Box-Shaped Dielectric Waveguides: A New Concept in Integrated Optics?
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Abstract—A novel class of optical waveguides with a box-shaped cross section consisting of a low-index inner material surrounded by a thin high-index coating layer is presented. This original multilayered structure widens the traditional concept of index contrast for dielectric waveguides toward a more general concept of effective index contrast, which can be artificially tailored over a continuous range by properly choosing the thickness of the outer high-index layers. An electromagnetic analysis is reported, which shows that the transverse electric and transverse magnetic modes are spatially confined in different regions of the cross section and exhibit an almost 90° rotational symmetry. Such unusual field distribution is demonstrated to open the way to new intriguing properties with respect to conventional waveguides. Design criteria are provided into details, which mainly focus on the polarization dependence of the waveguide on geometrical parameters. The possibility of achieving single-mode waveguides with either zero or high birefringence is discussed, and the bending capabilities are compared to conventional waveguides. The feasibility of the proposed waveguide is demonstrated by the realization of prototype samples that are fabricated by using the emerging CMOS-compatible Si₃N₄–SiO₂ TriPleX technology. An exhaustive experimental characterization is reported, which shows propagation loss as low as state-of-the-art low-index-contrast waveguides (< 0.1 dB/cm) together with enhanced flexibility in the optimization of polarization sensitivity and confirms the high potentials of the proposed waveguides for large-scale integrated optics.

Index Terms—Birefringence, integrated optics, multilayer waveguides, optical waveguides, polarization.

I. INTRODUCTION

NOWADAYS, integrated optics require waveguides with advanced performance to satisfy the need for large-scale integration, device miniaturization, implementation of system-on-chip architectures, and ultimately, cost reduction. All the figures of merit of dielectric waveguides, which concern, for instance, chromatic dispersion, polarization dependence, coupling loss with optical fibers, and bending capabilities, are strictly related to the refractive index contrast between the core and the cladding regions of the waveguide. Since the beginning of integrated optics, low-index-contrast (Δn < 1%) silica-on-silicon waveguides have been representing the leading technology in the field of planar lightwave circuits and still provide the state-of-the-art performance for passive devices [1]. More recently, high-index-contrast (Δn > 100%) silicon-on-insulator photonic wires have become the new frontier for optical waveguides because of their unequalled potential for ultradense on-chip integration [2], [3]. Indeed, within this wide-index-contrast gap between silica and silicon technologies, only a discrete set of index contrasts can be accessed because of the restricted variety of available optical materials. As a consequence, the refractive index contrast cannot be fully exploited as an arbitrary degree of freedom.

In addition to material shortage, there are also technological issues limiting the waveguide shape itself to a few basic cross-sectional geometries, which typically consist of rectangular buried or ridge waveguides, rib waveguides with partially etched core layers, or diffused waveguides. In some cases, even tighter constraints exist. A well-known example is provided by silicon nitride (Si₃N₄) waveguides that have been employed for several decades in integrated optics [4]. Si₃N₄ combines a wide spectral transparency window, i.e., from far infrared to visible frequencies, with a high refractive index (1.99 at 1.55 μm), which enables the realization of very compact devices [5]. Bending radii down to 25 μm and ring resonators with free spectral range (FSR) up to 9 nm wide have been recently demonstrated [6]. Furthermore, stoichiometric Si₃N₄ layers grown by low-pressure chemical-vapor deposition (LPCVD) exhibit a noticeable refractive index uniformity, highly controllable thickness, and extremely small interface roughness, the latter being the fundamental source of scattering loss in high-index-contrast waveguides. Propagation losses of around 1 dB/cm for the single-mode regime and down to 0.1 dB/cm in multimode waveguides were demonstrated in LPCVD Si₃N₄ channel waveguides at 1.55 μm [7]. Si₃N₄ technology also has the advantage to be well established in the field of integrated electronics [8], thus allowing fully compatible CMOS integration. The most severe drawback of LPCVD Si₃N₄ is related to its large internal tensile stress (about 1.3 GPa [9]), which limits the maximum layer thickness to less than 300–350 nm. As a consequence, Si₃N₄ waveguides are...
usually designed with strip geometries, which exhibit a strong polarization dependence due to the poor confinement of TM polarization [10].

In order to reduce the huge polarization dependence of $\text{Si}_3\text{N}_4$ strip waveguides, multilayer waveguides consisting of parallel overlapped layers of $\text{Si}_3\text{N}_4$ and $\text{SiO}_2$ have been recently proposed. A large number of layers can be stacked without altering the material optical properties thanks to the stress relaxation provided by the $\text{SiO}_2$ layer sandwiched between two $\text{Si}_3\text{N}_4$ layers [11]. However, in these waveguides, the transverse electric (TE) and transverse magnetic (TM) modes keep assuming a different confinement degree, so the polarization dependence of propagation loss, bending loss, and coupling efficiency with optical fibers is only partially reduced.

