Low-loss, high-index-contrast Si$_3$N$_4$/SiO$_2$ optical waveguides for optical delay lines in microwave photonics signal processing

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Abstract: We report the design and characterization of Si$_3$N$_4$/SiO$_2$ optical waveguides which are specifically developed for optical delay lines in microwave photonics (MWP) signal processing applications. The waveguide structure consists of a stack of two Si$_3$N$_4$ stripes and SiO$_2$ as an intermediate layer. Characterization of the waveguide propagation loss was performed in race track-shaped optical ring resonators (ORRs) with a free-spectral range of 20 GHz and a bending radius varied from 50 μm to 125 μm. A waveguide propagation loss as low as 0.095 dB/cm was measured in the ORRs with bend radii ≥ 70 μm. Using the waveguide technology two types of RF-modulated optical sideband filters with high sideband suppression and small transition band consisting of a Mach-Zehnder interferometer and ORRs are also demonstrated. These results demonstrate the potential of the waveguide technology to be applied to construct compact on-chip MWP signal processors.

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1. Introduction

Microwave photonics (MWP) signal processing techniques have gained a lot of attention in the last few years [1–4]. Various functionalities such as RF filtering [5–7], beamforming [8–11], differentiation [12], integration [13] and pulse shaping [14] have been demonstrated recently. As a part of these functionalities, the use of optical delay lines is virtually ubiquitous. A host of optical components and systems have been considered as the optical delay lines, such as optical fibers and fiber-Bragg gratings to name a few. However, as evident from the works reported in [5–14], the use of optical delay lines in an integrated photonic chip solution has recently been shown more and more. Such integrated photonic delay lines using optical waveguides are very attractive in terms of weight, compactness and cost, especially for CMOS-process compatible waveguide technologies. However, a potential drawback of these optical waveguides for RF signal processing is the high insertion loss. This is due to the fact that a linear increase in the optical loss is often manifested as a quadratic increase in the loss of the RF signal being processed. Although the use of waveguide tapers can effectively minimize the loss contribution from the light coupling interfaces of the chip to...
a negligible level, waveguide propagation loss may still give rise to a high chip insertion loss. In particular, narrowband RF filtering and beamforming for large-size phased array antennas may require optical delay path lengths of tens of centimeter or more. This will result in a low link-gain of the MWP signal processor if there is a significant waveguide propagation loss. A way to increase the link gain is to incorporate active functionality in the processor (for example semiconductor optical amplifiers [7]) but this will lead to an increase of the noise figure of the MWP signal processor. Thus, there is an imminent need for an optical waveguide technology that can provide compact optical delay lines with low propagation loss.

Low-loss optical waveguides and their characterization techniques have been widely reported [15–18]. Extremely low propagation loss in the figure of sub 1 dB/m have been reported in [17,19] but this has been shown in optical waveguides with very low refractive index contrast (<1%). Such a low contrast will lead to a large minimum bending radius and subsequently a large footprint of a photonic chip with moderate to high complexities. On the other hand, high-index-contrast optical waveguide in silicon-on-insulator (SOI) or InP technologies have shown their applications with very low bending radii (<30 µm [20,21]), however, these are accompanied by high waveguide losses (>1 dB/cm [20,21]). The low-loss waveguides in these technologies have also been greatly investigated and realized (in the order of 0.3 dB/cm [22,23]), an example of which has demonstrated a small bend radius as well (down to 50 µm [22]). In this paper, we investigate the performance of an optical waveguide structure fabricated in the TriPleX technology [24]. Very recently an optical waveguide of this technology has been shown to have a propagation loss as low as 8-9 dB/m at a bending radius of 0.5 mm [25]. It was predicted that a loss of 0.17 dB/cm can be achieved if the bending radius is reduced to 200 µm. This was shown with a single stripe of Si$_3$N$_4$ waveguide with SiO$_2$ cladding. Such a structure allows only a low mode confinement. In this work, we characterize a novel optical waveguide structure with two stripes of Si$_3$N$_4$, thereby increasing the mode confinement significantly and allowing low propagation loss at even smaller bend radii. The rest of this paper is organized as follows: in Section 2, the optical waveguide properties are described. The method to characterize the propagation loss of the optical waveguides using the optical ring resonators (ORRs) are presented in Section 3. In Section 4, the characterization of two structures of RF-modulated optical sideband filters fabricated using the optical waveguide technology are presented. In the final section the potential of constructing a high complexity MWP processor like an optical beamformer using the novel technology is discussed. The paper closes with conclusions.

