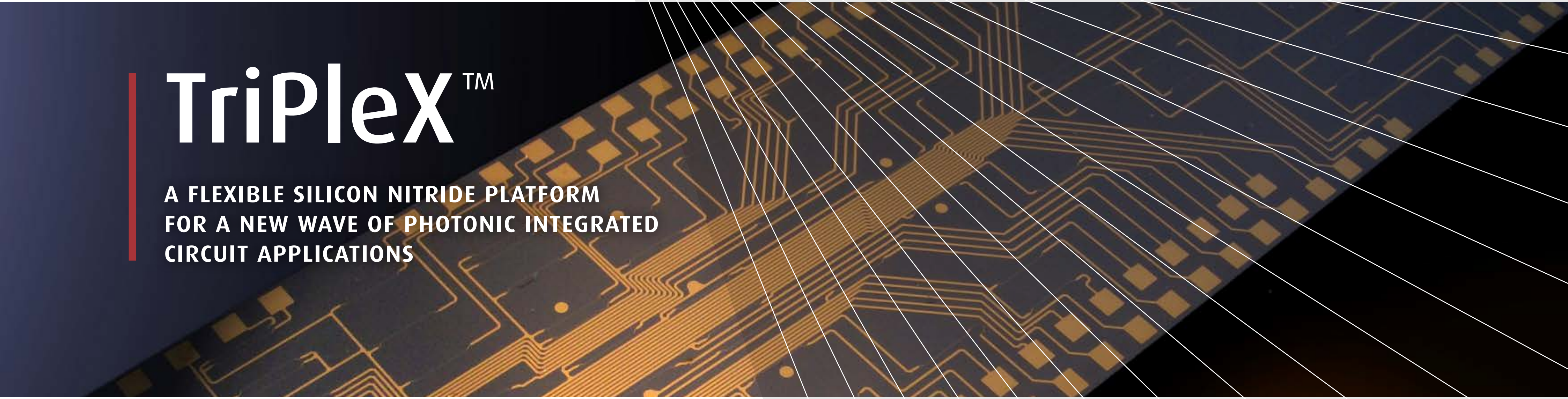
LIONIX INTERNATIONAL

TriPleX™

A FLEXIBLE SILICON NITRIDE PLATFORM FOR A NEW WAVE OF PHOTONIC INTEGRATED CIRCUIT APPLICATIONS



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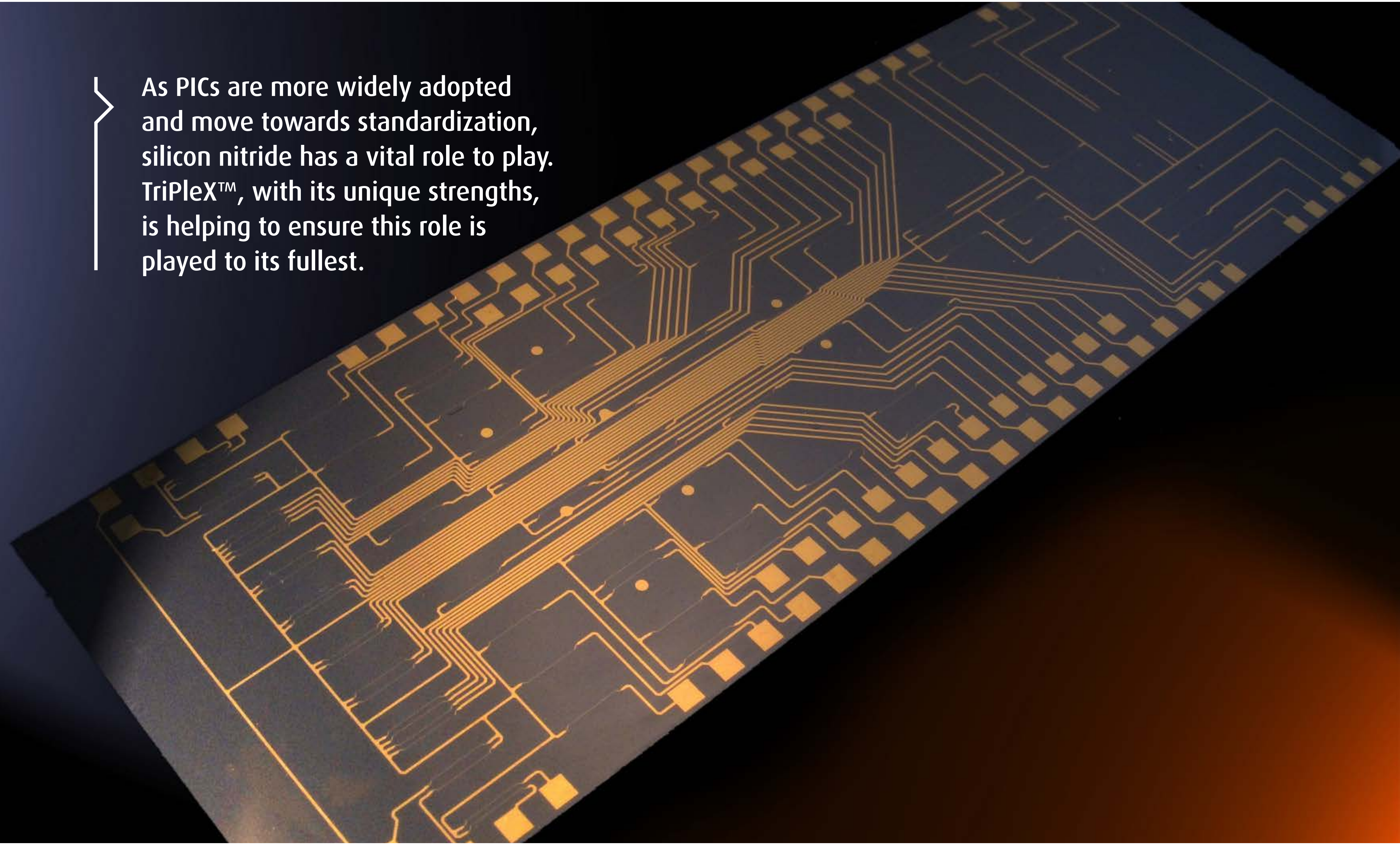
As PICs are more widely adopted and move towards standardization, silicon nitride has a vital role to play. TriPleX™, with its unique strengths, is helping to ensure this role is played to its fullest.



