TriPleX: a new concept in optical waveguiding

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Abstract: A novel optical waveguide, consisting of a thin high-index coating boxing a low-index inner material, is presented. Details on waveguide design, fabrication and experimental results are shown, demonstrating high potentialities for CMOS-compatible large-scale integrated optics.

Introduction

In optical fibers, the radial refractive-index profile is the most suitable and exploited mean to manage most of the propagation characteristics. Apart from the attenuation of the fiber, mainly dependent on the technological fabrication process, the radial index profile and contrast can be designed to tailor dispersion characteristics, mode shape and dimension, effective area and hence nonlinearities, bending capability and so on. In integrated optics, contrary to optical fibers, the shape of the waveguide is inflexibly connected to the technological process for the realization of the guiding structure and the transverse profile is typically a step function. Moreover, the restricted variety of available materials forces the index contrast to few fixed values, thus limiting the possibility to fully exploit such a parameter to optimize the trade-off between optical properties and technological implications.
Waveguides composed by a combination of layered materials, such as SiO_2, Si_3N_4, Si, and also Tellurium and Polymide, usually known as Multi-Layer Waveguides (MLWs), possess many intriguing characteristics and represent promising alternatives to overcome the previously described limitations. Optical waveguiding in MLWs or waveguides confined by multilayers has been recently widely investigated [1] for high power transmission, tight turning radii, dispersion compensation, hollow waveguide applications, sensors and so on. One of the main disadvantages of these confinements (hollow-core ARROW waveguides [2] and Bragg cladding waveguides [3]) is the large number of layers required for achieving low radiative losses, resulting in complex technological processes and low reproducibility.
In this contribution non-conventional waveguides, consisting of overlapped layers of dielectric media with different thickness and refractive index, are proposed as a way to merge the advantages of low index-contrast waveguides (low loss, low polarization dependent loss, low birefringence) to the potentialities of higher index ones (high curvature and devices' compactness). With respect to conventional structures, in the proposed waveguide additional degrees of freedom can be exploited for the optimization of the waveguide, whose effective index-contrast can be tailored by using only few (typically two) standard materials. Morover, the low-cost, simple and CMOS compatible technology makes the proposed waveguide an interesting candidate for highly integrated optical circuit applications.
The transversal profile of the proposed waveguide is shown in Fig. 1. It is made of a thin high-index box layer (50-150 nm) of Silicon Nitride (refractive index 1.99) surrounding and encapsulating a low-refractive-index material (SiO_2). This technology has been designed, patented and set up at LioniX – the Netherlands [4 - 7] and it is named TriPleX. Both the technological realization and the theoretical study of the propagation in TriPleX waveguides are challenging tasks, but the flexibility and the advantages of such a new composite structure are remarkable, as already demonstrated through the realization of several devices [8-10].
The paper is organized in three sections explaining the waveguide properties and design, the technological process for the waveguide fabrication and the experimental characterization.

Waveguide design

LPCVD Silicon nitride (Si_3N_4) is a widely used material in integrated optics, primarily because of its large refractive index (1.99 at 1.55 μm) enabling the realization of very compact devices [11]. Unfortunately, its large internal tensile stress limits the maximum layer thickness to < 350 nm, not

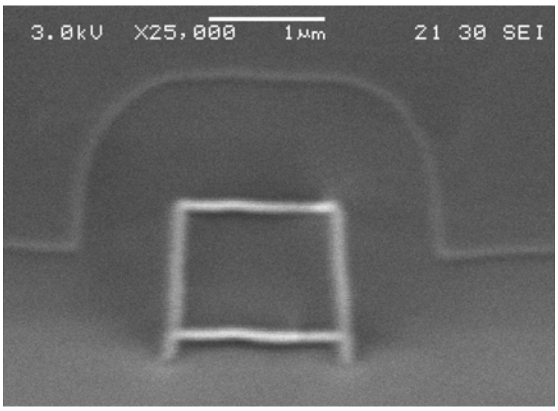

Fig. 1: Photograph of a box-shaped waveguide realized with TriPleX technology. The clear box is Si_3N_4 65nm thick; the gray surrounding is SiO_2.