2. Waveguide properties

2.1 Waveguide geometry

The optical waveguide consists of two strips of Si$_3$N$_4$ stacked on top of each other with SiO$_2$ as an intermediate layer and cladding material which have been produced using TriPleX technology. A scanning electron microscope (SEM) image of the waveguide cross section is shown in Fig. 1. The use of this two-strip geometry increases the effective index of the optical mode as compared to a single strip geometry, thus increasing the confinement of the mode and thereby reducing the bend loss. The width of the strips is designed to be 1.5 µm, and the thicknesses of the Si$_3$N$_4$ layers and the SiO$_2$ intermediate layer are designed to be 170 nm and 500 nm, respectively. This is optimized to result in a high effective index of the mode while the waveguide only supports a single mode at a wavelength of 1550 nm. Besides, this waveguide geometry design was also chosen in order to match TriPleX production standards which increase device reproducibility. The waveguide geometry supports a single mode of TE and TM polarized light. Due to a birefringence of about 0.053, the TM mode is much less confined and, therefore, experiences much more loss in bend sections as compared to the TE mode. Hence, in the following discussions of this paper, only TE polarized light is considered.
2.2 ORR device layout

To characterize the propagation loss of the waveguide, race track-shaped ORR test structures have been fabricated which have a waveguide width of 1.5 µm, a group index of 1.72, a circumference of 8783 µm, and bending radii varying from 50 µm to 125 µm. The resulting free spectral range (FSR) of the ORR is 20 GHz. The light is coupled into and out of the ring path through an Mach-Zehnder interferometer (MZI)-based power coupler. A schematic of the waveguide architecture of an ORR is depicted in Fig. 2a. Furthermore, the device is realized with full programmability by means of thermo-optic tuning mechanism. As depicted in Fig. 2b, two heaters are placed on top of two waveguide sections of the ORR: the upper one controls an additional round-trip phase shift of the ring path; the lower one controls the power coupling ratio of the MZI. To ensure sufficient tuning range of the power coupling ratio, two directional couplers in the MZI are carefully designed to approximate the desired −3 dB power coupling ratio such that the MZI reaches a power extinction ratio larger than 15 dB.

3. Waveguide propagation loss characterization

The working principle of ORR-based delay lines has been elaborated in [9,26]. The general transfer function $H(\Omega)$ of an ORR and its frequency responses in terms of power transmission $P(\Omega)$ in dB and number of effective delay round-trips $\tau(\Omega)$ are given by

$$H(\Omega) = \frac{\sqrt{1-\kappa} - r e^{i(\Omega + \phi)}}{1 - \sqrt{1-\kappa} r e^{i(\Omega + \phi)}}$$  

(1)

$$P(\Omega)_{\text{db}} = L(\Omega)_{\text{db}} = 10 \log_{10} \left( \frac{1 - \kappa + r^2 - 2r\sqrt{1-\kappa}\cos(\Omega + \phi)}{1 + r^2(1-\kappa) - 2r\sqrt{1-\kappa}\cos(\Omega + \phi)} \right)$$  

(2)

and

$$\tau(\Omega) = \frac{T(\Omega)}{T_R} = \frac{r\sqrt{1-\kappa}\cos(\Omega + \phi) - r^2\sqrt{1-\kappa}}{1 - 2r\sqrt{1-\kappa}\cos(\Omega + \phi) + r^2\sqrt{1-\kappa} + 1 - \kappa - 2r\sqrt{1-\kappa}\cos(\Omega + \phi) + r^2}$$  

(3)
respectively, where $\Omega = 2\pi f / \Delta f_{\text{FSR}}$ is the angular frequency of the light normalized to the free spectral range (FSR) of the ORR, $\kappa$ is the power coupling coefficient, $\phi$ is the additional round-trip phase shift, $L(\Omega) = -P(\Omega)$ in dB signifies the power loss of the ORR, $T(\Omega)$ indicates the effective time delay (group delay), $T_R$ is the characteristic round-trip time delay of the ORR, and $r$ is defined as the round-trip amplitude transmission coefficient which is determined by the waveguide propagation loss $L_{\text{wg}}$ in dB/cm, and the circumference of the ring path $C_r$ in cm, as in the following equation:

$$r = 10^{-\left(\frac{L_{\text{wg}} C_r}{20}\right)}$$  \hspace{1cm} (4)

Furthermore, $T_R$ equals the reciprocal of $\Delta f_{\text{FSR}}$ and is determined by the circumference of the ring path $C_r$, the group index of the waveguide $n_g$, and the speed of the light in vacuum $c_0$ as in the equation:

$$T_R = \frac{1}{\Delta f_{\text{FSR}}} = \frac{C_r n_g}{c_0}$$ \hspace{1cm} (5)

