On-chip Microwave Photonic Signal Processors in Low-Loss, High-Index-Contrast Si_3N_4/SiO_2 Waveguides

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***Abstract*—This paper gives a brief review of several world-first on-chip microwave photonic (MWP) signal processing functionalities which have been enabled by Si_3N_4/SiO_2 TriPleX^{TM} planar waveguide technology. The realized devices demonstrate that the on-chip solution for MWP signal processing has the capability of providing various functionalities in compact form and low manufacturing cost. This promises the future prevailingness of its implementation for practical MWP applications.**

Keywords-microwave photonic signal processing, on-chip, low-loss, high-index-contrast, Si_3N_4/SiO_2, photonic integrated circuit

I. INTRODUCTION

Microwave photonic signal processing leverages the small size, weight and power consumption, low propagation loss, and large instantaneous bandwidth of optics to realize high-frequency (microwave/millimeter wave) RF systems. Therefore, MWP signal processing systems have the potential to feature functionality and performance better or in excess to the capability of conventional electrical RF systems. Motivated by this promise, many dedicated investigations have been conducted in the past few decades to realize functionalities such as RF filtering, amplitude and phase manipulation, and beamforming [1]. Despite these appealing functionalities, conventional MWP signal processing systems constructed using discrete optical components usually suffer from the lack of robustness and cost efficiency that hinder their wide deployment for practical applications. Evident from the recent efforts [2], on-chip MWP signal processor will be the key to solve this problem. This requires photonic integrated circuits (PICs) implementation of the desired functionalities and a waveguide technology that provides low propagation loss, low chip-interface coupling loss, small bend radius and CMOS-comparable fabrication cost efficiency. We believe that the TriPleX^{TM} waveguide technology is well suited for the on-chip MWP processing. In this paper, we give a brief review of several on-chip MWP signal processing functionalities which have been realized in this CMOS-process-equipment compatible, low-loss, high-index-contrast Si_3N_4/SiO_2 planar waveguide technology. The advantageous feature of this waveguide technology is the very low propagation loss of 0.1 dB/cm at a small bend radius of 70 μm [3]. The waveguide technology is described in Section II. In Section III some examples of the on-chip MWP signal processing using TriPleX^{TM} technology are presented.

II. WAVEGUIDE TECHNOLOGY

The optical waveguide consists of two stripes of Si_3N_4 with a thickness of 140 nm stacked on top of each other with SiO_2 as an intermediate layer of 500 nm thickness and cladding material. A scanning electron microscope (SEM) image of the waveguide cross section is shown in Fig. 1a. The use of this double-stripe geometry increases the effective index of the optical mode as compared to the single-stripe geometry, thus increasing the confinement of the mode and thereby reducing the bend loss. The widths of the stripes have been optimized to result in a well confined mode and the waveguide only supports a single (TE) mode at a wavelength of 1550 nm. The propagation loss characterization of this waveguide is shown in Fig. 1b. A very low propagation loss of 0.1 dB/cm is achieved simultaneously with a small bend radius of 70 μm, which are the key factors to enable on-chip MWP signal processing and compact form for practical applications. Moreover, good fabrication uniformity is also evident from the measurement results.

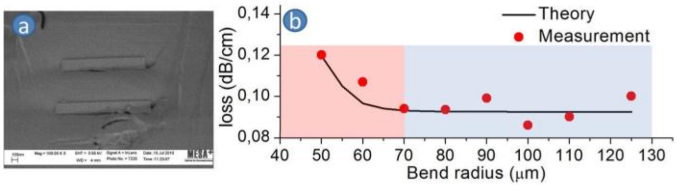

Fig.1. Measured waveguide propagation loss for various bend radii (inset: a SEM image of the double-stripe waveguide)

III. ON-CHIP IMPLEMENTATION OF MWP FUNCTIONALITY

A. *Optical beamformer*

As the most complex on-chip MWP signal processor to date, an optical ring resonator (ORR)-based 16 × 1 true-time-delay beamformer chip has been realized in TriPleX^{TM} technology. The beamformer chip is used to steer the beam direction of a phased array antenna system for mobile satellite communication applications [4]. For such an application, the photonic chip should be capable of delaying a wideband RF signal (with a bandwidth in excess of 4 GHz) in a programmable manner. The required maximum delay in this

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case is 290 ps. Since the delay is implemented using cascaded resonators, larger delay means higher losses for the signals. For this reason the propagation loss in the optical waveguides should be minimized. The maximum tolerable on-chip propagation loss in this case is 0.2 dB/cm [4]. The beamformer chip that fulfills these requirements is shown in Fig. 2. It consists of a 16 × 1 binary-tree combing circuit inserted symmetrically with a total of 40 ORRs delay elements, an optical sideband filter (OSBF) consisting of an asymmetric MZI with an ORR in each arm (for filter-based single-sideband suppressed-carrier modulation), and a dedicated coupling section for optical carrier-reinsertion operation. Thanks to the small bend radius of the waveguide, the complete footprint of the chip measures 0.7 × 2.2 cm. The chip is programmable using thermo-optical tuning scheme. The first successful antenna pattern demonstration of broadband squint-free beam steering using such an optical beamformer chip has been reported in [5].