In this paper, a novel and simple multilayer structure based on the emerging $\text{Si}_3\text{N}_4$ TriPleX technology [12]–[15] is presented with the aim of extending the classical concept of optical dielectric waveguides. The basic idea is to arrange a few layers of dielectric media with different thickness and refractive index to merge the benefits of low-index-contrast waveguides (low loss, low polarization-dependent loss (PDL), low birefringence) with the outstanding potentialities of high-index ones in terms of tight curvature and large-scale integration. With respect to classic multilayer waveguides barely made of horizontally overlapped parallel strips, the addition of vertically oriented high-index layers provides new adjustable degrees of freedom for the optimization of waveguide properties, especially for the control of polarization dependence. The original design of a boxed-shaped (BS) waveguide with a transverse section consisting of a thin high-index coating layer encapsulating a low-index inner material is discussed in details.

It is worthwhile to anticipate here two main concepts related to the proposed BS waveguide. The first one is that, similar to conventional waveguides, propagation in BS waveguides is based on the total internal reflection. The optical field is mainly confined in the external high-index layer, which plays a guiding role analogous to the core of conventional waveguides, while a weak power propagates in the inner low-index region. This is basically different from what happens in multilayer hollow core waveguides such as Bragg cladding waveguides [16] and antiresonant reflecting optical waveguides (ARROW) [17], [18], where the optical field is bounded inside the low-index core by interference effects occurring in the multilayered cladding, which provides stopbands for radiation modes. More specifically, in Bragg cladding waveguides, several dielectric bilayers are periodically arranged in order to build up an omnidirectional cladding mirror [19], while light confinement in ARROW waveguides is achieved by creating an antiresonant Fabry–Pérot reflector for the transverse component of the wave vector at the design wavelength. Although these two confinement strategies theoretically enable a tighter bending than total internal reflection, and interesting potentialities have also been pointed out for high-power transmission, dispersion compensation, and sensing, the propagation losses are still too high for many practical applications. State-of-the-art Bragg cladding waveguides realized in CMOS-compatible $\text{Si}_3\text{N}_4$–$\text{SiO}_2$ technology exhibit loss no lower than 6 dB/cm [20], while ARROW waveguides with about 7 dB/cm [21], [22] have been fabricated with $\text{Si}_3\text{N}_4$–$\text{SiO}_2$ multilayers.

The second remarkable point is that, in the BS waveguide, the concept itself of index contrast assumes a more general meaning with respect to conventional waveguides. In fact, an artificial effective index contrast can be arbitrarily tailored over a continuous range of values simply by combining a limited number (typically two) of standard materials. This property also enables the design of optical waveguides by only changing the cross-sectional geometry and without the need for tuning the refractive index of the materials, which can be conveniently kept to stoichiometric composition. As will be discussed in this paper, a BS waveguide comprising layers of LPCVD $\text{Si}_3\text{N}_4$ and LPCVD $\text{SiO}_2$ can reach effective index contrasts similar to those theoretically achievable by plasma-enhanced CVD (PECVD) silicon oxynitride (SiON) waveguides [23]. This allows exploiting all the advantages of PECVD over PECVD, including the possibility of manufacturing larger batch size and higher uniformity over the wafer. From this point of view, the concept of BS waveguide is undoubtedly more in line with the common design rules used in the integrated components industry.

This paper is organized into three sections that discuss the waveguide properties and design, the technological process for waveguide fabrication, and the experimental characterization, respectively. In Section II, a step-by-step procedure is explained, which shows how to build up a BS waveguide with desired effective refractive index and polarization birefringence. A simplified model based on the coupled mode theory (CMT) is used to support the electromagnetic study of the BS waveguide and to derive conditions for single-mode regime and zero birefringence. Bending capabilities and polarization dependence on the cross-sectional geometry are discussed. Section III reviews the basics of TriPleX technology and provides some details on the process flow used for the realization of the proposed BS waveguides. Section IV is devoted to an exhaustive experimental characterization of prototypal TriPleX BS waveguides and shows all the remarkable potentialities and the large flexibility of this composite structure.

