.[8]

Apart from governments and educational institutes, online platforms like Coursera and edX are also offering Semiconductor, Photonics, and Optics Technology certificates describing all the key concepts, including the quantum theory of solids, from the basics of advanced photonics devices.[9]

Companies like VLC Photonics and The Institute of Photonic Sciences (ICFO) in Barcelona are also prioritizing diversity, gender equality, equity, and inclusion by offering international fellowships, outreach programs, and worldwide recruitment to ensure that talented individuals from all over the world contribute towards strengthening the photonics industry.[9]

The recent increase in investments aimed at improving photonics education by in-house training platforms, specialized courses, and industry-academia collaborations proves that the skill gap has been recognized as a serious threat. The lack of talent is affecting the automation sector too, and as the skill gap widens, the technological advancements will begin to slow down drastically. A focus on industry-related educational courses and training modules is the only way to produce engineers and technicians with the required skill set to ensure constant progress in the photonics industry, and its interconnected sectors like quantum computing, AI automation, autonomous vehicles, and on-chip semiconductor manufacturing.

Further Reading

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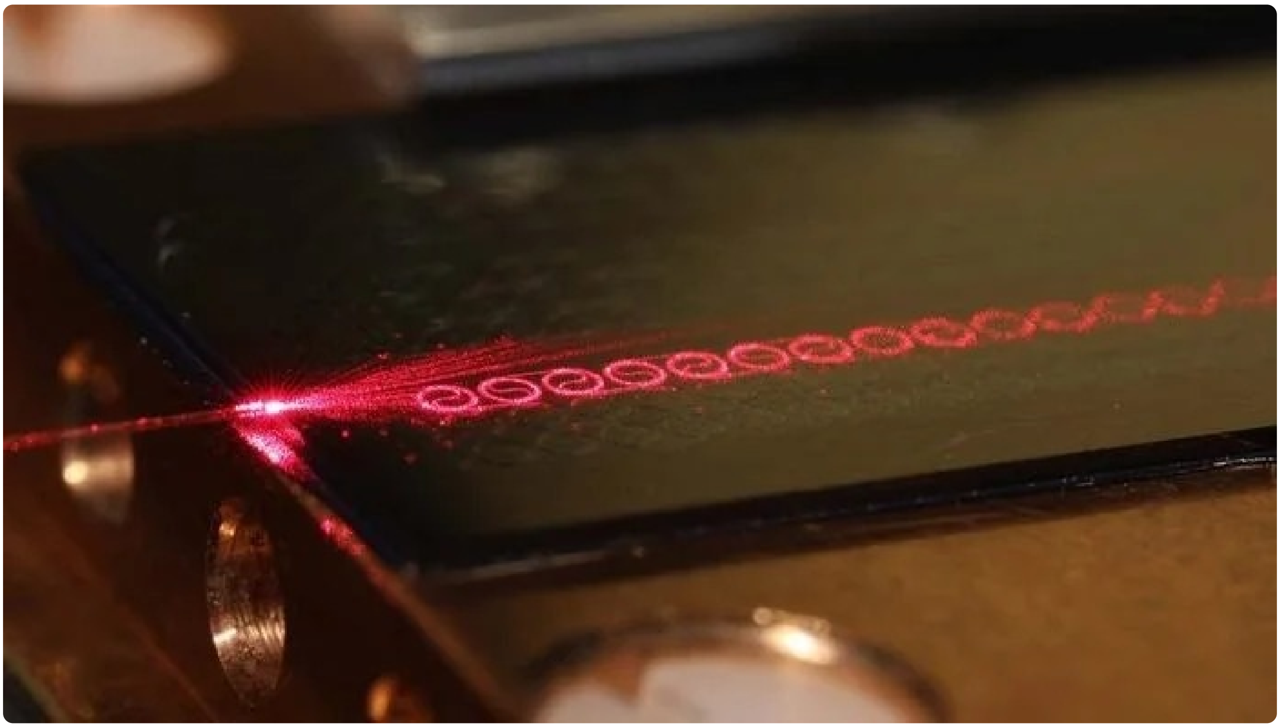
New Chip-Based Amplifier Revolutionizes Fiber-Optic Communication

In a recent study published in *Nature*, researchers from Chalmers University of Technology in Sweden introduced a new amplifier that enables a data rate ten times higher than what is currently achievable with fiber-optic systems. This amplifier, which can be integrated into a small chip, holds potential for a variety of important laser systems, including those used in medical diagnosis and treatment.



