Enabling advanced photonic architectures using state-of-the-art silica-on-silicon planar lightwave circuit platform

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ABSTRACT

We present advanced photonic architectures based on a state-of-the-art silica-on-silicon planar lightwave circuit (PLC) platform. The industry-leading performance characteristics of the platform with respect to fiber coupling, propagation losses, and polarization control have led to its mass deployments in telecom and datacom applications. Recently, a broad range of architectures has emerged that take advantage of the unmatched phase control in silica-on-silicon PLCs for demanding applications. We review some exceptional capabilities of our PLC platform and discuss how ultra-low propagation loss of <0.009 dB/cm is achieved concurrently with polarization-insensitive operation with relatively high confinement that allows loss-free waveguide bends with a 1 mm radius of curvature. Combined with fiber-matched mode converters and temperature-stable operation (< 10 pm/°C), consistent performance is achieved across entire optical communication bands. End-to-end optimizations allow us to reach high performance in advanced optical building blocks such as cascaded lattice filters, polarization-beam splitters, arrayed waveguide gratings (AWGs), and coherent systems. The robustness and versatility of the platform are demonstrated by a survey of mature designs that encompass multiple classes of applications. We discuss multi-channel (de-)multiplexer designs that address the challenging requirements of today's datacom and telecom deployments, the realization of 10+ meter long delay lines and K-clocks, the utilization of the platform in optical coherence tomography (OCT) systems, and PLC-based solutions for automotive manufacturers of LiDAR systems. Finally, we discuss how our design, manufacturing, and testing processes are controlled with machine learning, allowing in-situ monitoring of wafer fabrication, real-time process adjustments, and wafer-level predictions of device performance across a wide range of performance metrics.

Keywords: LiDAR, OCT, k-clock, delay lines, planar lightwave circuit, silica-on-silicon, integrated optics, machine learning

1. INTRODUCTION

Integrated photonics has emerged as a key technology to enable advancements in high-speed communication and advanced vision systems.[1,2] Among the different integrated platforms, silica-on-silicon planar lightwave circuit (PLC) technology stands out as a versatile and low-cost platform with powerful characteristics, including ultra-low propagation losses, efficient fiber coupling, unmatched polarization and phase control, excellent reliability and standard fabrication processes. These characteristics enable silica-on-silicon PLCs to reach widespread applications ranging from medical imaging to autonomous driving to environmental sensing.

In this paper, we review in detail the key performance characteristics of our silica-on-silicon PLC platform. We then describe a range of design capabilities and their performance as realized within the platform, and demonstrate important optical building blocks that are necessary for today's emerging applications. We conclude by describing our use of machine learning (ML) to control our design, manufacturing and testing processes as a powerful tool to extend the capabilities of the platform.

2. SILICA-ON-SILICON PLC PLATFORM

Our PLC platform utilizes buried silica-based waveguides with typical dimensions of 3.0×3.0 μm and a relatively low refractive index contrast of $\Delta n = 2.0\%$. The fabrication is done using standard atmospheric pressure chemical-vapor deposition (APCVD) and reactive ion etching processes.

End-to-end optimization of our process and design parameters allow us to achieve exceptional performance capabilities of fabricated devices. Previously reported results demonstrated 10-meter long spirals[3] with worse-case propagation

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losses of 0.01 dB/cm. Through further optimizations, we are able to achieve propagation losses of 0.009 dB/cm or better, with negligible polarization-dependent loss and wavelength-independent operation. Combined with fiber-matched mode converters (0.5 dB per facet) and temperature-stable operation (< 10 pm/°C), consistent performance is achieved across entire optical communication bands.

Progress in architectural solutions that allow densification of photonic functionality allows us to achieve ultra-compact devices despite the relatively low refractive index contrast (and thus the limitation on the waveguide radius of curvature to about 1 mm). Our previous work on scalable architectures that allow compact arrangement of arbitrarily-long interferometric structures demonstrated state-of-the-art optical performance characteristics of multiplexers for coarse-wavelength division multiplexing (CWDM) and LAN-WDM applications.[4,5] Comprehensive optimizations of our process and design parameters allow us to realize a wide variety of passive devices including arrayed waveguide grating (AWG) designs, coherent systems, and cascaded lattice filters. In addition to their high optical performance characteristics, the designs have proven to be remarkably robust in volume manufacturing, resulting in their large-scale deployments in commercial applications.

3. HIGH PERFORMANCE OPTICAL BUILDING BLOCKS

Polarization beam splitters (PBSs) are key building blocks in coherent communication systems. Among numerous applications in telecommunications, PBSs have enabled some of the most spectrally efficient fiber-optic communication systems, such as polarization multiplexed quadrature phase shift keying (PM-DQPSK).[6] Most recently, PLC-based PBSs have emerged as the key building block in advanced vision systems, such as time-of-flight (ToF) and frequency-modulated continuous-wave (FMCW) LiDARs. These systems typically contain from several to a few dozens of PBSs, requiring highly integrated chip-based solutions to make them practical.