Foreword

By Professor Roel Baets and Dr Abdul Rahim, ePIXfab - the European Silicon Photonics Alliance

The revolution taking place in Photonic Integrated Circuits (PICs) has seen the integration of more and more photonic solutions into scalable miniature devices with low barriers to entry. Fingertip-sized PICs with an unprecedented level of integration complexity offer endless possibilities. Innovators across diverse sectors are responding by adopting PICs in their next generation of technology. From automotive, transportation and space, to communication, health and agriculture—we're seeing exciting PIC-enabled technology drive increased performance and lower costs.

The story of PIC-enabled innovation takes place in a diverse landscape of PIC materials, in which silicon nitride has a special place. Through its particular strengths as a photonic material and the way it complements other PIC technology, it plays an important part in enabling the continued spread of innovations.

The PIC ecosystem can only thrive if there are industrial actors who serve end-users with a variety of technologies and modalities for access. Equally, different users require support for different volumes, from prototyping to high volume manufacturing. Serving these different needs has been a weak spot in the ecosystem for many years. Capability is gradually growing. Indeed the seed was sown by LioniX International at its founding in 2001. At that time, the company was an early adopter of a vision for PICs that served a range of customers from academia and, crucially, industry.

There is a lot that the PIC ecosystem can learn from LioniX International's success story. Today, they are one of the key players globally in the field of silicon nitride PIC technology. We have thoroughly enjoyed following the story they have summarized here.

ePIXfab

Initially used as a very low loss waveguide material, silicon nitride is also transparent at longer, visible wavelengths of light than other materials.

Introduction

New applications in integrated photonics require materials that can transmit different wavelengths of light, including in the visible range.

The need for a flexible platform

The world is waking up to the potential of chip-based photonic devices with low production costs and high performance characteristics. The benefits of such Photonic Integrated Circuits (or PICs) are far ranging – faster communications, more intelligent sensors and more compact medical devices. But with increasing application scope comes the need for a more adaptable technology platform.

Whilst the leading photonic platforms each have their strengths—intrinsic material limitations mean specifications cannot be met by one platform alone. How do PIC manufacturers respond?

LioniX International has one answer:

TriPleX™ — a versatile silicon nitride platform that integrates seamlessly with other materials for "best-of-both-worlds" performance.

The secret behind its effectiveness? It has something to do with plywood...

So why use light anyway?

To understand the value that a platform like TriPleX™ creates, it's useful to understand the more general benefits of photonics — the technology of generating and harnessing light— offers over electronics.

