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Silicon Nitride-on-Insulator Photonics Polarisation Convertor

D.M. Mokhovikov[1], E.S. Barbin[1], T.G. Nesterenko[1], A.A. Talovskaya[1], A.S. Myrzakhmetov[1], I.V. Kulinich[1], P.F. Baranov[2], D.P. Il'yaschenko[2]

*[1]Tomsk State University of Control Systems and Radioelectronics,
Lenin Ave., 40, Tomsk 634050, Russia*

*[2]National Research Tomsk Polytechnic University,
Lenin Ave., 30, Tomsk 634050, Russia*

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Abstract

Photonic integrated circuits constitute a vital component of contemporary telecommunications systems, facilitating traffic management and reducing energy consumption. However, the integration of these components presents a significant challenge in the form of high polarization sensitivity, which has the potential to limit the overall performance of the device. The objective of this study was to develop a design method and fabrication technology for polarization converters based on silicon nitride-on-insulator. The design of the polarization converters was optimised through the utilisation of finite element method simulations, conducted using the ANSYS Lumerical software. The device features an asymmetric rib waveguide, which facilitates efficient polarisation rotation. The technological implementation comprised plasma chemical vapor deposition of silicon nitride films, three-dimensional laser lithography, and reactive ion etching. A technological assessment determined that the reproducibility tolerance was ±60 nm. To address this limitation, a mirrored section was incorporated into the polarization converter design, thereby increasing the allowable fabrication tolerance to ±215 nm without compromising device performance. The optimised polarization converter exhibited a high level of polarization rotation efficiency, reaching 96.3 %, and an output power of 98.32 %. The utilisation of an asymmetric rib waveguide was pivotal in attaining these outcomes, facilitating the transfer of optical power from fundamental transverse electric to fundamental transverse magnetic modes. The incorporation of a mirrored section enhanced the device's manufacturability, maintaining performance despite geometric deviations. These findings highlight the robustness of the proposed design under typical fabrication constraints. This study presents a novel design and fabrication method for silicon nitride on insulator-based polarization converters. The proposed approach improves efficiency and stability. These results provide a foundation for future advancements in integrated photonics, with potential applications in telecommunications and beyond.

Keywords: polarisation converter; asymmetric waveguide; silicon nitride on insulator; photonic integrated circuits

Адрес для переписки:
Моховиков Д.М.
Томский государственный университет систем управления и радиоэлектроники,
пр-т Ленина, 40, г. Томск 634050, Россия
e-mail: denis.m.mokhovikov@tusur.ru

Address for correspondence:
Mokhovikov D.M.
Tomsk State University of Control Systems and Radioelectronics,
Lenin Ave., 40, Tomsk 634050, Russia
e-mail: denis.m.mokhovikov@tusur.ru

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Конвертор поляризации на основе нитрида кремния на изоляторе

Д.М. Моховиков[1], Е.С. Барбин[1], Т.Г. Нестеренко[1], А.А. Таловская[1], А.С. Мырзахметов[1], И.В. Кулинич[1], П.Ф. Баранов[2], Д.П. Ильященко[2]

[1]Томский государственный университет систем управления и радиоэлектроники, пр-т Ленина, 40, г. Томск 634050, Россия

[2]Национальный исследовательский Томский политехнический университет, пр-т Ленина, 30, г. Томск 634050, Россия

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Фотонные интегральные схемы являются важнейшим компонентом современных телекоммуникационных систем, упрощая процесс управления трафиком и снижая энергопотребление. Однако интеграция подобных компонентов представляет собой серьезную проблему в виде высокой поляризационной чувствительности, которая может ограничить общую производительность устройства. Цель данного исследования – разработать метод проектирования и технологию изготовления поляризационных конвертеров на основе нитрида кремния на изоляторе. Задача данного исследования – удовлетворить специфические требования российских систем плотного мультиплексирования с разделением по длине волны. Конструкция поляризационного конвертора оптимизирована с помощью моделирования методом конечных элементов, проведённого с использованием ANSYS Lumerical. Устройство имеет асимметричный гребенчатый волновод, обеспечивающий вращение поляризации. Технологическая реализация выполнена с использованием плазменно-химического осаждения плёнок нитрида кремния, 3D-лазерной литографии и реактивного ионного травления. В результате установлено, что технологическая погрешность воспроизведения геометрии составляет ±60 нм. Для увеличения допуска, в конструкцию поляризационного конвертора встроена зеркально-отражённая секция, что позволило увеличить допуск на изготовление до ±215 нм без ухудшения характеристик устройства. Оптимизированный конвертор поляризации продемонстрировал эффективность вращения поляризации, достигающую 96,3 %, и выходную мощность 98,32 %. Использование асимметричного гребенчатого волновода обеспечило достижение этих результатов, способствуя передаче оптической мощности от поперечной электрической фундаментальной моды к поперечной магнитной фундаментальной моде. В данном исследовании представлен новый метод проектирования и изготовления поляризационных конвертеров на основе нитрида кремния на изоляторе. Предложенный подход повышает эффективность и стабильность контроля поляризации, тем самым обеспечивая разработку надёжных и экономически эффективных оптических устройств в системах плотного мультиплексирования с разделением по длине волны. Эти результаты создают основы для будущих достижений в области интегральной фотоники в области телекоммуникаций и за её пределами.