II. WAVEGUIDE DESIGN

It is a trivial design rule that mode confinement in optical waveguides increases with the waveguide size. However, in some practical circumstances, for instance, in the case of $\text{Si}_3\text{N}_4$ waveguides, only the waveguide width $w$ can be enlarged arbitrarily, whereas the waveguide height $t$, which is intrinsically related to the thickness of the grown films, can be limited by technological constraints. Waveguides with $w \gg t$, which are typically referred to as strip waveguides, are commonly employed in integrated optics but have severe drawbacks in terms of polarization sensitivity. In this section, a design procedure is explained starting from the analysis of single-strip (SS) waveguides and shows how to effectively arrange several layers of high-index material to form a BS waveguide with
significantly improved performance with respect to the state-of-the-art waveguides.

All the numerical results presented in this section are obtained with a full-vectorial electromagnetic simulator based on the film mode matching method [24]. The refractive index of the high-index layers \( n_{\omega} = 1.99 \), and that of the low-index material \( n_c = 1.4456 \) are chosen to investigate the particular case of \( Si_3N_4 \) waveguides embedded in a silica (\( SiO_2 \)) cladding. However, it is worthwhile to clarify here that the peculiar properties of the BS waveguides are not restricted to a specific technology but generally hold for any combination of low- and high-index materials employed for the fabrication of the waveguide.

A. SS Waveguides

Fig. 1 shows the effective index of the first TE and TM modes of a generic SS waveguide whose cross section is schematically shown in the inset. The waveguide thickness is fixed to \( t = 150 \) nm, and if not differently specified, this value is held for the thickness of all the high-index layers employed in the waveguides discussed in this section. As is well known, modes with electric field prevalently oriented in the horizontal \( z \)-direction (namely, TE modes, with \( E_y \) mayor transversal field) can be strongly guided, while modes with almost vertical \( E_y \) electric field (TM modes) experience far less confinement. The vertical dashed–dotted line marks the boundary between the single-mode and multimode regions. To guarantee the propagation of the fundamental TE\(_{00}\) and TM\(_{00}\) modes, the SS width \( w \) must be larger than 0.6 \( \mu m \) but less than 1.8 \( \mu m \) if the propagation of the TE\(_{10}\) has to be inhibited. However, a strong birefringence \( B_{SS} \), i.e., higher than \( 10^{-2} \), is observed in the entire single-mode region because of the poor confinement of the TM polarization, which is also responsible for the very high PDL in bends. Therefore, in all applications requiring tight curvatures, strip waveguides typically operate with the TE polarization only, and if single-mode regime is desired, the waveguide width \( w \) is conveniently set just below the cutoff of the higher-order TE\(_{10}\) mode.

B. Double-Strip (DS) Waveguides

In order to increase the field confinement achievable by the SS waveguide, a widely used strategy consists of overlapping several parallel strips of high refractive index material sandwiched by alternating strips of lower refractive index material [9]. This approach enables building up waveguides with increased cross section so that the TM mode can be brought to full propagation while still keeping TE in the single-mode regime. Fig. 2 shows the effective indices of the TE and TM modes of the DS waveguide (shown in the inset) obtained by placing two identical single-mode SS waveguides, with the cross section depicted in Fig. 1, at a distance \( h \). The width of each SS waveguide is fixed to \( w = 1.5 \) \( \mu m \) so that the correspondent effective indices of the SS modes are \( n_{TE}^{SS} = 1.479 \) and \( n_{TM}^{SS} = 1.46 \), respectively (see Fig. 1).

A simplified model based on CMT can be used to straightforwardly explain the behavior of the four DS modes in Fig. 2 versus the strip distance \( h \). If \( h \) is much larger than the mode field penetration in the cladding region (\( h \gg 3 \) \( \mu m \)), the two strips are uncoupled, and the effective indices of the DS modes approach those of the SS waveguide. By reducing \( h \), waveguide coupling induces an effective index splitting between the fundamental TE\(_{00}\) (TM\(_{00}\)) mode and the higher-order TE\(_{01}\) (TM\(_{01}\)) mode of the DS waveguide. These modes coincide with the even and odd TE (TM) supermodes of two coupled SS waveguides. According to the CMT theory [25], the effective indices \( n_{e,o} \) of these supermodes are directly related to the effective indices \( n_{eff} \) of the SS modes as

\[
\begin{align*}
 n_{e,o}^{TE} &= n_{eff}^{TE} \pm \kappa^{TE} \\
 n_{e,o}^{TM} &= n_{eff}^{TM} \pm \kappa^{TM}
\end{align*}
\]

where \( \kappa \) is the polarization-dependent coupling coefficient between the coupled SS waveguides. The larger split of the
TM curves, which implies $\kappa_{\text{TM}} > \kappa_{\text{TE}}$, is expected from the weaker TM confinement in the SS waveguides. Because of the coupling mechanism, when $h$ decreases, the confinement of the $\text{TE}_{00}$ and $\text{TM}_{00}$ modes (even modes) increases, whereas the confinement of the $\text{TE}_{01}$ and $\text{TM}_{01}$ modes (odd modes) decreases. The single-mode condition for DS waveguides is thus obtained when the coupling $\kappa$ is sufficiently high to drive both $\text{TE}_{01}$ and $\text{TM}_{03}$ odd modes to cutoff, that is, $n_{\text{TE}}^0 = n_{\text{TM}}^0 = n_c$. In the example of Fig. 2, this occurs for $h < 0.6 \, \mu\text{m}$.

