OPTICAL INTEGRATION THROUGH PLANAR LIGHTWAVE CIRCUITS

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ABSTRACT

In this article we review how Planar Lightwave Circuit (PLC) technology, originally developed for low-cost optical access products, is now being applied to other markets including advanced 40G/100G applications. Earlier applications in Fiber-to-the-Home utilized PLCs mainly for their lower cost and better manufacturability compared to bulk-optic alternatives. New applications have begun to rely exclusively on PLCs for delivering optical functionality that is not readily achievable in bulk-optics. At the core is a highly flexible PLC platform that allows precise phase control and the ability to integrate a myriad of active components on the optical chip. The advantages of this on-chip photonic integration are evident in the small size and unprecedented functionality that can be achieved through no other technology platform. We review the PLC platform itself, along with the manufacturing and performance advantages that arise from it.

In recent years, the development of Planar Lightwave Circuits (PLCs) was focused mainly on Fiber-to-the-Home applications, where small size and low cost were paramount. PLCs collapsed many optical elements onto a single optical chip, manufactured using processes comparable to those used in the fabrication of electronic integrated circuits, making them very well suited for this FTTH application. PLCs continue to play an important role in the FTTH market today. However, Planar Lightwave Circuits have evolved significantly in recent years, and in some cases now offer functionality that is often not even achievable in micro-optic assemblies.

Most recently, the interest in advanced 40G/100G networks has grown dramatically, and this presents a new opportunity for Planar Lightwave Circuits. In a significant departure from the FTTH application, in which PLCs were sought mainly for their low-cost and high-volume manufacturability, these new 40G/100G applications are looking to PLCs to deliver optical functionality that is not readily achievable using traditional bulk optics.

There are typically two ways in which 100G links are established: through the use of Dense Wavelength Division Multiplexing (DWDM), or through advanced modulation formats like Differential Quadrature Phase Shift Keying (DQPSK) and Polarization Multiplexed Quadrature Phase Shift Keying (PM-QPSK). These advanced modulation formats have revolutionized the way networks are designed, but present a number of challenges to system designers and optical component manufacturers alike.

DQPSK and other similar technologies present a means of transmitting 40G or even 100G optical signals along optical fiber, most of which was designed to support 10G traffic. To enable this, QPSK and similar techniques utilize phase modulation as a means of encoding data at extremely high bitrates. Optical demodulators work at the receiving end to decode these signals.

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Very precise phase delays and other subtle optical effects are utilized at each end of the 40G/100G optical link. Some of these effects can be extremely hard to control in traditional fiber-based optical components. Even relatively simple tasks, like splicing and connectorizing fibers, become complicated in these systems. For example, the 90^o optical hybrid demodulator in a PM-QPSK receiver can include eight separate fibers each coupled to its own detector. In order to control phases in such a receiver, it is necessary to splice or connectorize each fiber in a way that all fibers exiting the mixer are equal in length, with millimeter-scale precision. That means that if seven fibers are successfully completed and then the eighth fiber gets damaged and needs to be re-cleaved, all seven other splices must be broken and re-cleaved to match the new shorter length. This complicates assembly, and has a significant impact on yields and even the viability of this approach for large-scale deployment.

PLCs have a clear advantage in this application, since the waveguides that route light inside an optical chip are lithographically defined. This means that physical path lengths on the PLC itself can be controlled with nanometer precision. PLCs can also be hybridized with lasers and photodetectors that are mounted directly to the PLC itself, with micron or even sub-micron accuracy.

In addition to lithographically defined phase delays, PLCs also provide a means to integrate thermo-optic phase shifters throughout the optical chip. This allows for active phase control that can be adjusted as necessary, and monitored in real-time. This has proven to be a valuable building block for advanced 40G/100G components.

In addition to the phase shifting elements and other optical functionality embedded in the PLC itself, there is an equally important need for integrating active components with the PLC. These active components include things like lasers and photodetectors, along with transimpedance amplifiers and other electronic circuitry. In most cases these active components are hybridly integrated to the PLC, which allows PLC designers to utilize the best possible active components for their application, without compromising performance by trying to fabricate everything on a single wafer. This also simplifies PLC processing, and the use of multiple vendors helps minimize risk and lower costs through competition.