Knowing the working principle of an ORR and using the close approximation of a linear relation of power loss $L(\Omega)$ to effective delay path length $D(\Omega) = C_r r(\Omega)$ for low round-trip loss scenario ($L_{\text{wg}}, C_r < 0.5$ dB) [26], one can retrieve the waveguide propagation loss $L_{\text{wg}}$ from a given pair of $P(\Omega)$ and $r(\Omega)$ by applying the equation

$$L_{\text{wg}} = \frac{dL(\Omega)}{dD(\Omega)} = \frac{-dP(\Omega)}{C_r \Delta r(\Omega)} = \frac{-\Delta P_{\text{on-off}}}{C_r \Delta r_{\text{on-off}}} \quad (\kappa_c < \kappa < 1)$$ \hspace{1cm} (6)

where “on” and “off” indicate the on-resonance frequency ($\Omega + \phi = 2n\pi$, $n$ is integer) and the off-resonance frequency ($\Omega + \phi = 2n\pi \pm \pi$) of the ORR, respectively; the condition $\kappa_c$ (critical coupling coefficient) $< \kappa < 1$ ensures the resonance enhancement effect in the ORR, which is characterized by a delay maximum/power transmission minimum at the on-resonance frequencies and a delay minimum/power transmission maximum at the off-resonance frequencies [9,26]. These characteristic maximums and minimums can be addressed by frequency sweeping over one FSR of the ORR. In practice, $\Delta P_{\text{on-off}}$ can be measured by means of a CW laser with sweeping wavelength $\lambda$ and an optical power meter, or alternatively by measuring the magnitude response of an RF frequency $f_{\text{RF}}$ externally modulated on a wavelength-sweeping CW laser, and then using the square-law relation of the optical detector to calculate $\Delta P_{\text{on-off}}$ from the measured magnitude response $A_{\text{RF}}(\lambda)$ in dB by

$$\Delta P_{\text{on-off}} = A_{\text{RF}}(\lambda_{\text{on}}) - A_{\text{RF}}(\lambda_{\text{off}})$$ \hspace{1cm} (7)

To measure $\Delta \tau_{\text{on-off}}$, the so-called RF phase-shift method is needed [27]. Similar to the second method for $\Delta P_{\text{on-off}}$ measurement, a wavelength-sweeping CW laser is externally modulated by an RF frequency $f_{\text{RF}}$ and the measured RF phase response $\phi_{\text{RF}}(\lambda)$ in degree can be translated into $\Delta \tau_{\text{on-off}}$ by using the equation

$$\Delta \tau_{\text{on-off}} = \frac{T_R}{f_{\text{RF}} T_R} \left( -\phi_{\text{RF}}(\lambda_{\text{on}}) + \phi_{\text{RF}}(\lambda_{\text{off}}) \right)$$ \hspace{1cm} (8)

In this work $A_{\text{RF}}(\lambda)$ and $\phi_{\text{RF}}(\lambda)$ are obtained using the setup illustrated in Fig. 3. An Agilent N5230 vector network analyzer was used to generate the RF frequency and measure the detected relative amplitude and phase of the RF signal. An EM4 1550 nm/100 mW CW laser was driven by a ramping current source and operated as a high resolution wavelength-sweeping CW light source. The optical modulation and detection were implemented using an Avanex Powerlog20 Mach-Zehnder modulator and an Emcore 20 GHz-bandwidth optical...
detector, respectively. Given that the ORR filters have an FSR of 20 GHz, a wavelength resolution of 0.0008 nm (≈100 MHz) was chosen to ensure accurate acquisitions of the frequency response of the ORR filters. Correspondingly, an $f_{RF} = 50$ MHz, which yields measurement results robust to the system phase noise, was used to achieve sufficient measurement accuracy. To further increase the accuracy of the resulting waveguide propagation loss, the same measurements were repeated for different $\kappa$’s of the ORR, and the final result was obtained by means of averaging.

The waveguide propagation losses extracted from the measurements and the theoretical calculations are depicted in Fig. 4. The theoretical values are calculated using the equation

$$L_{wg}(R) = \frac{2\pi RL_{bd}(R) + C_r L_{st}}{C_t}$$

where $R$ is the bend radius of the ORRs, $L_{bd}(R)$ and $L_{st}$ are defined to be the optical power loss per unit waveguide length due to bend radiation and scattering effect, respectively. The determination of $L_{bd}(R)$ and $L_{st}$ ($\lambda = 1550$ nm) was performed using the loss modeling.
approach described in [25] in association with the characteristic parameters of the waveguide technology. In the inset of Fig. 4 a pair of measured frequency responses of the ORR are fitted by their theoretical counterparts (Eq. (2) and 3, using $\kappa$ as the fitting parameter) with respect to the matched round-trip loss. The fitting result clearly verifies the accuracy of the measurement approach being used.