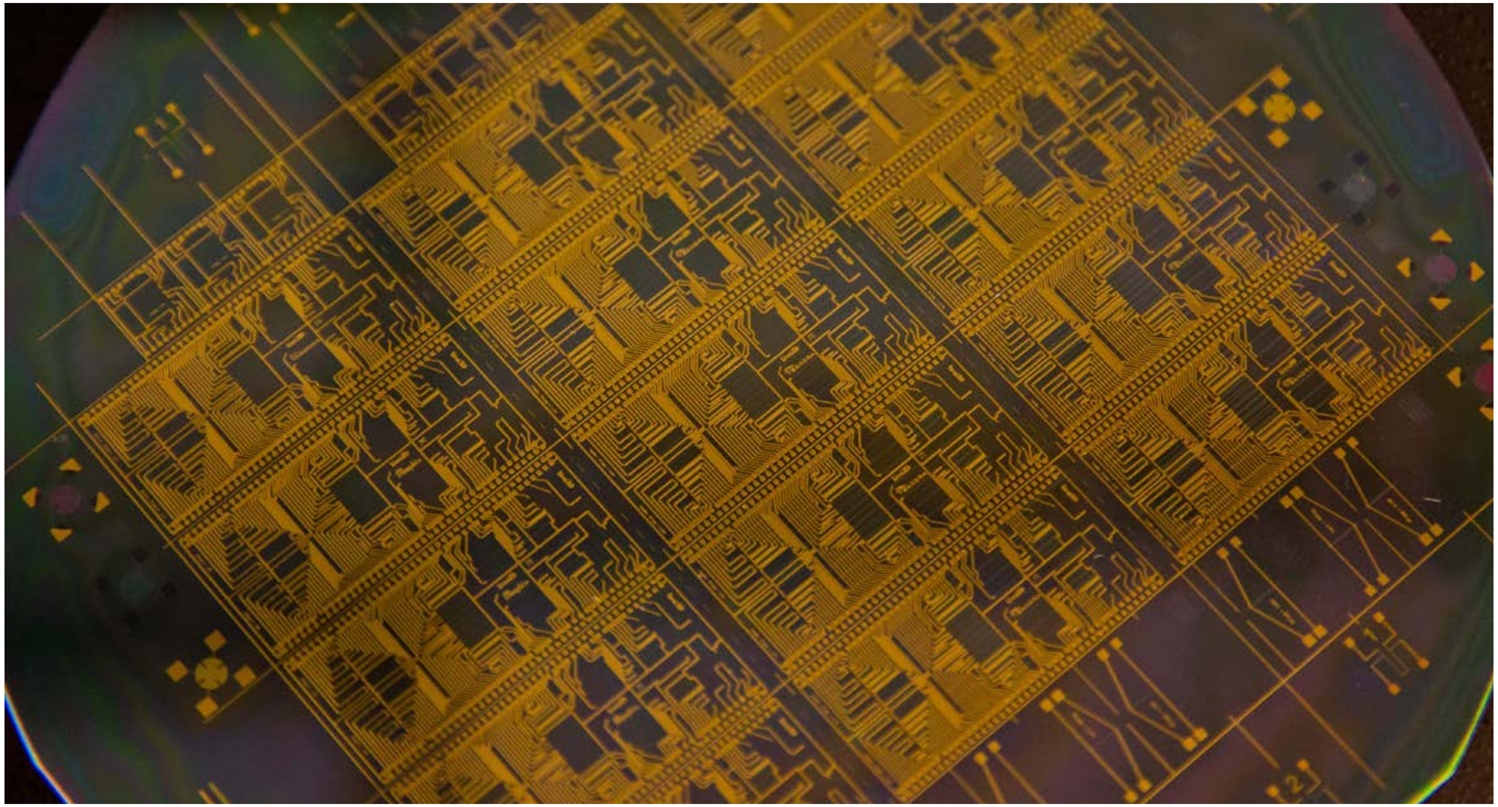
Fundamentally, photonics offers higher bandwidth signal processing compared to electronics. Whereas only one analogue electronic signal can be transmitted along a cable at any one time, light signals of different wavelengths can be transmitted along the same channel without interfering. Furthermore, such signals are virtually immune to electronic interference. Moreover, they can be transmitted along optical fibres at lower power and with lower losses than electronic counterparts along copper wire.

On a more subtle level things are even more interesting. Light interacts with its environment in unique ways. Transmission, reflection, absorption, interference and polarization effects can all be used to build novel devices that respond more sensitively to the world around them than is possible with electronics.

These ideas are not new of course. Optical components have been used in communications, imaging and sensing for decades, even centuries. However, the reliance on separate bulk optical components has hampered commercial adoption. Fragility, cost, difficulty in volume scaling and miniaturization have all been problems. This is especially true for the bulky and expensive laser sources that the industry relied on.

But what electronic integration did for information technology in the 80s, the integration of photonics is doing again today.

The fabrication of cost-effective lasers and efficient light routing components directly onto chips is driving a new era of high-volume, cost-effective PIC technology in applications from datacom to biosensing.