Although the TM confinement is effectively increased with respect to the SS waveguide (the effective index moves from 1.46 to almost 1.48 at the boundary of the single-mode region), the DS birefringence $B_{\text{DS}}$, which is given by the distance between the $\text{TE}_{00}$ and $\text{TM}_{00}$ lines in Fig. 2, is practically independent of $h$ and keeps the same value as in the case of SS. In fact, according to (1), $B_{\text{DS}} = n_{\text{TE}}^0 - n_{\text{TE}}^0 = B_{\text{SS}} + \kappa_{\text{TE}} - \kappa_{\text{TM}}$, and a strongly polarization-dependent coupling coefficient would be required to compensate for the SS birefringence $B_{\text{SS}}$. This condition is not easily achievable in practice. Further limitations of the DS waveguide are related to the fact that, similar to the SS waveguide, the TE and TM modes assume different dimensions and shape, which lead to different coupling efficiency with optical fibers, bending capabilities, losses, and PDL. From this point of view, numerical simulation (not reported here for brevity’s sake) shows that no significant advantages are obtained if more than two parallel high-index layers are overlapped.

In the next section, an original approach is presented, which demonstrates how additional vertical layers of high-index material can bring the TM modes of a DS waveguide to the same confinement degree as that experienced by the TE modes, thus reducing, and even canceling, the polarization dependence of the structure.

C. Box-Shaped (BS) Waveguides

The transverse section of the BS waveguide proposed in this paper, as shown in the inset of Fig. 3, consists of a thin high-index coating layer encapsulating a low-index inner material. In agreement with the previous discussion, let us define $t$ as the thickness of all the nitride layers surrounding the low-index inner material and $h_x$ and $h_y$ as the distance between the vertical and horizontal parallel strips, respectively. In the following, $h_x$ and $h_y$, which define the size of the inner low-index region, are also conveniently referred to as the waveguide width and height of the BS waveguide. The feasibility of such a structure is demonstrated in Section III, where the fabrication process flow of the waveguide is discussed in some details. Here, the modal analysis and design criteria of the BS waveguide are provided by effectively exploiting some concepts and results obtained for SS and DS waveguides.

The transversal distribution of the major electric field component of the TE and TM BS modes is reported in Fig. 4 for the case $h_x = h_y = 0.6 \, \mu\text{m}$. It can be noticed that the vertically oriented high-index layers are responsible for a 90° rotational symmetry between the quasi-TE and quasi-TM guided modes. The two modes do not spread over the entire high-index region, i.e., the quasi-TE mode being mainly confined by the horizontal layers of the waveguide and the quasi-TM mode by the vertical strips. Therefore, at a first approximation, the TE (TM) mode is expected to behave similarly to the mode of a DS waveguide with parallel horizontal (vertical) strips.

Numerical simulations confirm this prediction. Fig. 3 shows the dependence of the effective indices of the TE and TM modes of a BS waveguide with $t = 150 \, \text{nm}$ and $h_y = 0.6 \, \mu\text{m}$ versus the waveguide width $h_x$. When $h_x$ decreases, the effective index of all the TE modes drops down because of the reduction of the horizontal strip width, which is similar to the case of the SS waveguide (see Fig. 1). On the contrary, from the point of view of TM modes, the $h_x$ reduction induces a stronger coupling between the two vertical strips. According to (1), a stronger coupling improves the confinement of the fundamental (even) TM mode, while the higher-order (odd) TM mode is progressively pushed to cutoff. Similarly, when $h_y$ is varied with a fixed $h_x$, the behavior of the TE and TM modes just reverses because of the 90° rotational symmetry shown in Fig. 4.

In the example of Fig. 3, the single-mode condition is obtained when $h_x < 0.75 \, \mu\text{m}$. This result can be roughly

![Fig. 3](image1)

**Fig. 3.** Effective index of the TE and TM modes of the box-shaped waveguide (shown in the inset) versus the distance $h$ between the vertical high-index Si$_3$N$_4$ strips. For $h_x = 0.95 \, \mu\text{m}$ and $h_y = 0.75 \, \mu\text{m}$ (single-mode boundary), the higher-order TM$_{01}$ and TE$_{03}$ modes are driven to cutoff, respectively. Waveguide parameters $n_w = 1.99$, $n_c = 1.4456$, $h_y = 600 \, \text{nm}$, and $t = 150 \, \text{nm}$ are assumed.