As shown in the result, the maximum waveguide propagation loss was measured to be 0.12 dB/cm in the ORR with a bend radius of 50 µm, and an average waveguide propagation loss as low as 0.095 dB/cm was achieved for the bend radii $\geq$ 70 µm where the loss contribution of the bend radiation is negligible compared to the scattering loss of the waveguide. Note that in Eq. (9) we assumed that the excess insertion loss of the coupling section between the waveguide bus and the ring path is negligible. Therefore, it is likely that the waveguide propagation loss has been overestimated. To our knowledge, this waveguide significantly outperforms the low-loss waveguides in other common high-index-contrast waveguide technologies [20–23]. With this demonstration the waveguide technology proves its capability to realize compact, low-loss on-chip functionalities.

4. Characterization of optical sideband filter

To further demonstrate the functionalities of the waveguide technology for MWP signal processing, two types of RF-modulated optical sideband filters (OSBFs) with high frequency selectivity have been fabricated and characterized. One filter consists of an asymmetric MZI with an ORR inserted in its shorter arm [28]. The other is an upgraded version of the first one obtained by adding a second ORR to the longer arm of the asymmetric MZI [29]. Both filters were designed with an FSR of 6.7 GHz and full filter-shape programmability by using the thermo-optic tuning mechanism of the waveguide. For the mask layout design of both filters, a waveguide bend radius of 125 µm was used, which results in footprints of 0.3 x 1.5 cm (MZI + 1 ORR) and 0.4 x 1.5 cm (MZI + 2 ORRs). The insets of Fig. 5 depict the schematics of the filter architectures and the corresponding mask layouts. The measured filter shapes are shown in Fig. 5.

Fig. 5. Measured filter shapes of the single and double ring-assisted MZI (Inset: schematic of the filter architecture and mask layout design)
In agreement with the filter design [28,29], the realized filter with one ORR demonstrates a flattened passband and significant stopband suppression with the allocation of the three zeros clearly displayed; the filter with two ORRs demonstrates a significantly improved frequency selectivity by means of introducing two more zeros in the stopband using the additional ORR. In Fig. 5 the measured filter shapes are normalized to their passband transmission. For these devices the waveguide technology allows for low on-chip losses. However, due to mode profile mismatch, high fiber-chip coupling losses of about 10 dB/facet will occur when using regular single mode fibers with a mode field diameter of 10.4 µm. As an effective solution, a linearly tapered waveguide section can be introduced to every facet. This can be realized by additional production steps, and in theory minimizes the coupling loss to 0.5 dB/facet.

5. Design of an optical beamformer chip (an example of on-chip MWP signal processor)

With the demonstrated functionalities and performances, the waveguide technology investigated in this work proves its potential to be applied to construct complex on-chip MWP signal processors. As an illustration, the design of an on-chip MWP signal processor using the ORRs and OSBFs as the basic building blocks, i.e. an optical beamformer chip for phased array antennas [8,9,26], is described in the following. The functionalities of such an optical beamformer chip have been described in [9,11], where an OSBF and an optical carrier reinsertion coupler are incorporated together with the primary signal-combining circuit using ORR-based delay lines. The desired chip is intended to serve for a phased array antenna system for mobile broadband satellite communications [10]. It is required to provide 16 inputs, 4.5 GHz optical bandwidth, and a maximum delay of 290 ps. Correspondingly, this is translated into a functional design which consists of a 16 × 1 binary-tree combining circuit inserted symmetrically with a total of 40 ORR-based delay lines, an OSBF using an asymmetric MZI with two ORRs, and an optical carrier reinsertion coupler. The schematic of the beamformer architecture is depicted in Fig. 6a. Using the waveguide bend radius of 125 µm, a chip mask layout has been generated as shown in Fig. 6b, which has a footprint as small as 0.7 × 2.2 cm. This features a size reduction of nearly 10 times compared to a previously reported optical beamformer chip with even lower complexity [9].

6. Conclusion

We have reported the design and characterization of Si₃N₄/SiO₂ optical waveguides which are specifically developed for optical delay lines in MWP signal processing applications. A record low waveguide propagation loss of 0.095 dB/cm has been measured in compact, race track-shaped ORRs with a circumference of 8783 µm (20 GHz FSR) and bend radii ≥ 70 µm. Using this waveguide technology two types of RF-modulated optical sideband filters have been demonstrated. These results demonstrate the potential of the waveguide technology to be applied to construct compact on-chip MWP signal processors.
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