From Chip to Module: Silicon-Nitride for Visible Light

Douwe Geuzebroek; Arne Leinse; Ronald Dekker; Raimond Frentrop; Edwin Klein; Sadoon Al-Obaidi
LioniX International, Enschede, The Netherlands
d.h.geuzebroek@lionix-int.com

Abstract: Integrated photonics present an exciting opportunity to accelerate the development of optical devices via on-chip integration. The advantages of photonic integrated circuits include increased operational sensitivity, durability, and the opportunity to develop entirely new devices with unprecedented functionality. Silicon nitride circuits offer especially high-fidelity signal propagation and manipulation capabilities, with TriPleX® being a particularly powerful example. However, it is not enough to replicate optical functions on-chip without careful consideration of how the chip connects to other optical devices and electronics, and how it is protected from its operational by-products and the environment.

1. The Case for Integration

The advantage of on-chip integration of optical functions can be most readily grasped in the case of evanescent wave sensors. The design of such sensors can be simplified and made more robust using on-chip waveguides. PIC waveguide cladding composes the outermost layers of a photonic chip, which can be exposed directly to sensing media. Such a sensing window could host reversible polymer matrices for the capture of airborne species, thus relating changes in the refractive index of the polymer based on the airborne concentration [1]. Supramolecular compounds capable of the selective trapping of airborne molecules can also be used as cladding for such sensors [2]. Biosensors are particularly popular with evanescent wave sensing. By patterning microfluidic channels on top of waveguide cladding, absorption spectroscopy can be used to detect specific biomolecules in liquids. Visible light operation of such a biosensor means less light damage to many biomolecules which absorb infrared light while lowering its production cost due to the availability of visible light components [3].

Another example can be observed in flow cytometry, a microfluidic method used to characterize particles in a liquid flow as they pass a sensing window illuminated with a laser. By using a fast flow and a stable laser source, it is ensured that no more than one particle is characterized at a time. Integrated photonics are thus a suitable technology to provide a consistent laser beam using similar planar chips to the microfluidic counterparts. Fluorescent molecules are often attached to particles of interest for characterization in flow cytometry. To enable the excitation of different fluorescent labels, PIC-based multicolor laser engines (MLEs) are used, often to illuminate several spots with different wavelengths [4]. The beams need to be distanced and shaped with high accuracy to avoid spot overlap and cross-excitation. A PIC for flow cytometry MLE was designed on TriPleX® for the multiplexing and optical attenuation of four different illumination lasers [5]. The PIC handled light at 640 nm, 561 nm, 488 nm, and 405 nm.

Successful integration of optical functions for a particular application thus relies on a suitable waveguide platform and the design of its packaging and interfaces. The following sections will go over the photonic properties of TriPleX® and a few examples of visible light modules powered by it in different fields.

2. What Is TriPleX®?

While SiN is itself a waveguide platform, its use is limited by several material properties, such as its brittleness. TriPleX® is a multi-layer formulation of SiN, with silicon oxide (SiO) top and bottom layers as cladding [6]. Besides improving on the material properties of SiN, the multilayer oxide-nitride core allows for different waveguide layouts to be fabricated using similar processing steps. The simplest of these layouts is single-stripe geometry, where a single-mode SiN film of 50 nm thickness and 5.3 µm width can propagate 1550 nm light at 0.007 dB/cm loss. The bending radius of single-stripe waveguides is 2000 µm, which is significantly longer than the minimal 100 µm achievable in double-stripe geometries. A symmetric double-stripe, with two SiN films of the same thickness separated by a 500 nm SiO layer, can achieve 0.1 dB/cm propagation losses. An asymmetric double-stripe, with variable top SiN layer thickness and a 100 nm SiO middle layer, allows for easy coupling to fiber arrays and other PICs. Changing the thickness of the top SiN allows for fine control of the mode field size, which can also be used to transition from double-stripe to single-stripe waveguides and back. The combination allows for high

density, complicated designs to be produced on the same chips as long, low-loss sections. A box shell geometry, with a rectangular SiN border filled in with SiO, has reduced polarization dependence and high light confinement. All waveguide geometries except for the single stripe have high- and low-index contrast, with the former being better suited for high density designs and the latter being ideal for coupling light into and out of the PIC.
As a primarily passive platform, the standard building blocks available in TriPleX® range from routing blocks (straight and constant-radius bent waveguides), spot size converters (using vertical and lateral tapers), Y-junctions (for splitters, combiners, and couplers), thermo-optic phase modulators, and stress-optic actuators (using piezoelectric lead zirconate titanate). These can be combined and redesigned to form multi-mode interferometers, arrayed-waveguide gratings (AWGs), (asymmetric) MZIs, and other complex designs.