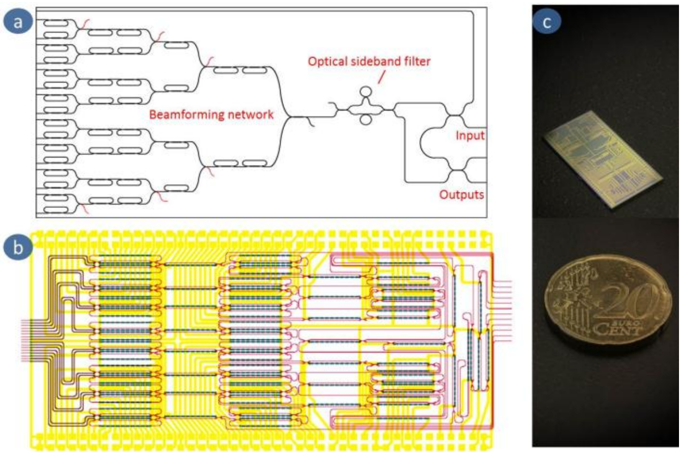

Fig.2. (a) beamformer architecture, (b) chip mask layout, and (c) a photo of fabricated beamformer chip.

B. *Separate optical carrier phase tuning*

In addition to the use as true-time delay lines, the ORRs of the beamformer can also perform separate carrier tuning (SCT). Hence, a single delay line using a cascade of multiple ORRs can separately and independently control the group delay over the sideband and the carrier phase shift of an optical single-sideband full-carrier (OSSB-FC) modulated signal. This is an essential functionality in several MWP signal processing systems which require true time delay and SCT. As a result, this ORR-based solution allows the realization of on-chip MWP signal processing such as multi-tap microwave photonic filters and beamformers using OSSB-FC modulation. The first demonstration of this on-chip functionality has been reported in [6]. The demonstrator circuit uses the same building blocks as in the beamformer chip, which consists of a cascade of a 2-ORR delay line, a 2-ORR carrier tuner, and an OSBF.

C. *Photonic chip frequency discriminator*

Another enabling MWP functionality that has been realized using TriPleX^{TM} technology is PM/IM conversion. By properly arranging multiple stages of add-drop ORRs, the world-first on-chip MWP frequency discriminator has been realized [7], as shown in Fig. 3. This discriminator enables various functionalities like high performance microwave photonic link and ultrawideband pulse shaping. Using this chip, a high performance phase-modulated microwave photonic link has been demonstrated [7], which exhibits a high spurious-free dynamic range (SFDR) of 113 dB·Hz$^{2/3}$. Furthermore, the chip has also been implemented for the world's first on-chip impulse-radio ultrawide-band (IR-UWB) pulse shaper [8]. With full programmability, the chip is capable of generating wideband RF pulses with high complexities. This opens up the path to the realization of low cost and compact UWB transmitters.

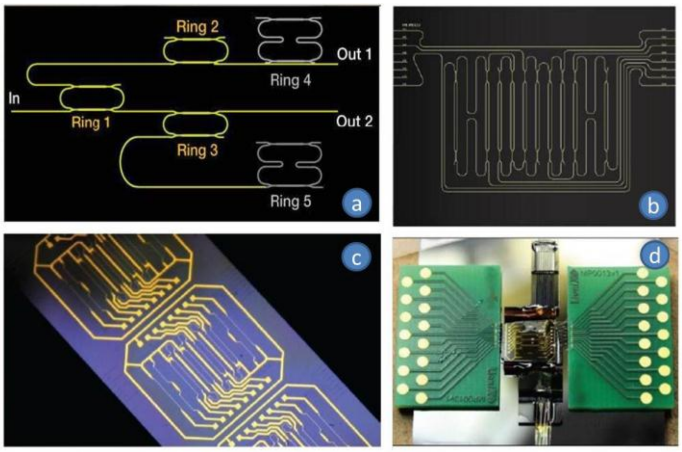

Fig.3. (a) architecture, (b) chip mask layout, (c) bare chip, and (b) packaged chip of frequency discriminator.

IV. CONCLUSION

Several integrated MWP signal processing devices enabled by a low-loss, high-index-contrast Si_3N_4/SiO_2 waveguide technology has been presented. These demonstrations emphasize the important role of PICs for the future of microwave photonics.

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