Optimization of on-chip photonic delay lines for telecom wavelengths

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Abstract. In this work, we experimentally studied optical delay lines on silicon nitride platform for telecomm wavelength (1550 nm). We modeled and fabricated spiral optical delay lines with different waveguide widths and radii as well as measured their transmission and time delays. We achieved the losses in the range of 3 dB/cm and the group delay time up to 1 ns, which can be used as an element of optical integrated switchers for on-chip spontaneous four-wave-mixing.

1. Introduction
Integrated optical delay lines can be successfully used for time delay in microwave photonics, highly stable microwave generators, in the processing of optical signals as well as in the construction of quantum-photonic integrated circuits (QPICs) [1, 2]. To reduce the overall footprint, usually the delay lines fabricated in the form of a long waveguide, twisted into a spiral. As waveguide material we used low pressure chemical vapor deposited (LPCVD) silicon nitride (Si_3N_4), which is a promising platform for nanophotonic circuits and combines good mechanical properties, low optical absorption in the infrared (IR) and visible wavelength ranges as well as possibility for creation of single-photon sources based on four-wave mixing [3].

2. Device design and fabrication
For experimental testing of devices in the telecomm wavelength range (near 1550 nm) focusing grating couplers (FGCs) at the both ends of the double Archimedean spirals are designed [4]. The commercially available wafers on a silicon (Si) substrate with a thickness of 450 µm had 2.6 µm silicon buried oxide (SiO_2) and 450 nm silicon nitride (Si_3N_4) layer. For fabrication process we use one step of electron-beam lithography and dry reactive-ion-etching (RIE) in CHF_3-Ar mixture. Figure 1(a) shows an optical image of a fabricated spiral waveguide with a full length of 121875.50 µm

3. Experimental setup and results
In the first step, we use a numerical calculation in COMSOL Multiphysics for extracting the effective and group refractive indexes for different waveguide geometries. In Figure 1(b) shown the calculated fundamental quasi TE-mode for silicon nitride waveguide with a 1 µm width and 450 nm height as well

as in Figure 1(c) shown the group delay time. In the second step, we characterize the transmission of integrated delay lines in the wavelength range of 1510-1620 nm. The transmitted power was analyzed by a low-noise photodetector and controlled by PC. Dependence of optical losses on the spiral waveguide length with a minimum radius of 50 μm is shown in Figure 1(d). Although such a device has a smallest footprint, due to large losses ≈3dB/mm, the use in integrated optics is strongly limited and reducing of losses needed.

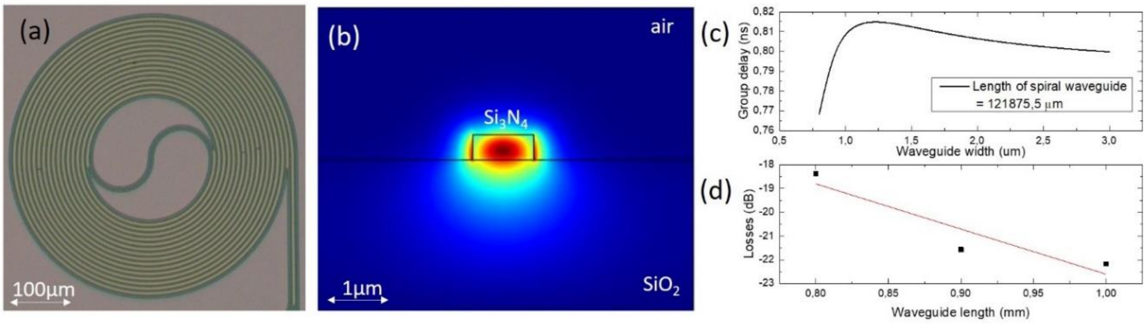

Figure 1 (a-d). (a) Zoom-in spiral; **(b)** The finite element simulation of the optical mode propagating inside the waveguide; **(c)** Group delay time on the waveguide width; **(d)** Losses in spiral waveguide vs waveguide length for the minimum spiral radius 50 μm.

To reduce optical losses, we systematically changed both the minimum spiral radius and the width of the waveguide. We found that as the width of the waveguide increases, the time delay increases (due to the increase in the effective refractive index) and the losses are reduced (by removing the maximum of the mode from the edges of the waveguide where the greatest scattering of light occurs). In the third step, we measured group time delay with femtosecond laser and the fast photodetector. We achieved the losses in the range of 3 dB/cm as well as the group delay time up to 1 ns for the best fabricated devices.

4. Conclusion

We fabricated delay lines with different parameters of the length and width of the waveguide and studied their optical transmission and time delay performance. We found the spiral losses in a range 3 dB/cm as well as the group delay time up to 1 ns. Further work will be devoted to the fabrication of delay lines for integrated optical switchers using in spontaneous four-wave-mixing, as well as their integration with other integrated optical elements including sources, logic elements and single-photon detectors [6].

5. Acknowledgments

E. Zubkova, P. An, V. Kovalyuk and G. Goltsman acknowledge support of the Russian Science Foundation (project 16-12-00045, waveguide fabrication and transmission measurements). W. Pernice acknowledges support by the DFG grants PE 1832/1-1 & PE 1832/1-2 and the Helmholtz society through grant HIRG-0005 (design and modeling).

References

[1] Lee H, Chen. T, Li J, Painter O, and Vahala K J 2012 *Nat. Commun* **3** 867

[2] Silveerstone J, Bonneau D, O'Brien J L, Thompson M G 2016 *IEEE* **22** 390

[3] Ramelow S, Farsi A, Clemmen S, Orquiza D, Luke K, Lipson M, and Gaeta A L 2015 *ArXiv:1508.04358v1*

[4] Van Laere F, Claes T, Schrauwen J, Scheerlinck S, Bogaerts W F L, Taillaert D, O'Baolain L, Van Thourhout D, Baets R G F *IEEE* **19** 1919

[5] Bogdanov S, Shalaginov M Y, Boltasseva A, and Shalaev V M 2016 *Opt. Mater. Express* **7** 111

[6] Pernice W H P, Schuck C, Minaeva O, Li M, Goltsman G N, Sergienko A V, Tang H X 2012 *Nat. Commun* **3** 1325