![Fig. 4](image2)

**Fig. 4.** Transversal profile of the major electric field components of the (a) quasi-TE and (b) quasi-TM modes of the BS waveguides shown in Fig. 3 with $h_x = h_y = 0.6 \, \mu\text{m}$. 

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predicted by applying the single-mode condition of the DS waveguide (dashed-dotted line in Fig. 2) to each of the two polarization states of the BS waveguide. It should be noticed that the additional vertical layers do not substantially affect the TE effective index, which is around 1.527 for both DS and BS waveguides, but are responsible for the increase of the TM effective index, which is around 1.527 for both DS and SS waveguides, respectively.

From the point of view of the bending capability, the BS waveguide with $t = 150$ nm shows an effective index contrast $\Delta n_{\text{eff}}$ that is equivalent to a conventional buried waveguide with about $\Delta n = 20\%$, i.e., an index contrast rather difficult to achieve with available materials [27]. A further peculiarity of the BS waveguide is that, thanks to its multilayered structure, this effective index contrast can be adjusted arbitrarily and continuously over a wide range by simply playing on the nitride thickness $t$. By this approach, a BS waveguide comprising layers of LPCVD Si$_3$N$_4$ and LPCVD SiO$_2$ can assume an effective index contrast in the range theoretically covered by PECVD SiON waveguides with the remarkable advantage of using stoichiometric material composition only.

To this aim, numerical simulations (not reported here for brevity’s sake) were also performed for waveguides with different $t$’s. For instance, by reducing $t$ down to 65 nm, a single-mode zero-birefringence BS waveguide with $h_x = h_y = 65$ nm can be designed to operate at 1550-nm wavelength. A detailed experimental investigation of this waveguide is discussed in Section IV. Here, we can anticipate that when $t = 65$ nm, the BS waveguide shows an effective index contrast $\Delta n_{\text{eff}} = 3\%$, which supports a bending radius down to about 500 $\mu$m. All the values between 3% and 20% can be synthesized by means of intermediate nitride thicknesses. As expected, thinner nitride layers lead to mode confinement reduction and poorer bending capabilities. On the other hand, thin nitride layers also imply a larger mode field diameter (MFD), which eases the coupling with optical fibers, and relax technological issues. Simulations predict a coupling loss lower than 0.15 dB per facet, with less than 0.05 dB PDL, between the BS waveguide with $t = 65$ nm and small core fibers with MFD on the order of 3.5 $\mu$m.

Very thick nitride layers can also be employed to improve the curvature below 65-$\mu$m radii when required by wideband advanced applications. To give an example, ring resonators with FSR up to 2 THz can be realized with a BS waveguide with nitride thickness $t = 250$ nm. However, when $t$ increases, the waveguide dimensions need to be scaled down to guarantee single-mode regime with unavoidable implications in the interconnection with optical fibers. In these cases, lensed fibers, tapered fibers, or mode-matching adapters like inverse tapers are required to keep the coupling loss down to acceptable values.

D. A-Shaped (AS) Waveguides

As pointed out many times throughout this paper, the peculiarities of the BS waveguide are strictly related to the confinement of the TM mode provided by the high-index vertical layers. Different geometries with an arbitrary number of layers and based on the same confinement mechanism can also be designed as alternative structures to the BS waveguide. For example, Fig. 6 shows the field distribution of the TE and TM modes of a waveguide, where two vertical layers and three horizontal layers are arranged to give an AS cross section [14]. The design rules for the AS waveguide are analogous to those of the BS waveguide and are not reported for brevity. As in the case of the BS waveguide, the polarization dependence can be finely adjusted from almost zero to large birefringence [28].
The addition of the lower horizontal slab placed at a distance \( e \) from the central horizontal layer provides additional degrees of freedom for the manipulation of the waveguide properties. As shown in Fig. 6, while the TM mode is almost similar to the TM mode of the BS waveguide, the lower horizontal slab accommodates a large portion of the TE mode whose field distribution spreads largely in the \( x \)-direction. This property can be exploited to enhance the polarization dependence of the waveguide for the realization of strongly polarization-sensitive devices. To give an example, Fig. 7 shows the coupling coefficient \( \kappa \) (a) between two BS-coupled waveguides and (b) between two AS-coupled waveguides with the same parameters \( h_x = 0.4 \mu m, h_y = 0.6 \mu m, \) and \( t = 150 \mu m \). The under-etch of the AS waveguide is \( e = 0.35 \mu m \). In the case of the BS waveguide, despite of the above-discussed 90° rotational symmetry between the TE (solid line) and TM (dashed line) modes, it is possible to achieve a polarization-insensitive coupling for any choice of the gap distance \( g \). The reason is that the field distribution of the two modes is clearly different only in the proximity of the high-index region, but it becomes almost the same moving outwards, as shown in Fig. 4. On the other side, the AS waveguide shows a strong polarization dependence of the coupling coefficient versus \( g \). At large \( g \), the coupling for the TE mode is larger than that of the TM mode because of the wider horizontal field extension, which enhances the field overlap between the coupled waveguides. Conversely, at small \( g \), the TM coupling becomes higher than the TE one because the waveguide interaction is mainly due to the intense TM field confinement in the vertical high-index layer surrounding the gap of the coupler. As a consequence, the coupler with AS waveguides is polarization insensitive only at a given gap distance \( (g = 0.79 \mu m) \), whose value strictly depends on the parameters of the AS cross section.