3. A Package Deal

Visible light presents a fundamental challenge to standard optical interconnection and hybrid integration techniques [7]. Techniques such as edge-coupling fiber arrays for light input and output are optimized for telecom applications working in the infrared spectrum. The lower wavelengths of visible light decrease the alignment tolerances of such coupling methods, and their higher energy densities make epoxies unfeasible. To couple visible light into a PIC, lens systems can be used focus light onto the input facet, as was done in the case of the four-wavelengths MLE chip [5]. Another approach is to combine grating couplers, which direct light out-of-plane of the PIC, with flip-chipping. This is best suited for adding small terminal components, whether they are detectors like photodiodes or light sources like VCSELs. To apply these strategies effectively, photonic circuit design must anticipate and include packaging and interfacing solutions. As each of these strategies are suited for different components, the application must be the starting point of the design. As the TriPleX® platform is widely suited for many applications, creative implementations of these strategies have produced modules with different functionalities.

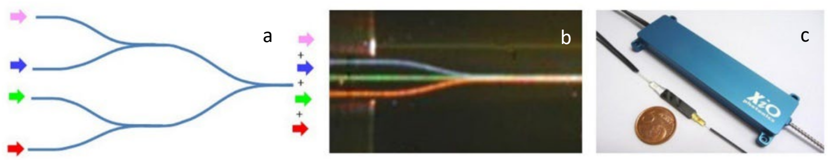

Figure 1. An integrated laser beam combiner. (a) shows a waveguide schematic illustrating its function. (b) shows the PIC in action. (c) shows the complete packaged module.

3.1. Integrated Laser Beam Combiner

Combining visible light inputs into a single output is a common use case in microscopy applications. It is also an excellent use of passive waveguides. A TriPleX® PIC was used to combine up to 8 visible wavelengths into one waveguide, which output the light into a polarization maintaining single-mode fiber. The PIC was composed of several of the aforementioned building blocks, including MZIs and AWGs. The broad transparency and ultra-low losses of TriPleX® meant that all target wavelengths were combined while maintaining signal fidelity.

3.2. Integrated Spectrometry

Point-of-care diagnostic devices are often limited by the number of components necessary to detect and analyze sample response. For spectral tissue sensing, a broadband light source is used to illuminate a tissue sample, which then scatters light at wavelengths characteristic of the tissue type and condition. A detection scheme which can simultaneously separate and identify the scattered wavelengths is thus required. An ultra-wide band spectrometer was integrated on TriPleX®, covering 400 nm to 1700 nm. Using filter AWGs, the scattered light was first separated into three bands: visible (400 nm to 700 nm, pictured in Fig. 2), near infrared (700 nm to 1000 nm), and short-wave infrared (1000 to 1700 nm). AWGs were used to divide each band into five narrower bands, and a

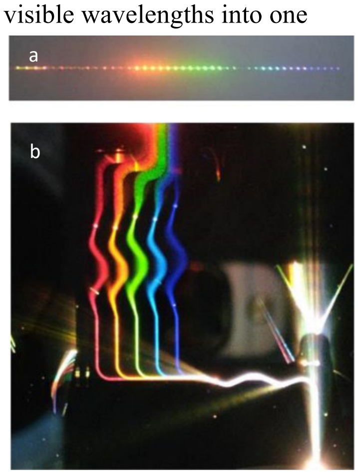

Figure 2. Cascaded AWGs for visible spectrum identification. (a) shows the end facet view, and (b) shows the top view.

second set of AWGs further divided the signal into 50 channels. This cascaded AWGs design thus performed analogue spectral analysis on the tissue response.