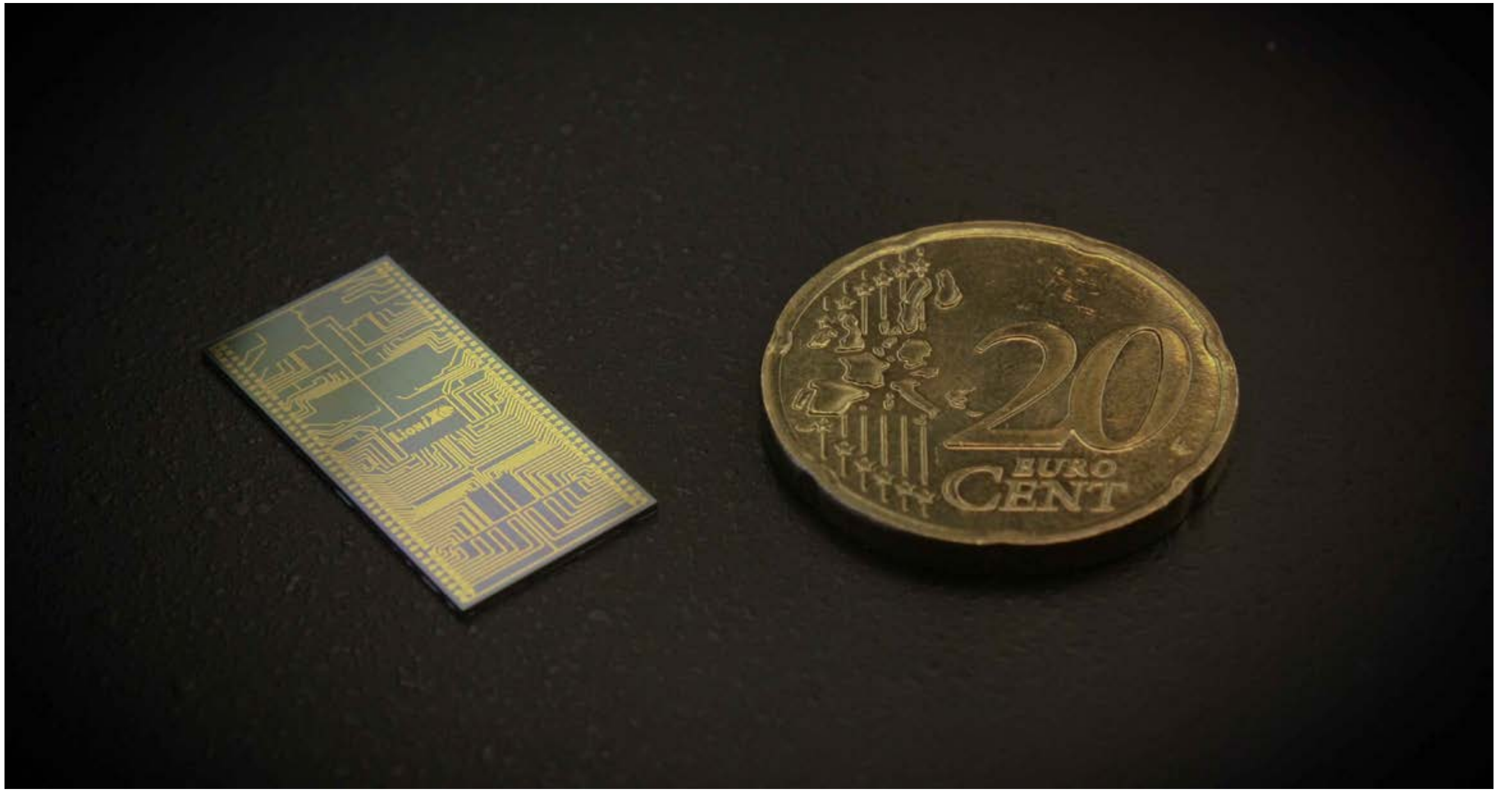
Photonic integrated circuits fabricated on a wafer. Photonic components are built into chips using wafer-level fabrication processes to enable scalability similar to electronic integrated circuits.

The promise of integrated photonics

What exactly is it that has new users in different markets paying attention to PICs? The list of benefits that PICs offer is compelling. In terms of performance, PICs offer precise routing and control of light, high density integration of components and even solid-state, real-time reconfigurable operation.

Just as exciting is the scope for PICs to be used in applications or environments where traditional optics are too fragile to cope. Here PICs, with their solid state operation and robust integrated components offer huge benefits in terms of form factor, reliability and ease of interfacing.

Photonic integrated circuits offer robust integrated functionality in tiny form factors with improvements in performance and reliability.



Further to their operational merits, PICs offer clear economic advantages too. They are manufactured in very similar ways to electrical IC chips and can benefit from similar bulk processing steps that are used in integrated circuit chip foundries. These processes are highly scalable and capable of producing PICs in volumes ranging from a handful to the millions.