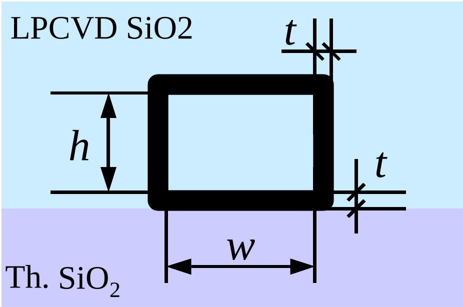

Fig. 2: Transverse shape of the realized waveguide

Table 1: Characteristic dimensions and properties of two box-shaped TriPleX waveguides for null birefringence

	t = 65 nm	t = 150 nm
$w = h$ [μm]	1.10	0.60
R_{min} [μm] (FSR [GHz])	500 (60)	60 (530)
η (UNHA) [dB]	0.13	4.5
PDL η [dB]	<0.02	<0.05
n_{eff} (TE, TM)	1.465	1.521

sufficient to realize optical waveguides able to support single mode operation of both TE and TM modes. As a consequence, silicon nitride waveguides are typically designed as strip waveguides.

The effective thickness of the waveguide can be increased by overlapping parallel strips of Si_3N_4 and SiO_2. The SiO_2 layers sandwiched between the nitride layers relax material stresses and several layers can be deposited, as shown in Ref [12]. In this way also the TM mode can be brought to full propagation still keeping the TE in the single mode regime. However, in this way, the birefringence increases to values higher than 10^{-2}. As a further disadvantage, in a MLW waveguide the TE and TM modes assume different dimensions and shape, leading to different coupling efficiency with optical fibers, bending capabilities, losses and PDL.

On the contrary, the presence of vertically oriented high-index layers, such as in the case of the "box-shaped" waveguide of Fig. 1, is found to add interesting features with respect to MLWs barely made of horizontally overlapped parallel strips. The transverse section of the proposed waveguide is shown in Fig. 2, where t is the thickness of the nitride layer, w is the inner width and h the inner height of the low index core. The optimal relationship between these dimensions guarantees the null birefringence condition in single mode regime, good bending capabilities and fiber coupling efficiency with very a very low PDL.

Following several numerical simulations and technological feasibility evaluations, the optimal dimensions has been found and reported in Table 1 for two different thickness values of the nitride layer.

Even though the square shape is the best one to reduce form birefringence, in practice a slightly wider box is required to compensate for the small anisotropy of the vertical nitride walls. Waveguide dimensions, minimum bending radius (to get radiation losses of 0.1 dB/rad), coupling efficiency η with a small core optical fiber with NA=0.38 (UHNA - Nufern, 3.6 μm spot size), PDL and effective refractive index are reported in Table 1. These results were obtained with a simulator based on the eigenvalue expansion method and validated by a BPM tool. Both waveguides have a null birefringence at a wavelength of 1550 nm. A thicker nitride layer allows a much tighter bending radius, because of the higher mode confinement, and hence a low coupling efficiency with optical fibers. In brackets it is shown the maximum Free Spectral Range attained by a ring resonators realized with the corresponding waveguide. The FSR can be increased up to 2 THz for a nitride thickness t = 250 nm. The fiber coupling efficiency is excellent for the t = 65nm waveguide, while lensed or tapered fibers or mode matching adapters should be used if thicker nitride layers are used. Note, in both cases, the almost null PDL that, furthermore, remains below 0.05dB per facet in the wide range from w = 0.5 to 2 microns.

An interesting feature is the low effective refractive index of the guided modes, despite of the small minimum bending radius. As shown Fig 3a) and b), the optical field is not strictly confined into the nitride layers, but widely spreads over the whole cross section. The shapes of the two modes are very similar, but rotated by 90 deg. The field of the quasi-TE mode is mainly confined by the horizontal layers

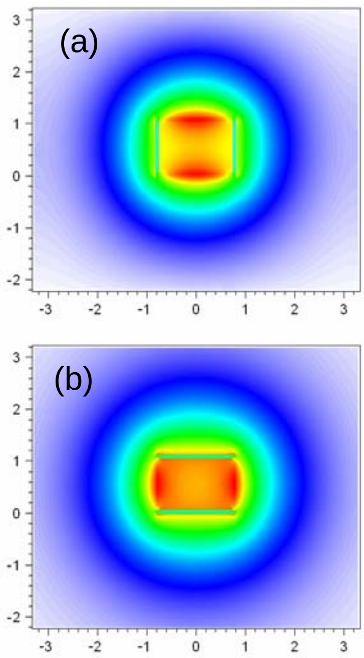

Fig. 3: Electric field transverse intensity of TE (a) and TM (b) modes.