3.3. Variable Optical Attenuator

For many bioscience applications, high power lasers can damage or destroy the biological samples under investigation. At the same time, lasers are most thermally stable and produce the least noise when operated at >80% of their maximum output power. A TriPleX® PIC featuring a MZI was used to cause a laser's output to undergo destructive phase interference before illuminating a sample (Fig. 3). In combination with AWGs, light from a broadband source can be tuned to specific wavelengths and intensities for micro- and spectroscopic applications. By combining splitters with attenuators, the interference patterns can be adjusted according to user settings. The same PIC can use free-space output to produce precise visual patterns for machine vision applications, such as quality testing of manufactured surfaces.

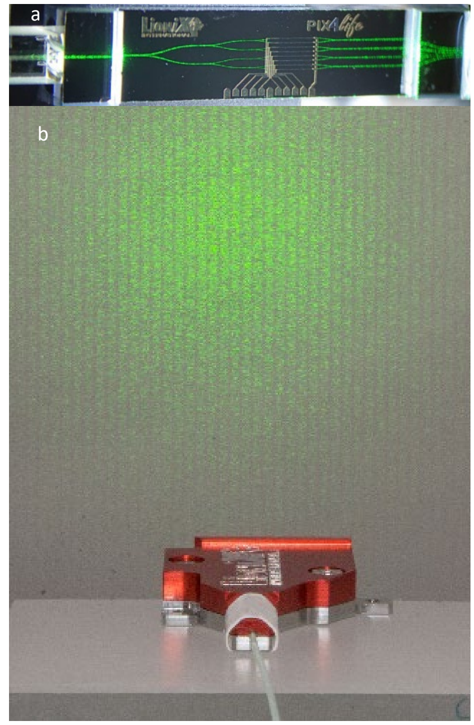

Figure 3. Variable optical attenuators in action. (a) shows the PIC with splitters and MZIs. (b) shows the packaged module projecting the light onto a screen.

3.4. Visible laser

Tunable lasers in the visible range are useful in biophotonic, metrology, and quantum applications. TriPleX®-based tunable external cavity lasers were first developed for 1550 nm, and demand for a visible light variant instigated work on one. As the TriPleX® platform is transparent for the visible spectrum, the primary challenge of producing visible light lasers was in finding an optical amplifier chip capable of visible light production. One such material is aluminum gallium indium phosphide (AlGaInP), which was coupled to the PIC where the laser is tuned [8]. Micro-ring resonators were used with straight waveguides to produce Vernier filters capable of producing high Q cavities, able to produce linewidths as narrow as 2.3 kHz. The light was coupled to an optical fiber at the output. Edge-coupling with a non-epoxy adhesive was used to assemble the components, with spot size converters implements leading up to the input and output facets. The laser produced was the first hybrid-integrated tunable diode laser in the visible range.

3.5. Quantum Ion Traps

Fine control of single and multiple ions are necessary for quantum processing. Classical optics face intrinsic difficulties in addressing quantum control due to beam drift, thermal vibrations, and airborne particles. Integrated photonics resolve these issues with on-chip waveguides. Novel ion traps have utilized TriPleX® PICs (Fig. 4) to deliver 729 nm light to trapped ions, enabling ground-state ion motion cooling [9]. The same PIC was used to create out-of-plane structured light for ion trapping by guiding the visible light into integrated grating couplers [10]. The PIC was wire-bonded and glued to a control PCB, while an optical fiber connects the light input to its input facet.

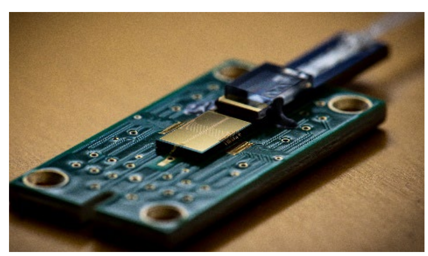

Figure 4. Quantum ion trap PIC assembled with a PCB and fiber optic input by ETH Zurich [9]. Reprinted with permission.

4. References

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