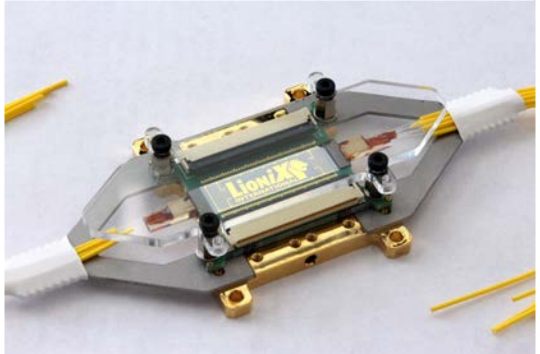
Strengths and weaknesses of available waveguide materials

The integrated photonics space is organized around a number of different waveguide materials. Three materials attracting the most attention are silicon, indium phosphide, and silicon nitride. Each material has its own strength.

1 Silicon

Silicon as a waveguide material offers compatibility with existing infrastructure for the volume production of integrated electronics (so-called complimentary metal-oxide semiconductor or CMOS). As a result, silicon PICs are now produced on high-volume lines on the industry's largest (200mm and 300mm) substrates.

In terms of performance, silicon photonics offers compact devices with high density configurations of optical components. This capability stems from the optical properties of the material—namely the contrast in refractive index between the waveguide and its surroundings. Such high contrast confines light tightly to the waveguide for tight bends, resulting in small component features.



An MPW run is perfect for developing prototype devices

Accessing PIC technology

Initial costs for dedicated production of a photonic integrated circuit at a commercial foundry can be high.
Luckily, all three photonic integrated circuit platforms discussed here are available through an open access foundry model known as a Multi Project Wafer (MPW) run. In this model, chip designers share space on a run and use standardized building blocks, materials and standard processes. This reduces development and production risks and controls costs for low volume prototyping.

2 Indium phosphide

Indium phosphide is the go-to waveguide material for active functionality. That is to say, further to just passive light routing, it can emit, amplify and detect light. This strength is however also a drawback and the same properties that make indium phosphide such an effective active material make it a lossy passive waveguide.

3 Silicon nitride

Initially used as a very low loss waveguide material, silicon nitride is also transparent at longer, visible wavelengths of light than alternate materials. Indeed, an even wider transparency window is possible with silicon nitride by applying specific fabrication steps. Such processes are employed in LioniX International's silicon nitride-based TriPleX™ waveguides, to support wavelengths from near ultra-violet to infrared (400nm to 2350nm) with record low losses.

An additional strength of silicon nitride is its ability to handle high optical power, which along with low loss capability has driven excellent performance in a range of applications including life sciences, sensing, metrology and telecom/datacom.

Silicon nitride has no light generating capacity and requires the integration of active materials to for light emission, amplification or detection.

Section summary

- Photonics offers inherent benefits over electronics. Namely higher signal band width and signal fidelity.
- Photonic Integrated Circuit (PIC) technology is enabling the integration of more and more complex optical function onto compact chips.
- PICs fabrication can be scaled easily to millions of devices with corresponding reductions in cost-per-chip.
- PICs offer improvements in cost-effectiveness, form factor, reliability and robustness.
- There are currently three predominant material platforms for PICs in the eco-system silicon nitride, indium phosphide and silicon nitride. Each has its own strength.
- Silicon nitride excels as a low loss material with broad transparency.

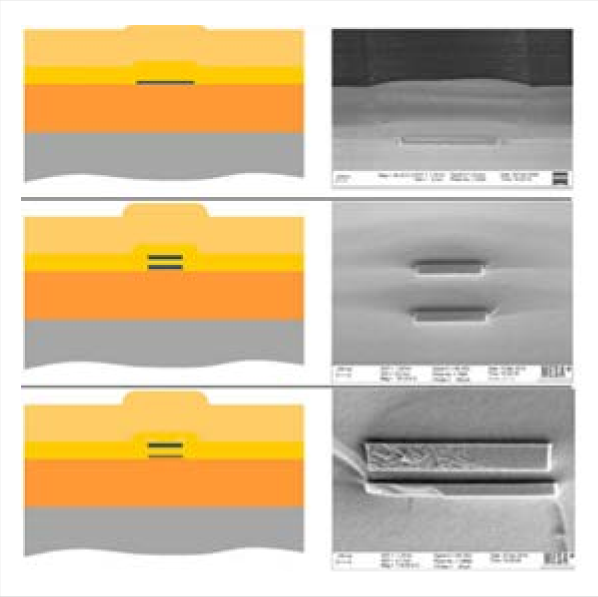
TriPleX™: Core features and benefits

An introduction to TriPleX™

TriPleX™ is a proprietary technology from LioniX International [1]. We use it to engineer the "light wires" or rather waveguides that form the basis of Photonic Integrated Circuits or PICs.

One of the main ingredients of TriPleX™ is silicon nitride, a material that is already well-known in the PIC world as the low-loss, broad transparency material of choice for integrated photonics.

