PLANAR LIGHTWAVE CIRCUITS FOR USE IN ADVANCED OPTICAL INSTRUMENTATION

AN ENABLENCE ARTICLE WRITTEN BY
DR. MATT PEARSON, VP TECHNOLOGY &
ASHOK BALAKRISHNAN, DIRECTOR OF PRODUCT DEVELOPMENT
PUBLISHED IN LASER FOCUS WORLD MAGAZINE

September, 2010

ABSTRACT

Optical instrumentation products have traditionally been built almost exclusively with bulk-optic components. More recently there has been an increasing need for miniaturization of these instruments, along with a further need for increased functionality. In the past several years, Planar Lightwave circuit (PLC) technology, originally developed for telecommunications, has been adapted for use in optical instrumentation products. These PLCs have been used mainly for passive optical elements, as a means of miniaturizing optical routing and filtering. But recent advances in PLC design, processing, and hybridization techniques allow for active elements such as lasers, detectors, phase shifters, and other key building blocks to be integrated directly on a PLC platform. This high level of integration presents a myriad of challenges in the design and fabrication of these optical circuits, but enables a wide range of new applications in advanced optical instrumentation. In this article we review some of the optical elements and photonic circuits that have been developed for use in biophotonic sensors, security applications, and other optical instrumentation applications, and some of the technical challenges that arise in the design and fabrication of these components.

Planar Lightwave Circuits (PLCs) integrate a number of optical elements onto a single optical circuit, significantly improving the size, cost, and functionality compared to more traditional optical assemblies. These optical chips are being used increasingly for optical instrumentation applications because of continuous improvements to performance, size, and complexity they afford. Optical instrumentation applications generally comprise equipment that include light sources, various optical elements to processes light signals, and detectors to receive light. Traditionally, these instruments have been made using bulk optics, and miniaturization and ruggedization have been extremely challenging. PLCs now present a paradigm shift to the way that these systems are designed and assembled.

One of the earliest uses of PLCs was for multiplexing and demultiplexing signals in telecommunications networks, where several signals are carried on different wavelengths. Arrayed waveguide grating devices slowly replaced bulk grating and filter devices as AWG performance specifications improved. Optical splitters shared many of the same size and cost advantages. However, from the 1980s to the early 2000s, this was primarily the extent to which PLCs replaced bulk optics. In fact, it was long assumed that multichannel applications were the only ones that could take full advantage of the size reductions provided by PLCs.

In the early 2000s, some applications arose, in spectroscopy and in fiber-to-the-home (FTTH), that started to break this assumption. For instance, FTTH chips that operated on only two channels had a revolutionary effect on how photonic chips were used in optical systems. In this case, the channels were each very broad, at 20 – 100 nm width, and operated bi-directionally in the same waveguide and optical fiber.

Densely-packed PLC chips were designed to handle these requirements, incorporating all the WDM functionality, lasers, detectors, and other optical elements, on a single chip. Despite the apparent simplicity of this application, PLCs still provided substantial cost and size reductions over their bulk counterparts, with hundreds or even thousands of devices fabricated on each silicon wafer.