Silica-on-silicon PLCs provide an ideal platform for realizing polarization control on a chip. We have specifically focused on the development of PLC-based PBSs with minimal wavelength dependence. While many different PBS architectures have been explored,[7,8] we have chosen an architecture that comprises a pair of Hermitian-conjugated multi-section couplers interjected with a birefringent region formed by lithographically varying the waveguide width. We applied our end-to-end optimization technique to simultaneously achieve wavelength-independent couplers, a π-difference between the two polarizations in the birefringent region, and phase error-cancelling performance. A typical transmission spectrum of such a PBS is shown in Figure 1, where isolation of more than 22 dB has been achieved in the entire measurement range of 1510-1575 nm (and possibly beyond). The use of these arrayed PBSs has dramatically improved the range of LiDAR systems by means of crosstalk suppression and added selectivity with respect to depolarized scattering.

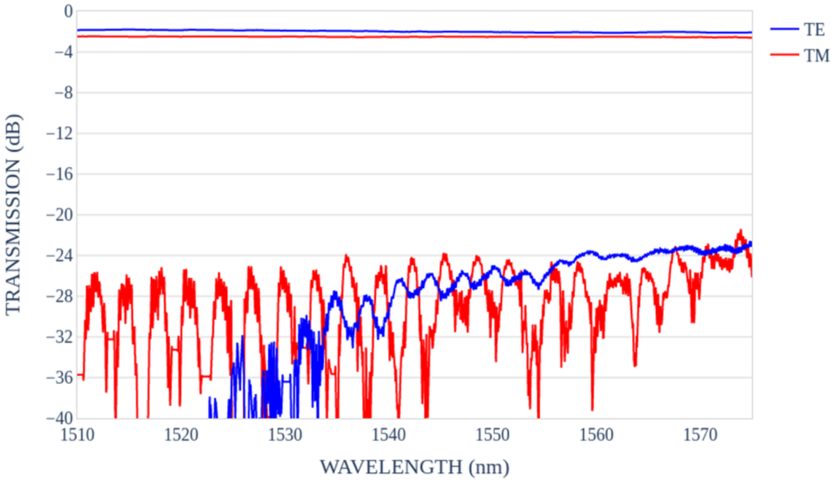

Figure 1. Typical transmission spectrum of a polarization beam splitter, achieving more than 22 dB isolation in the entire measurement range of 1510-1575 nm. The transmission losses include coupling to both input and output fibers.

The low propagation losses and tight polarization control possible in silica-on-silicon PLCs make them also a highly suitable platform for optical coherence tomography (OCT) applications.[9,10] The reference signal is optically delayed on the chip to match the round trip pathlength to the studied object, creating interference between the reference and the sample signals. Digital processing of the interference signal allows high-resolution, real-time and in-situ imaging of tissue microstructure in a non-invasive manner.

Both OCT and LiDAR systems measure the signal in the momentum (k)-space, which is linear to the change in optical frequency of the swept source. We leverage the advantages of the PLC platform to realize variable free spectral range k-clocks, whose frequency is inversely proportional to the length of the delay line in a Mach-Zehnder interferometer. The sampled output provides a highly linear optical frequency fiducial marker.[11] The extremely low propagation losses of the PLC platform allow for a wide range of k-clocks to be easily manufactured, from 10 GHz k-clocks typically used in OCT systems to 10 MHz k-clocks used in LiDAR. Figure 2 shows design examples of k-clocks with vastly different frequency responses.

(a) (b)

Figure 2. Examples of k-clock systems based on delay lines and interferometers for (a) GHz frequency systems, and (b) MHz frequency systems. The compact form factor allows for a wide range of customized k-clocks to be realized in PLCs within a small footprint.

4. MACHINE LEARNING IN PLC DESIGN AND MANUFACTURING

In order to achieve highly homogenous performance among fabricated devices, both within a wafer and among different batches of wafers, we utilize machine learning (ML) algorithms. To handle systematic variability within a wafer, we deploy a multivariate regression model to optimize the design parameters of individual devices on a production mask. We use deep learning to study the measured variations in the performance of individual chips, and then predict the design adjustments required to compensate for such variability in the design of an enhanced mask.[12] The optimization of the design parameters based on the predictions of the trained model allows us to achieve consistently high performance over hundreds of optical devices fabricated on a single wafer.

To address process variations between fabricated wafers, we have developed a new technology that collects position-related metrology data from a wafer and uses a support vector machine (SVM) to predict the performance of hundreds of chips on the wafer, without requiring the wafer to be diced. This approach is a powerful alternative to the labor-intensive task of optical chip testing, and allows an unprecedented control over the fabrication process, including in-situ monitoring of wafer production and real-time process adjustments. The combination of the two ML approaches allows us to achieve consistently high-yield production of PLCs in large-scale deployments.

5. CONCLUSIONS

Silica-on-silicon PLCs have grown into a mature platform with diverse designs that encompass multiple classes of applications. End-to-end optimizations of our process and design parameters allow us to achieve exceptional performance capabilities within the platform, including ultra-low propagation losses, efficient fiber coupling, temperature stability, and unmatched polarization and phase control. When combined with our use of machine learning to optimize the design parameter space and wafer-level predictions of device performance, we are able to achieve an unprecedented performance homogeneity in a high-volume production environment. Advancements in the design of integrated polarization beam splitters and variable frequency k-clocks pave the way for the utilization of the silica-on-silicon platform in OCT and LiDAR applications.

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