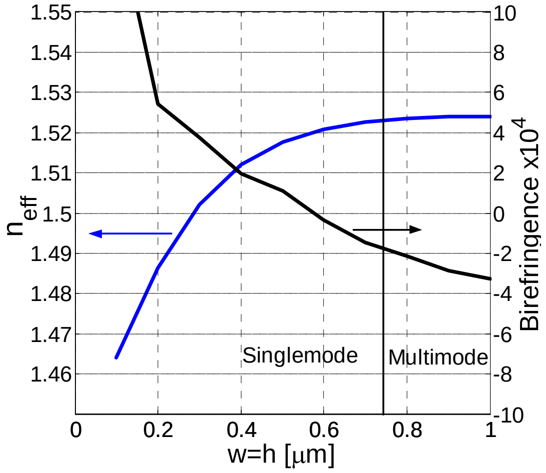

Fig. 4: Refractive index and birefringence of a box-shaped waveguide with t = 150 nm.

of the box, while the quasi-TM mode is confined by the vertical layers. This shape guarantees an excellent compromise between minimum bending radius, fiber coupling efficiency and technological feasibility, allowing accessing to effective index contrasts otherwise not available with standard materials. Moreover, it can be efficiently exploited to design polarization independent or strongly polarization sensitive devices (like directional couplers).

Fig. 4 shows the effective refractive index and birefringence of the square waveguide with t = 150 nm vs waveguide dimensions. Differently from classical buried waveguides, the n_{eff} tends to saturate rapidly and, in the multimode region, even to decrease. With respect to the waveguide width (with fixed height and vice versa), the TE and TM effective indexes, have opposite behaviours. As one can perceive from mode shapes of Fig. 3, by increasing w the TE confinement increases, while the TM confinement decreases and n_{eff} varies accordingly. The opposite holds for the h dependency. This unusual property can be conveniently exploited to easily get the zero birefringence point, tune the propagation characteristics in bends and in general de-couple the TE and TM behaviour.

Technology and realization

The box-shaped waveguide is based on alternating LPCVD Si_3N_4 and LPCVD SiO_2 layers. The latter is called TEOS SiO_2. Figure 5 depicts the schematics of the LioniX fabrication procedure for the square shaped waveguides. The process starts with thermal oxidation of a 100 mm-diameter silicon wafer (1 and 2) to form the lower cladding. Then LPCVD Si_3N_4 (3) and TEOS SiO_2 (4) are deposited. Then photolithography is performed (5), followed by RIE (6), photo resist removal (7) and a second LPCVD Si_3N_4 deposition (8). Finally, the Si_3N_4 is locally removed to obtain the box-like waveguide geometry (9), followed by the deposition of the passivating top cladding layer (10).

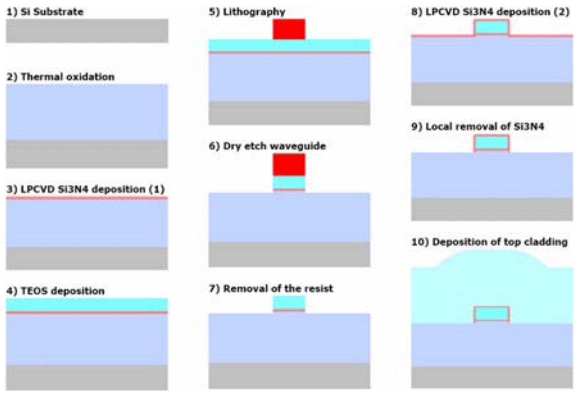

Figure 5: Flow process scheme for the box- shaped waveguides as made with Flowdesigner process modeller (PhoeniX BV, Enschede, the Netherlands).

Waveguide characterization

Several wafers were produced and characterized both at structural and optical level. Samples were prepared as usual, by cutting the wafers with a circular saw and no particular difficulties arose from the layered structure. Waveguides were characterized in butt coupling, without facet polishing, with a small core fiber (UHNA) with a measured MFD = 3.6 μm. All the results reported in this contribution refer to waveguides with t = 65nm on chips 6.25 cm long.

Fig. 6a) shows the measured fiber-to-fiber insertion losses of the TE mode versus the waveguide width and also the simulated fiber to waveguide total coupling efficiency (two facets). Apart from the damaged 3.5 and 0.5 μm wide waveguides, the insertion loss is very low and the attenuation ranges from 0.06 to 0.08 dB/cm over the whole third telecom window. Also the overall PDL, shown in Fig. 6b), partially due to the fiber coupling efficiency and partially to the higher TM attenuation (estimated around 0.17dB/cm for every waveguide width), keeps very low levels. At present the reasons of the higher TM insertion loss is under investigation and cut-back measurements will be carried out. Note that the PDL due to the fiber coupling can be reduced by properly tapering the waveguide near the chip edges.

The second important parameter experimentally and theoretically investigated is the group refractive index of the two modes, and hence the group birefringence. The simulated and the measured TE and TM group refractive index of the same waveguides are reported in Fig. 7. Measurements were carried out with a phase sensitive optical low coherence interferometric technique [13]. Group index and also birefringence are in very nice agreement with simulations for waveguide widths larger than 1.5 μm. In the narrower waveguides, the TM mode group index is slightly lower than expected. The zero group birefringence point is very close (about 100 nm in width) to the expected one. A possible explanation is that material dispersion and material anisotropy are neglected in these simulations.