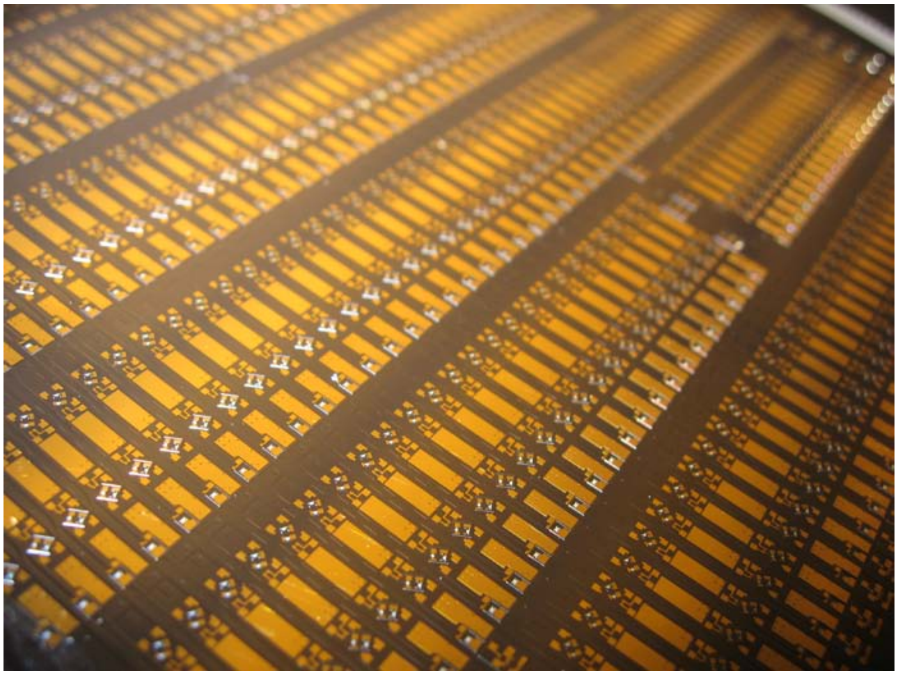

Fig. 1. PLC wafer containing hundreds of highly-integrated optical transceiver chips.

It is relatively easy to incorporate wavelength splitting and basic power splitting into PLCs. However, many more functions are required in a sophisticated optical instrumentation application. Over time, waveguide designers have developed many significant optical elements on PLCs, including NxM splitters that are virtually insensitive to wafer fabrication non-uniformities, ultra-low backreflection Fiber-to-Waveguide couplers, and other passive structures. Active functions are also crucial to every optical instrument. The hybridization of lasers began in the early days of FTTH, and has been perfected to achieve very good optical coupling even in high-volume processes. Lasers can now be passively coupled to PLC waveguides with coupling losses approaching 0.5 dB, entirely through computer vision and robotic die attach. No lenses and no active alignment are needed. Complex but highly reproducible photolithography and etching are already part of the PLC wafer process, and are leveraged to achieve high alignment accuracies for hybrid components.

In a PLC circuit, light is guided in a horizontal plane, confined by glass. Coupling this light to a detector has always been challenging. One makeshift approach to this problem is to butt-couple photodetectors to the edge of the PLC chip, where the light exits. While this approach works, it requires some active alignment, some issues in packaging, and leads to complications in the wirebonding to extract the photocurrent.

Robust mirror structures, etched into the PLC circuit itself, have been devised and fabricated which can redirect the guided light into the vertical direction. Standard surface-illuminated photodetectors can then be integrated onto the PLC over the mirrors. The top of the PD includes electrical pads to accommodate standard wirebonding. Avalanche photodetectors and p-i-n photodetectors can be hybridized to PLC chips this way, making it a very flexible platform, with collection efficiencies exceeding 96%, and yields close to 100%, again entirely through computer vision and robotic die attach.

Other application-specific functions, such as polarization beam-splitters and optical isolators, are also being implemented into a PLC environment. While the former can be done through careful process control, both can take advantage of the implementation of optical bench techniques onto PLC. Thus, the majority of functions necessary to construct any typical optical test instrument, in a very small form factor, is available from PLCs.

It is now relatively easy to incorporate any single function, or group functionality, into a small PLC chip. While form and function can be addressed simply, the concept of fit poses unique challenges when multiple functions are required on the same PLC. This is the case when all or much of an optical instrument is to be reproduced on a single optical chip. Each function imposes its own design constraints and processing requirements, and all of these issues must be simultaneously addressed in order for the full system-on-a-chip to work.

For instance, process-independent splitters achieve their independence by requiring precise waveguide geometries, stress-cancelling sacrificial features, and precise clearance from adjacent structures. Wavelength splitters require precise etch depth control, regardless of the etch requirements of other elements. Hybridization of active elements requires metallization, which in turn imposes a temperature budget, metal-to-silica wall clearances, alignment marks, and metal deposition thickness control.

The following figure shows an example of a PLC chip that meets this high level of complexity. The application is for an uncompressed video link for use in a number of specific military applications. One wavelength of light is created by the onboard DFB laser, seen in the top right of the chip, which modulates at up to 2.5 Gb/s to provide data and instructions to a remote module. There are two incoming light streams, at two unique wavelengths, each also operating at up to 2.5 Gb/s. Each incoming data stream provides data from different cameras. Detectors on the PLC demodulate this data into electronic pulses. In this figure, one can see the transimpedance amplifier that is placed close to a photodetector to reduce wirebond impedance. The chip contains a front facet monitor photodetector as well, to eliminate laser power drift with temperature. Note the lattice structure which is embedded throughout the optical layer, which defines areas where light is permitted to propagate within the chip. To create these optical structures in conjunction with laser and detector hybridization requires a tight link between optical layout, modeling, fabrication, and assembly.