Ключевые слова: контроль, конвертор поляризации, асимметричный волновод, нитрид кремния на изоляторе, фотонные интегральные схемы

Адрес для переписки:
Моховиков Д.М.
Томский государственный университет систем управления и радиоэлектроники,
пр-т Ленина, 40, г. Томск 634050, Россия
e-mail: denis.m.mokhovikov@tusur.ru

Address for correspondence:
Mokhovikov D.M.
Tomsk State University of Control Systems and Radioelectronics,
Lenin Ave., 40, Tomsk 634050, Russia
e-mail: denis.m.mokhovikov@tusur.ru

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Introduction

The necessity for more rapid and energy-saving broadband networks is driving global research policy in optical transmission [1]. Photonic integrated circuits are utilised in modern telecommunications networks to create networks capable of accommodating increasing traffic. This approach reduces power consumption by at least 50 % compared to traditional integrated circuits [2]. Integrating photonic integrated circuits elements has led to a new challenge: high sensitivity to polarisation. This issue can be addressed by implementing polarisation diversity or conversion schemes. As a result, there has been a surge develop passive components designed to meet the demanding requirements for polarisation sensitivity in circuits [3–5].

The process of polarisation conversion is achieved through special passive components, namely polarisation converters. Convertors are constructed as asymmetric ribbed waveguides with distinctive cross-sectional shapes. By the findings reported in [6–8], the lengths of these structures range from 20 to 150 μm. Furthermore, the devices can convert transverse electric (TE) versus transverse magnetic (TM) modes with an efficiency exceeding 90 %. Additionally, this outcome can be attained by cone waveguides with a length ranging from 200 to 1500 μm, which exhibit a comparable conversion efficiency but with larger dimensions [9, 10].

The primary challenge is reproducing the geometry of the integral optical polarisation converters, which causes high lithography precision, many technological operations, and minimal roughness of both the waveguide walls and the substrate surface [11]. A comparative analysis of integrated-optical polarization converters on different photonic platforms has revealed several advantages associated with silicon nitride on insulator devices. These devices are characterised by low insertion loss, less than 1 dB, high polarisation conversion efficiency exceeding 95 %, and a wide range of operating wavelengths [12, 13]. It is also noteworthy that silicon nitride on insulator polarization converters present fewer challenges to the lithographic process and that they can be integrated with a variety of photonic platforms based on thin-film lithium niobate ($LiNbO_3$), silicon-on-insulator, and indium phosphide (InP) [14, 15].

This paper presents new geometrical solutions for integral-optical polarisation converters, enhancing polarisation conversion efficiency with reduced dimensions. We also describe a detailed technological roadmap for cheap polarisation convertor fabrication. This study aims to improve the design and manufacturing capabilities of Russian dense wavelength division multiplexing systems on any photonic platform by creating a comprehensive design methodology and technology for silicon nitride on insulator polarisation converters. This comprehensive design methodology and technology involve a detailed analysis of the polarisation converter, modelled and simulated in ANSYS Lumerical software using the finite element and finite difference methods in the time domain. Additionally, it includes the technological implementation method, which involves using 3D laser photolithography and reactive ion etching of silicon nitride formed by plasma chemical deposition in high-density plasma.

Section I outlines the main issues related to polarisation control in modern photonic systems. Section II, titled "Materials and Methods", comprehensively analyses the polarisation converter, modelled and simulated in ANSYS Lumerical software using the finite element and finite difference methods in the time domain. Additionally, this section describes the technological implementation method, which involves using 3D laser photolithography and reactive ion etching of silicon nitride formed by plasma chemical deposition in high-density plasma. Section III, "Results", presents the observations of the simulations using optimisation and compares the accuracy and error of the models against the fabricated sample. Section IV, "Discussion", compares the results with previous studies.