A wide array of PLC technology platforms were developed in order to address the low-cost, high-volume FTTH market, and that development continues today. However, it is clear that the most successful PLC platforms to date are those that include passive hybridization methods that do not require the lasers or detectors to be powered up and monitored during high-volume assembly. Such active alignment is much more complex and requires significantly more time and expense in assembly.

Passive integration of sub-components onto a PLC platform has evolved dramatically over the past five to 10 years. At one time it was considered nearly impossible to bond photodetectors to a PLC in a repeatable, high-volume assembly process. But more recent developments in PLC wafer fabrication, automated alignment systems, and component design have revolutionized the way optical components are manufactured. In addition to photodetectors, it is now also possible to align and bond high-performance lasers that require nearly 10 times the alignment accuracy of a photodetector, using processes capable of producing tens of thousands of units per month, or more.

The ability to passively integrate diode lasers to a PLC platform is a result of several innovations in wafer processing and optical design. In the past, only custom lasers were compatible with most PLC hybridization processes. This limited the number of vendors, and thereby affected the cost of these lasers. Recent advances have shown that standard diode lasers of virtually any type can be integrated onto a PLC platform through passive alignment. This approach uses a multi-core waveguide platform, in which light from hybrid lasers mounted on top of the PLC is collected by a series of specially formed waveguides, then coupled to more typical waveguide structures buried well below the surface of the chip. A primary focus during that development was on reducing backreflections within the PLC structure, which now allows nearly any type of laser to be hybridized to the PLC, even those that are highly sensitive to backreflections. Distributed feedback (DFB) lasers, and even new externally modulated lasers (EMLs), can potentially be bonded in very high-volume processes, enabling significant advances in the way long-haul optical components for 40G/100G networks are manufactured.

Most laser diodes used in telecommunications rely on thermal tuning to ensure the laser wavelength remains on the correct ITU grid. In a bulk-optic approach this is normally accomplished by packaging every laser in its own separate package, which includes a thermo-electric heater/cooler to maintain the proper temperature. In PLCs we often want to add significantly more functionality into a much smaller package, and it is not uncommon for a single PLC chip to contain four, eight, 12, or even more lasers integrated to a single PLC chip. Each laser must be thermally tuned to the correct grid, and it is impossible to accomplish that with a single large heater/cooler under the PLC substrate. Instead, the same technology used to manufacture thermo-optic phase shifters in PLCs can now be leveraged to make miniature heater elements on the surface of the PLC. These small, localized heating elements can be included under each hybrid laser, and are all individually addressable, allowing each laser to be thermally tuned to the ITU grid. This is but one example demonstrating how PLCs incorporate not just optical elements, but also thermal, mechanical, and electrical integration as well.

At the opposite end of the link, high-speed photodetectors can be bonded directly to the PLC surface, creating receiver modules ideally suited for use in high-bandwidth 40G/100G applications. While waveguide-based photodetectors can be used if needed, standard surface-illuminated photodetectors sometimes offer more simplicity, lower cost, and in some cases even higher performance. In order to couple light from the PLC waveguide to the surface-mounted photodetector, it is necessary to bounce the light 90^o from horizontal to vertical. This is accomplished through on-chip mirrors that are fabricated in the PLC itself as part of the wafer manufacturing process.

Like their electronic counterparts, Planar Lightwave Circuits can be designed with impedance matched electrical traces, which are used to interface detectors with TIAs and package feedthroughs. This provides the most optimal high-bandwidth electrical performance available, clearly an important consideration for 40G/100G components that are running at extremely high data rates.

PLCs have at times been mistakenly viewed as nothing more than a means to manufacturing low-cost optics. In actuality, PLCs now offer performance that is sometimes not viable in bulk-optic assemblies, and integrate thermal, mechanical, and electrical innovations, in addition to the underlying optics. As 40G/100G network requirements continue to evolve, so will the demands for increased functionality from optical components. PLCs provide a clear path for integrating that functionality onto a single PLC platform that is suitable for high-volume assembly.

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