The amplifier developed by Chalmers researchers is compact, measuring just a few centimeters, yet it can process ten times larger amounts of data per second than current optical communication systems. This innovation leverages a unique combination of design and material selection, providing technical benefits such as minimal noise and a compact form factor. The amplifier features a pattern of spiral-shaped, interconnected waveguides that efficiently direct the laser beam with high precision and minimal loss. Image Credit: Chalmers University of Technology | Vijay Shekhawat

Data traffic is expected to double by 2030, driven by factors such as the advancement of AI technology, the growing popularity of streaming services, and the proliferation of new smart devices. This increase in data usage is raising the demand for communication systems capable of handling large volumes of data.

Currently, telecommunications, the Internet, and other data-intensive services rely on optical communication systems. These systems use light to transmit information over long distances. Laser pulses travel through thin glass strands in optical fibers at high speeds, enabling data transmission.

Optical amplifiers play a critical role in preserving data quality by preventing signals from being overwhelmed by noise. The amplifier's bandwidth, or the range of light wavelengths it can process, is a key determinant of the data transmission capacity in an optical communication system.

> *The amplifiers currently used in optical communication systems have a bandwidth of approximately 30 nm. Our amplifier, however, boasts a bandwidth of 300 nm, enabling it to transmit ten times more data per second than those of existing systems.*
>
> *Peter Andrekson, Professor and Study Lead Author, Photonics, Chalmers University of Technology*

Small, Sensitive, and Powerful

The new amplifier uses several small, spiral-shaped, interconnected waveguides in silicon nitride to direct light with minimal loss. The combination of this material with an optimized geometric design has resulted in several technical advantages.

> *The key innovation of this amplifier is its ability to increase bandwidth tenfold while reducing noise more effectively than any other type of amplifier. This capability allows it to amplify very weak signals, such as those used in space communication.*
>
> *Peter Andrekson, Professor and Study Lead Author, Photonics, Chalmers University of Technology*

Additionally, the system has been successfully miniaturized by the researchers to fit onto a chip just a few centimeters in size.

"While building amplifiers on small chips is not a new concept, this is the first instance of achieving such a large bandwidth," added Peter Andrekson.

Contributes to Earlier Detection of Diseases

The researchers have integrated multiple amplifiers onto the chip, making the design easily scalable. This configuration allows for the creation of laser systems capable of quickly adjusting wavelengths over a broad range. As optical amplifiers are critical components in all lasers, this invention has numerous potential applications.

> *Minor adjustments to the design would enable the amplification of visible and infrared light as well. This means the amplifier could be utilized in laser systems for medical diagnostics, analysis, and treatment. A large bandwidth allows for more precise analyses and imaging of tissues and organs, facilitating earlier detection of diseases.*
>
> *Peter Andrekson, Professor and Study Lead Author, Photonics, Chalmers University of Technology*

In addition to its versatility, the amplifier can help reduce the size and cost of laser systems.

"This amplifier offers a scalable solution for lasers, enabling them to operate at various wavelengths while being more cost-effective, compact, and energy-efficient. Consequently, a single laser system based on this amplifier could be utilized across multiple fields. Beyond medical research, diagnostics, and treatment, it could also be applied in imaging, holography, spectroscopy, microscopy, and material and component characterization at entirely different wavelengths," explained Peter Andrekson.

Further Insights into the Amplifier's Potential

The researchers demonstrated that the amplifier operates effectively within the 1400–1700 nm range of the optical communication spectrum. Due to its broad 300 nm bandwidth, the amplifier can be adjusted for use at other wavelengths.

By modifying the waveguide design, signals in other ranges, such as visible light (400–700 nm) and infrared light (2000–4000 nm), can also be amplified. This flexibility opens the possibility for the amplifier's use in applications such as disease diagnosis, treatment, internal organ and tissue visualization, and surgery, where visible or infrared light is essential.

Journal Reference:

Zhao, P., *et al*. (2025) Ultra-broadband optical amplification using nonlinear integrated waveguides. *Nature*. doi.org/10.1038/s41586-025-08824-3.

Source:

Chalmers University of Technology

High-Throughput Alignment System for Photonics Arrays & PICs – Live Demos at SPIE Photonics West

4DOF and 6DOF alignment systems for photonics and fiber optics components provides cutting-edge performance and high ROI.