In developing TriPleX™, LioniX International have turbo-charged the properties of silicon nitride by sandwiching silicon nitride between layers of silicon oxide. The resulting layered structure, named "TriPleX™" after the Dutch word for plywood, offers great benefits in terms of optical performance. **More importantly, this unique structure enables PIC designers to create powerful functionality by optimizing the properties of light for different purposes.** This can be low losses on-chip, efficient light coupling or effective hybrid integration of specialist components.



Left: Schematics and corresponding SEM images of different TriPleX™ waveguide cross sections. Each waveguide is around 400nm across.

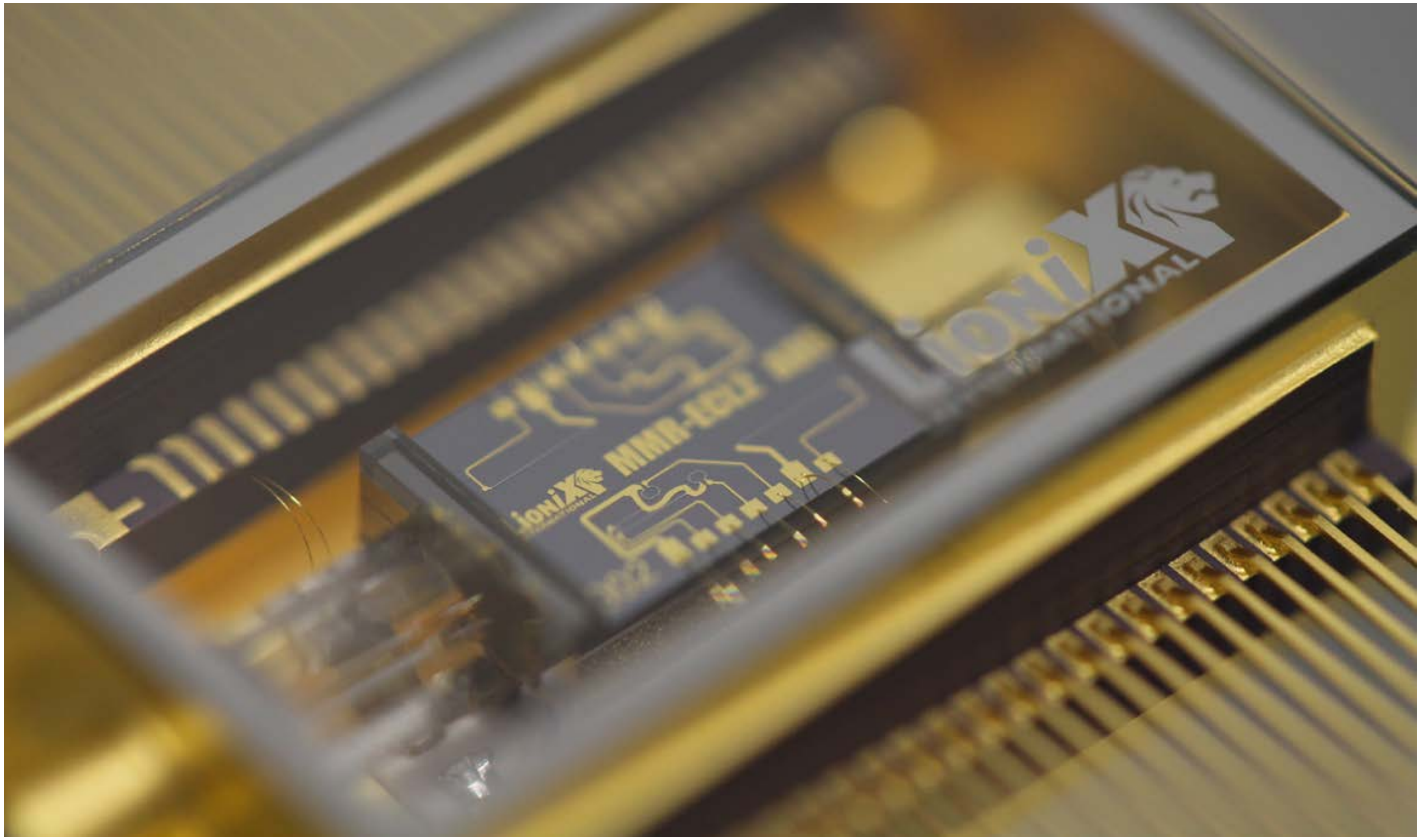
A platform for optimum interfacing and integration

Optimizing for low losses on chip whilst ignoring the performance of light at interfaces (coupling to fibers, free space optics or other PICs) can result in performance no better than that of bulk optics. Only by optimizing performance across a whole system can the real power of PICs be utilized. This optimization is by no means trivial and requires very precise tailoring of light properties.