### III. TECHNOLOGY AND REALIZATION

For the realization of prototypal BS waveguides, an emerging technology named TriPleX and developed at LioniX BV [29]–[31] was employed. The potentialities and the versatility of this technology have been already demonstrated through the realization of several devices [32]–[35]. The exhaustive discussion of all the technological implications of the fabrication process is far from the aim of this paper and is reminded to more specific contributions [12]–[14]. For completeness’ sake, in this section, only a brief description of the basic features of the TriPleX technology is summarized.

TriPleX technology is based on low-cost CMOS-compatible LPCVD processing. The superposition of alternating LPCVD Si\(_3\)N\(_4\) layers, which have large tensile stress, with LPCVD SiO\(_2\) layers, which have large compressive stress, originates a multilayer stack with largely reduced overall stress. Fig. 8 depicts the schematics of the TriPleX fabrication procedure for BS waveguides. To ease the fabrication process, in the first production run, BS waveguides with thin nitride layers \( (t = 65 \mu m) \) and large cross sections \( (h_y = 1 \mu m) \) were realized. The process starts with the thermal oxidation of a 100-mm-diameter silicon wafer (1 and 2) to form the 8-\( \mu m \)-thick lower cladding layer. Until now, all fabricated and analyzed waveguides have been manufactured on standard-quality 100-mm Si (100) wafers. Then, LPCVD Si\(_3\)N\(_4\) (3) with a thickness of 65 nm is deposited and immediately followed by the deposition of a 1-\( \mu m \) LPCVD SiO\(_2\) layer called TEOS (4). Then, contact photolithography is performed (5) followed by an optimized reactive ion etch process (6). This dry-etch procedure is stopped after reaching the lower cladding layer of the thermal oxide. After the subsequent photoresist removal (7), the second LPCVD Si\(_3\)N\(_4\) layer is deposited again with a thickness of 65 nm (8). This LPCVD Si\(_3\)N\(_4\) is locally removed to obtain the box-like waveguide geometry (9) followed by the deposition of the passivating top cladding layer (10) with thickness of \( \geq 5 \mu m \). The top cladding layer is a combination of TEOS (1 \( \mu m \)) and PECVD oxide \( (\geq 4 \mu m) \), respectively. The whole layer stack is afterward annealed at 1150 °C. A remarkable point is that only one photolithography step is required in the fabrication of the BS waveguide, thereby limiting the costs of fabrication and the uncertainties due to subsequent mask alignments.
A scanning electron microscope photograph of the resulting transversal profile of the BS waveguide is shown in Fig. 9, where the thin high-index silicon nitride layers encapsulating the SiO$_2$ inner low-refractive-index region are clearly distinguishable in lighter gray.

IV. Waveguide Characterization

Prototypes of BS waveguides were realized by using the technological process flow described in Section III. Structural inspection of the waveguide end facets showed that conventional dicing techniques do not damage the layered structure. Butt coupling with small core fibers with measured MFD = 3.6 $\mu$m was used to couple light to all the waveguides under investigation. The results reported in this paper refer to either straight waveguides or bent waveguides with $t = 65$ nm and $h_y = 1$ $\mu$m. Different widths $h_x$ were conveniently explored to experimentally demonstrate the peculiar properties of the BS waveguides predicted in Section II.

Fig. 10 shows in solid line the measured fiber-to-fiber insertion losses (TE mode) of 6.25-cm-long straight waveguides versus the waveguide width $h_x$. The overall insertion loss is far below 1 dB, apart from waveguides 3.5 and 0.5 $\mu$m wide, which are probably affected by some structural imperfections. Numerical simulations performed by means of a Beam Propagation Method (BPM) tool provide an estimate of the loss contribution given by the fiber-to-waveguide coupling at the two input/output facets (dashed line). Pure propagation losses are expected to range from 0.06 to 0.08 dB/cm over the whole third telecom window.