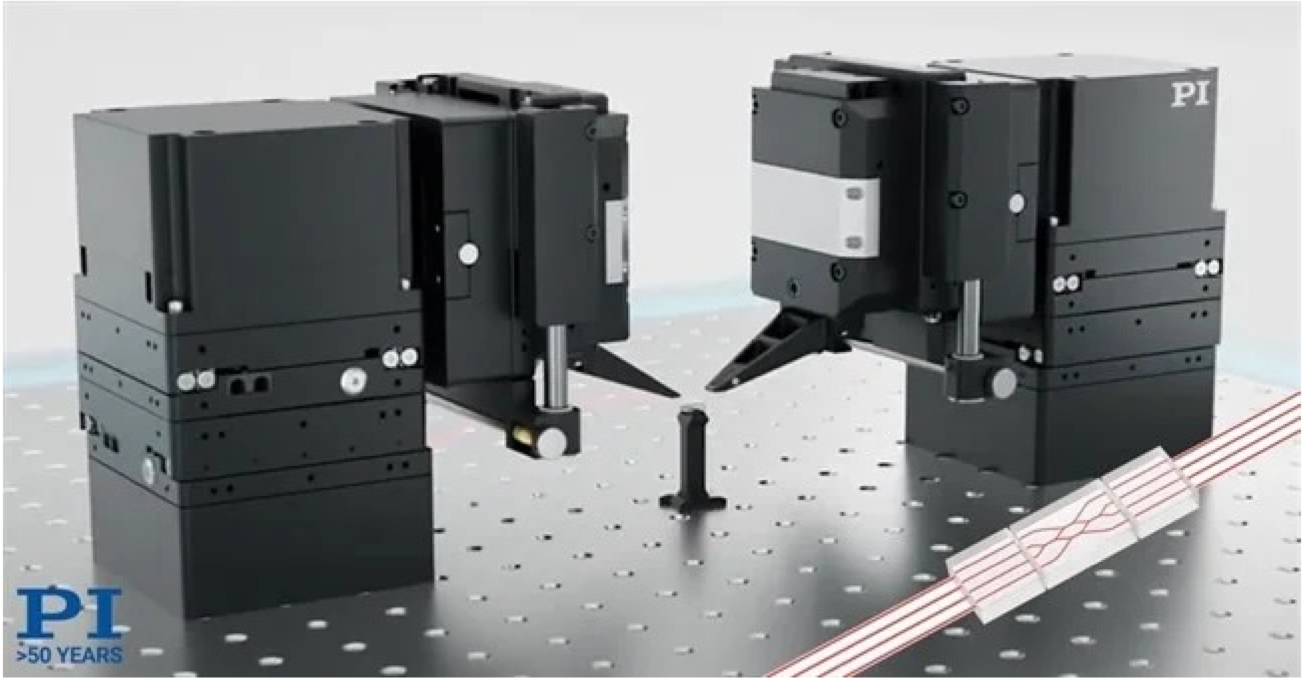


Image Credit: Physik Instrumente

PI's **new F-141 photonics alignment system** provides high throughput with motion in 4 and 6 degrees of freedom for industrial test and assembly of photonic integrated circuits (PIC). This ultra-compact precision alignment system fits inside a space of ~5x7x4 inches (WxLxH) while providing 40mm of XYZ travel and 12 degrees of rotation around the optical axis, ideal for array alignment. Direct drive motors provide high acceleration, speed, and resolution, along with excellent lifetime. Precision guidance is guaranteed by crossed-roller bearings and flexure guides.

Optional 6-Axis Version

In addition to the 2, 3 and 4-axis versions, an optional pitch/yaw module allows for full adjustment in all six degrees of freedom. Other configurations are available for applications with different optical axis orientations..

High-Performance Alignment Controller, Industry-Leading Scan and Alignment Routines

The system is controlled by an advanced multi-axis EtherCAT®-based control system with rapid signal analysis for onboard machine learning. Sophisticated scan and alignment routines are embedded in the controller, offering improved performance and simple integration compared to software-based alignment algorithms running on the host computer.

Shortest First-Light Detection and Signal Optimization Times in the Industry

PI proprietary alignment algorithms provide unparalleled performance with the shortest first-light detection and signal optimization times in the industry - up to two orders of magnitude faster than conventional methods. The system can manage all tasks in the field of photonics and fiber-optic alignment including simultaneous alignment in several degrees of freedom. The use of ultra-low noise electronics, PWM amplifiers, and onboard integrated 24-bit analog inputs for the high-bandwidth optical power meter enable repeatable and stable optical signal coupling in a variety of environments.

Application Fields

Alignment of PICs, fiber alignment, alignment of optical components; automatic photonic wafer tests, assembling technology in silicon photonics.

Specifications, Datasheet: **F-141 Compact 2 ... 6 DOF Fast Photonics Alignment System**

Industries Served

Photonics, Optics, Fiber Optics, Silicon Photonics