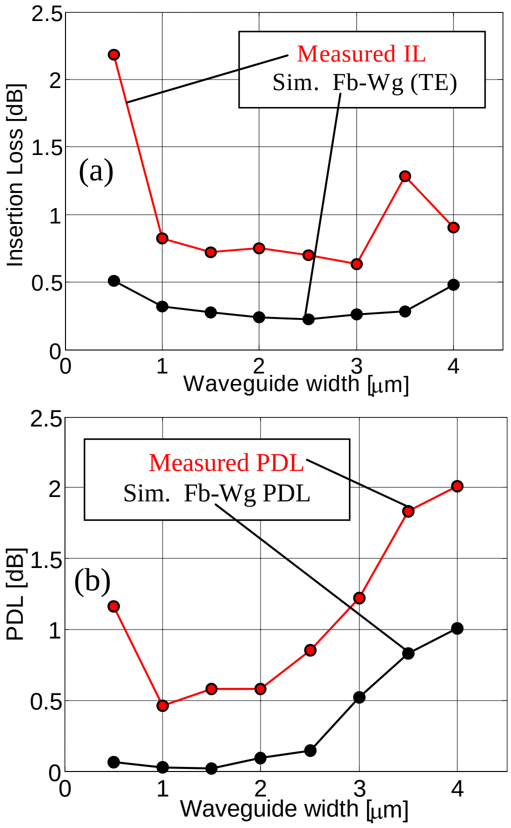

Fig. 6: Measured insertion loss, simulated coupling efficiency and PDL of the waveguide with *t* = 65nm.

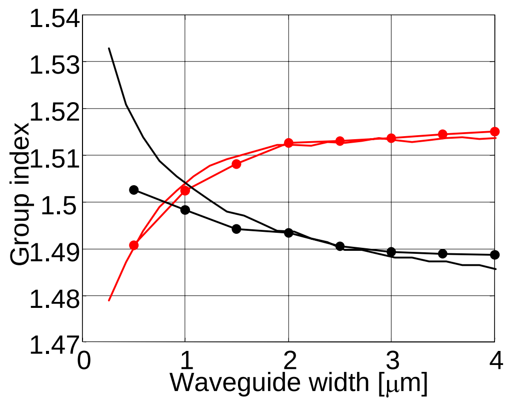

Fig. 7: Simulated (lines with marks) and measured TE and TM group refractive index (*t* = 65 nm).

To investigate the bending capabilities of the TriPlex waveguides, the insertion loss of several waveguides with radii ranging from 3mm to 250μm were measured with a polarimetric set up. As shown in Fig. 7, where the attenuation of the TE mode in the bends is reported, minimum bending radii down to 750 and even 500 μm with negligible radiation losses were obtained, in agreement with numerical predictions (Tab. 1). By increasing the channel width, the bending loss for the TE polarization reduces. However, one has to take care of PDL that increases with the channel width because the TM mode suffers from waveguides widening, as suggested by the effective index reduction shown by

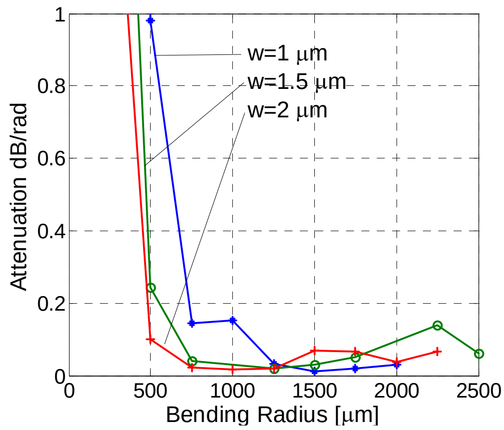

Fig. 8: Measured TE bending losses (*t* = 65 nm).

Fig. 6. PDL remains however unaffected respect the straight waveguide down to 1.25mm bending radius. Waveguides with a thicker nitride layer should are expected to support even tighter bends, as predicted by Table 1.

Conclusions

A new class of optical waveguides, combining enhanced design flexibility, advanced optical properties and a simple, fully CMOS-compatible technology, has been presented. Experimental results show values of attenuation, PDL, birefringence and fiber-to-waveguide coupling loss comparable to conventional low-index contrast waveguides, but with significantly increased bending capabilities. These results demonstrate that the TriPleX technology can fulfil the requirements of large scale integrated optics, with promising applications in the field of optical communications and sensors.

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