This is particularly true in silicon nitride, where a lack of active capability requires not only coupling to fibers but hybrid integration with active indium phosphide PICs. In hybrid integration, separate PICs, often made from different materials are carefully aligned and bonded to create a single device. This "best of both worlds" approach utilizes the capabilities of both platforms. Consequently it can yield very high performance and lower cost devices, but requires very careful optimization of couplings if the integrated device is going to work at all.

So optimum system performance can only be enabled by a technology that is designed with connectivity in mind. This is where TriPleX™ waveguides excel. The primary benefit of the layered structure of TriPleX™ is that it offers losses as low as any solid cross section waveguide of similar aspect ratio, but can adapted flexibly to optimize for other capability.

The adaptation of waveguide cross section is known as tapering (see box *Tapering explained*), and it is a powerful way to engineer light properties. It can do more to change how light behaves in a waveguide than is possible by adapting material properties alone. Furthermore, tapers can be very accurately engineered to precisely match the optical performance requirement of any usage specification.



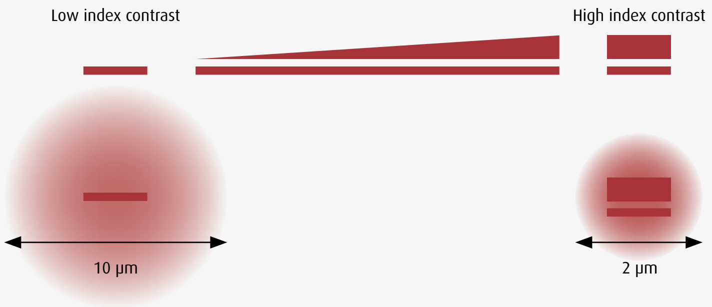
Using hybrid integration it is possible to make integrated photonic modules that combine the strengths of different platforms. This hybrid integrated tunable laser uses and indium phosphide gain section and low-loss silicon nitride for an external cavity.

Being able to optimize different regions on the same PIC for different capabilities means TriPleX™ can unlock the full potential of silicon nitride. Configured for optimal routing on chip, it excels as an ultra-low loss waveguide material. In this capacity it can be used to create high performance components like resonators, laser cavities, spectrometers and non-linear components. Optimized instead for efficient coupling, TriPleX™ eliminates avoidable losses at interfaces and unleashes the power of hybrid integration.

Tapering between waveguides cross sections for different light confinement.

Tapering explained

Different waveguide cross-sections are optimal for different purposes. Tapering provides an optimal way of transitioning between these specialist functions.



CROSS SECTION	SINGLE STRIPE	DOUBLE STRIPE
INDEX XONTRAST	low	high
LIGHT FIELD DIAMETER	large	small
IDEAL FOR	low propagation loss fiber coupling	tight bends effivient use of space

Strongly confining waveguides support efficient light routing and therefore small chip sizes. This is because they can be coiled very tightly without light "spilling" from bends. However, with most of the power inside the waveguide, light interacts strongly with any roughness at the waveguide edges, leading to propagation losses.

Conversely, weakly confined light is relatively unaffected by surface wall roughness and can achieve very low (<0.001dB per cm) propagation losses. The trade-off is that weakly confined waveguides cannot be bent as drastically and require bigger chip areas as a result.

Section summary

- TriPleX™ is a proprietary silicon nitride waveguide platform from LioniX International.
- TriPleX™ enables optimum routing and coupling of light for low losses and dense functionality.
- Hybrid integration is easy with TriPleX™ because of its native ability to adjust confinement for ideal coupling to other photonic materials.
- Hybrid integration enables "best-of-both-worlds" combinations of active and passive photonic materials to realize complex devices like a PIC-based tunable laser.