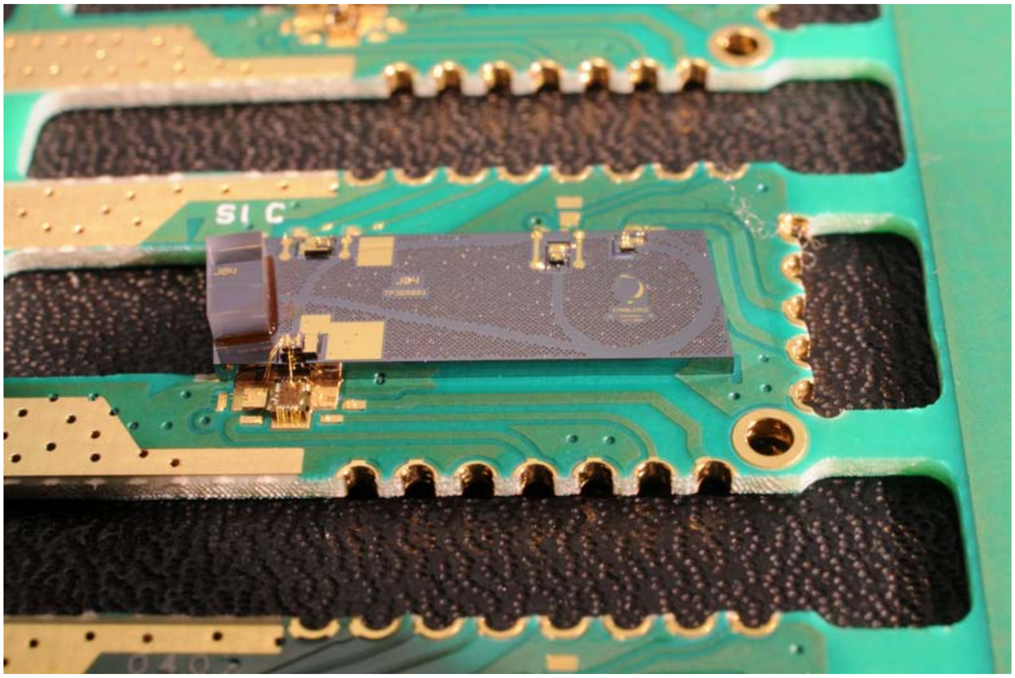

Fig. 2. A hybrid PLC chip for use in short-reach data links.

The next figure shows a PLC chip with a more classical waveguide design. The chip is designed for use in biophotonic application, and at a very high level contains four interferometers configured for polarization diverse detection. On the PLC itself, there are in fact 26 inputs/outputs, some of which are used bi-directionally. This chip contains a low percentage power tap, nearly 20 NxM power splitters, a polarization rotating element, and several test lines to monitor fabrication accuracy. Despite the high level of functionality, the chip is less than 9 x 20 mm in size. One can see the overall waveguide paths in the photo. The bends on each waveguide are carefully computed to reduce bend loss and polarization effects, while allowing optimum approach from one sub-function on the chip to the next. They are configured to ensure that waveguide crossings always happen at a reasonably large crossing angle. Compact routing is needed both to reduce the overall product size and to improve the on-chip uniformity. Minimum waveguide gaps are respected at all times to virtually eliminate crosstalk (to nearly -70 dB level depending on the guide). Because of its complexity, an automated computer optimization routine is needed to create the design and translate this design into a photolithography maskset.

Fig. 3. A optical circuit for use in a custom biophotonic application.

PLCs can also be used in other biophotonic applications. Biochemical reactions are often monitored with fluorescent tags, keyed to specific chemicals. The presence of an analyte is indicated by the strength of fluorescence at a specific wavelength. Silica is transmissive from the infrared to slightly beyond visible (0.3 to 2.0 microns). A PLC chip can provide the fiber coupled laser excitation source, and it can spectrographically isolate and detect fluorescence. Such applications have been slow to be adopted because of the large variety of applications, each of which uses different wavelength schemes. Standardization of these schemes will ease the adoption of PLC technology for biophotonics.

IN CONCLUSION

PLC technology has now matured to the point where complex optical instrumentation can be integrated onto a single system-on-chip. PLCs will continue to be used in the telecommunications domain where they have steadily grown in market reach. But recent advances in hybridization of active elements, driven mainly by the needs of telecommunications, have also been the driving force behind the adoption of PLCs into optical instrumentation. The ability to fabricate passive optical elements, from filters to polarization splitters, means that most problems can be tackled on-chip. Finally, sophisticated design algorithms are able to fluently incorporate these active and passive functions without any sacrifice to wafer fabrication. The coming years will see more use of PLCs in place of bulk-optic assemblies in optical instrumentation.

For more information
visit www.enablence.com