In addition, very low levels were also measured for the waveguide PDL, as shown in Fig. 11 (solid line). The measured PDL is due to both the polarization-dependent fiber-to-waveguide coupling efficiency (BPM simulations, dashed line) and the polarization-dependent propagation loss. The higher
propagation loss is observed for TM polarization, which is about 0.17 dB/cm more than TE polarization, independent of the waveguide width. A possible explanation for the higher TM loss can be related to the different field distributions of the TE and TM modes, as shown in Fig. 4. The TM mode, whose intensity is located mainly in the vertical nitride layers, is likely to suffer much more than TE from the roughness of the inner TEOS interfaces, which are shaped by the etching process. On the contrary, the TE mode is almost entirely confined in the horizontal layers, whose interfaces are reasonably much smoother, being obtained by deposition processes only. At present, this issue is still under investigation, and further cut-back measurements will be carried out to reach a better insight into the effect. Note that the PDL due to fiber coupling (dashed line in Fig. 11) can be reduced by properly tapering the waveguide near the chip facets.

One of the key points of the experimental investigation concerns birefringence measurements. Fig. 12 shows the measured group birefringence $B_g$ (circles) and the phase birefringence $B_p$ (squares) of the straight waveguides in Figs. 10 and 11. The group birefringence was directly measured by means of a polarization-sensitive optical low-coherence interferometric technique [36]. The local phase birefringence was derived from the analysis of the polarization rotation of the light backscattered by the waveguide [37]. The accuracy of the measurement is $\pm 10^{-3}$ for the group birefringence and $\pm 10^{-4}$ for the phase birefringence. A strong dependence of the birefringence on the waveguide width is observed. Nonetheless, the noticeable agreement with numerical simulations (dashed lines) proves that the technological process employed is sufficiently controllable to tailor the waveguide birefringence to any desired value. From one side, both $B_g$ and $B_p$ can contemporarily be reduced to very low values, as required by polarization-insensitive devices. Even the zero crossing point, where the sign of birefringence reverses, was demonstrated to be very close to the expected one ($h_x = 1 \mu m$). On the other hand, large values of birefringence $(10^{-2})$ can be easily obtained by playing on the waveguide width. As discussed in Section II, these high-birefringence waveguides could find a large number of applications for the realization of polarization-sensitive devices, such as polarization splitters and filters. For the waveguides in Fig. 12, the width $h_x$ can be increased up to 2.5 $\mu m$ while keeping the single-mode regime.

It can be noted that the agreement with simulation gets worse at small $h_x$ only for the case of group birefringence. To justify this behavior, Fig. 13 displays the measured (circles) and simulated (dashed lines) group indexes of the TE and TM fundamental modes. It is evident that the discrepancy observed in the group birefringence has to be attributed to the TM mode, whose group index does not strictly follow the numerical prediction for waveguide narrower than 1.5 $\mu m$, where the group index is slightly lower than expected. This effect could be due to the fact that the TM mode is much more sensitive than TE to any inaccuracy concerning the vertical layers (e.g., thickness, side-wall angle, material anisotropy), whose realization is more critical than that of the horizontal ones. Besides technological tolerances, the origin of such discrepancy could partially depend also on simulation inaccuracies, since material dispersion and material anisotropy and stresses were neglected at a first approximation. Anyway, this issue is going to be further investigated in the next fabrications.

The bending capabilities of the BS waveguide were evaluated from the insertion loss of several waveguides with radii ranging from 65 nm. Dashed lines (simulation) show the contribution given by the PDL of the fiber-to-waveguide coupling (two facets). The local phase birefringence, which is $\pm 10^{-4}$ for the phase birefringence, was demonstrated to be very close to the expected one ($h_y = 65 \text{ nm}$). Numerical simulations are shown in dashed lines.

Fig. 11. Solid lines show the measured PDL of a 6.25-cm-long BS waveguide for different waveguide widths $h_x$. The thickness of the $\text{Si}_3\text{N}_4$ layers is 65 nm. Dashed lines (simulation) show the contribution given by the PDL of the fiber-to-waveguide coupling (two facets).

Fig. 12. Measured (circles) group birefringence $B_g$ and (squares) phase birefringence $B_p$ of straight BS waveguides versus the waveguide width $h_x$ ($h_y = 0.6 \mu m$, $t = 65 \text{ nm}$). Numerical simulations are shown in dashed lines.