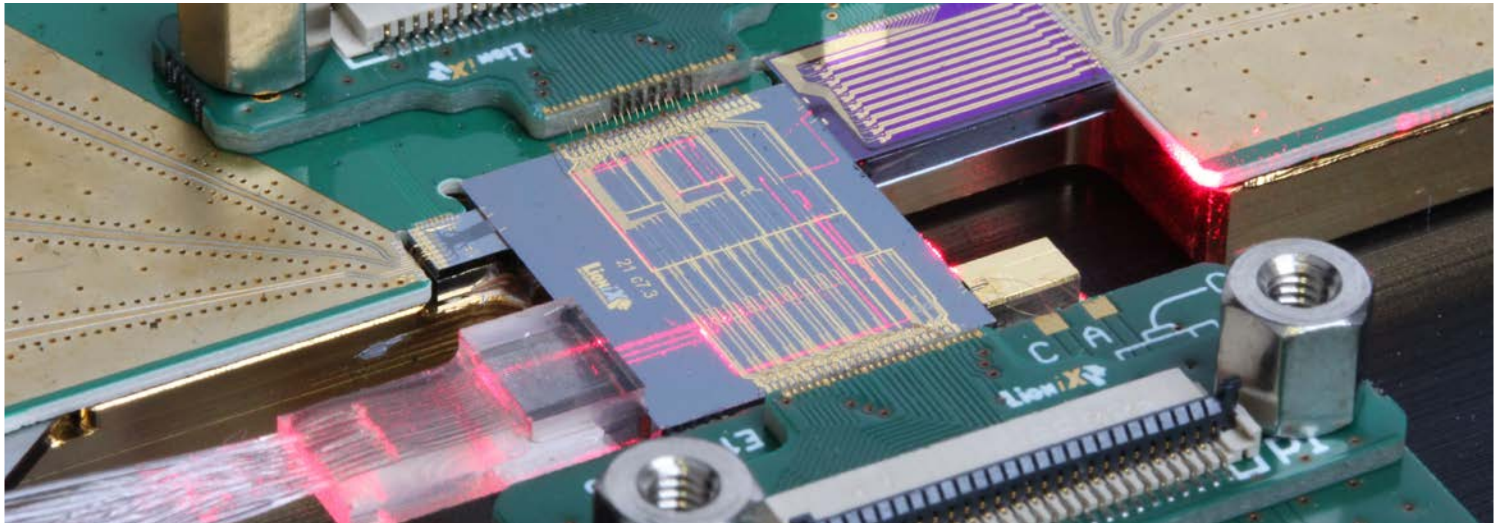
More added value with TriPleX™

Tunability for next generation applications

Tunable components take flexibility one step further to address the demands of next generation PIC-based technologies. In such applications a PIC-enabled device needs to perform not only within a given set of parameters, but should be capable of being tuned or even reconfigured in real time. This functionality makes for PICs with flexible performance. It is also valuable for devices that need to be very finely tuned after production – enabling even greater accuracy in meeting a performance specification.

Most excitingly perhaps, tunable PICs offer real-time reconfigurable performance. Applications include solid state steerable beam forming networks [2] for communications antennas or reconfigurable photonic or even quantum photonic processors (as realized recently by QuiX a Dutch quantum processor developer [3]).

This tuning and reconfiguration is done by integrating metal heaters above a waveguide, which, when activated alter the properties of the waveguide to affect light as it travels through. Such heaters suffer from low power efficiency and interference in operation with nearby neighbors, limiting how closely they can be spaced.



A hybrid integrated photonic beamforming module. The next generation piezoelectric tuning enables real-time solid state reconfiguration of the silicon nitride signal processing PIC.

LioniX International are addressing these constraints by developing next generation piezoelectric tuning for use with TriPleX™. **Not only are such switches able to reconfigure around at speeds around a thousand times faster** (in microseconds rather than milli-seconds) but they can be placed closer without interfering. This enables large arrays of low power tunable elements to be integrated on-chip, opening up a new world of capability. Most notably, LioniX International is developing networks of such low power tuners along with hybrid integrations of active lasers, modulators and detectors to build low power, steerable microwave transceivers for space based applications.

Packaging for purpose

For an integrated photonics platform to truly offer broad value and accessible technology, integration with wider systems is paramount. The optical and electrical interfaces as well as systems for thermal management and robust operation, all need to optimized.

This is not trivial, and even experienced chip designers often do not have the expertise and facilities to package and make use of their bare chips. This is where TriPleX™ again occupies an ideal niche. With its strengths in low loss interfacing with other components TriPleX™ already has the wherewithal to optimize for packaging and integration.

Section summary

- Elements on a PIC can be switched to modulate a signal in real time or tuned to refine performance beyond manufacturing limits.
- The TriPleX™ platform is especially suitable for use with tuners because of the flexibility it offers in light confinement.
- Next-generation piezo electric tuners in development at LioniX International offer a 1000X improvement in tuning speed with lower cross talk between elements.
- For users to access PIC technology, packaging solutions are required whereby chips can be packaged into usable modules. In this context TriPleX™ offers ease of interfacing and assembly.

Summary

The development of integrated photonics continues at pace. PIC designers are integrating more and more functionality into their devices, creating new functions and serving new applications.

As the breadth of technology powered by PICs increases, so does the need for more diverse PIC capability. This is unlikely to be supported by one material platform alone, given that each of the three prevailing platforms has its own particular strength. So the most exciting applications in integrated photonics will require integration of different platforms and interfaces.

LioniX International's TriPleX™ builds on the inherent strengths of silicon nitride as a waveguide material—low loss and broad transparency—using geometry that enables waveguide tapering. This opens up the scope for the hybrid integration, optimal interfacing and effective packaging solutions required in new applications.

TriPleX™ is also at the heart of next generation piezoelectric technology enabling real-time tuning. The powerful addition of configurability gives TriPleX™ a key role in high-performance applications such as space-based communications and quantum technology.

As PICs are more widely adopted and move towards standardization, silicon nitride has a vital role to play. TriPleX™, with its unique strengths, is helping to ensure this role is played to its fullest.

References

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