Fig. 13. (circles) Measured and (dashed lines) simulated group effective index of the fundamental TE and TM modes of straight BS waveguides versus the waveguide width $h_x$ ($h_y = 0.6 \mu m$, $t = 65 \text{ nm}$).
PDL increases faster for the waveguide with waveguides in Fig. 14. With the reduction of the bending radius, is defined as the difference between TM and TE loss, of the bent the effects on TM polarization. Fig. 15 shows the PDL, which bending loss for TE polarization, one has to also take care of nitride layer, as shown by Fig. 5. from 2 mm to 250 μm. A polarimetric setup was employed to discern TE and TM bending losses. As shown in Fig. 14, where the TE case is reported, bending loss keeps below 0.15 dB/rad for radii down to 750 μm (h_x = 1 μm) and down to 500 μm for wider waveguides (h_x = 2 μm). A good agreement with BPM numerical simulations (asterisks) was observed. As anticipated in Section II-C, looking at the mode confinement in bends, it can be stated that the BS TriPleX waveguide with t = 65 nm behaves as a conventional buried waveguide with effective index contrast Δn_{eff} = 3%. However, larger Δn_{eff} and tighter bends are predicted for waveguides with a thicker nitride layer, as shown by Fig. 5.

Although a larger channel width allows the reduction of the bending loss for TE polarization, one has to also take care of the effects on TM polarization. Fig. 15 shows the PDL, which is defined as the difference between TM and TE loss, of the bent waveguides in Fig. 14. With the reduction of the bending radius, PDL increases faster for the waveguide with h_x = 2 μm. This result is in agreement with the numerical simulation reported in Fig. 3, which states that waveguide widening, while increasing TE confinement, pushes the fundamental TM mode toward the cutoff. Therefore, larger BS waveguides necessarily exhibit larger PDL in bends. However, it should be noted that PDL remains almost unaffected with respect the straight waveguide (dashed line in Fig. 15) down to 1.25-mm bending radius.

**V. CONCLUSION**

The BS waveguide presented in this paper is believed to open many attractive perspectives in the integrated optics panorama. First of all, it offers the unequalled possibility of arbitrarily and continuously tailoring the waveguide effective index contrast by simply combining a few layers of two fixed conventional materials. By only acting on the waveguide geometry and without changing the refractive index of the materials, which are conveniently kept to stoichiometric composition, different confinement regimes can be achieved and optimized to the specific application. This concept fits well the design rules of the integrated components industry, because it enables the reuse of the same technology for devices requiring either very low or very high index contrasts, and is expected to carry remarkable advantages in terms of cost effectiveness of the fabricated devices. Furthermore, it provides a powerful strategy to access all those intermediate index contrasts not achievable by conventional technologies, with remarkable advantages with respect to alternative solutions employing material refractive index tuning (e.g., PECVD SiON).

High flexibility in the optimization of the BS waveguide polarization dependence has been pointed out. Thanks to the unusual field distribution of the guided modes, birefringence and PDL can be accurately reduced or increased by slightly changing the waveguide geometry. Simple rules for the design of zero-birefringence waveguides have been discussed and supported by experimental validation. Propagation regimes suitable for the realization of either polarization-insensitive devices or strongly polarization-sensitive devices can be found, thus opening the way to the straightforward integration of different functionalities on the same chip.

The fabrication of the BS waveguide does not require outstanding technologies but can be effectively realized by means of standard low-cost process. Experimental results on first prototypical samples fabricated in CMOS-compatible LPCVD Si_3N_4 TriPleX technology exhibited highly competitive optical properties. Propagation losses as low as the state-of-the-art low-index-contrast waveguides (< 0.1 dB/cm), very low PDL (< 0.1 dB/cm), and easy interconnection with optical fibers (< 0.15 dB/facet) have been demonstrated in single-mode BS waveguides. With respect to conventional Si_3N_4 strip waveguides, a tighter curvature can be reached with the additional benefit of a strongly reduced polarization sensitivity.

All the presented results undoubtedly demonstrate that the BS waveguide can be a promising candidate to satisfy the new requirements of large-scale integrated optics for applications in the field of both optical communications and sensors. For sensing devices, further interesting developments could be oriented to the realization of hollow BS waveguides with a high-index layer surrounding an air inner region. With respect to the hollow-core waveguides discussed in Section I, a lower interaction between the guided field and the material filling the waveguide is expected, the optical field being mainly confined in the high-index outer layer. However, the extremely simpler fabrication process and the advanced optical properties
discussed in this paper demonstrate that BS waveguides could provide a valuable alternative to sensors exploiting propagation in hollow-core ARROW waveguides.

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REFERENCES


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