Materials and methods

The cross-sectional geometry of the polarisation converter is modelled using the finite element method [16]. This method offers high accuracy in the model's convergence with the real world. Several techniques can fabricate thin films, with radio-frequency magnetron sputtering [17] and plasma chemical vapour deposition [18] being two methods. This work utilises the latter method in high-density plasma [19]. It can produce films with a broad spectrum of stoichiometric compositions with greater precision, which prioritises the characteristics of the film.

Design of polarisation converter

The mathematical model for the integral optical polarisation converter was created using software for calculating and designing photonic integrated circuits, specifically ANSYS Lumerical. This was achieved through the use of the finite element method, a technique employed in the analysis of various photonic devices based on their geometry and properties of the materials included in their composition. The principal mathematical apparatus of this method is concerned with mode profiles, cut-off frequencies, and effective refractive indices, which enables the geometry of the waveguide in an integrated photonic system to be optimised, as shown by Wang Q. [20].

The model of the integral optical converter is a waveguide rib structure based on silicon nitride on insulator, comprising a rectangular rib waveguide at the input, an asymmetric rib waveguide performing the polarisation rotation function, and a rectangular rib waveguide at the output (Figure 1).

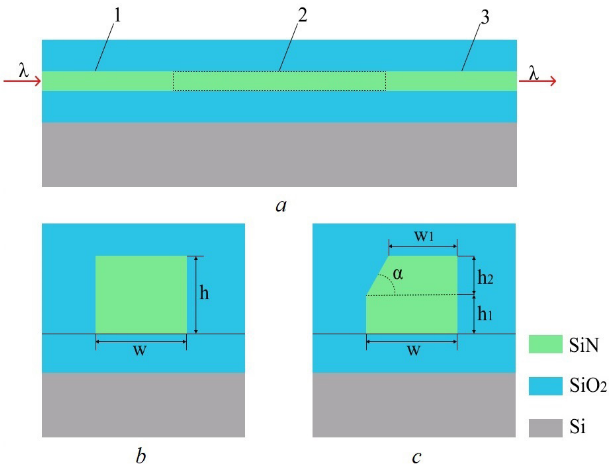

Figure 1 – A scheme of the integrated optical converter: *a* – a structure of polarisation converter system top view; *b* – a cross-section of the direct ridge waveguide; *c* – a cross-section of the asymmetric ridge waveguide; 1 – input ridged waveguide; 2 – asymmetric ridged waveguide; 3 – output ridged waveguide

This model presents plane-polarised light with a wavelength of 1.55 µm propagates in the crest of the SixNy-based waveguide with a refractive index of 2. After that, the light wave passes through the rotation section, which is an asymmetric waveguide. This asymmetric waveguide, a key component in the polarisation conversion process, is designed to induce a 90° polarisation rotation in the light wave. The light wave exits the rectangular rib waveguide, completing the polarisation conversion process.

Fabrication of polarisation converter

The initial stage involves treating the wafer surface to remove organic contaminants (Figure 2*a*). A 100 mm diameter Silicon-based wafer with crystallographic orientation (111) is used. It is placed in dimethylformamide at 150 °C for 20 min. Then, it is treated in isopropyl alcohol at 25 °C for 5 min. Finally, it is dried in a nitrogen atmosphere.

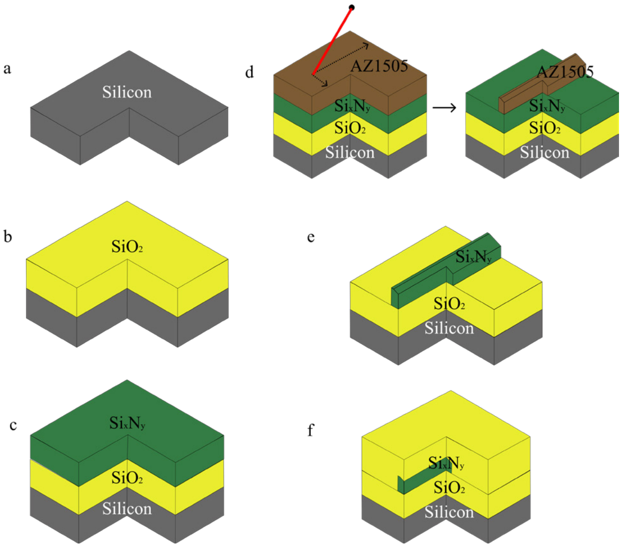

Figure 2 – Technological process route for the fabrication of an integrated-optical polarisation converter: *a* – wafer cleaning; *b* – deposition of SiO_2; *c* – deposition of Si_xN_y; *d* – laser lithography; *e* – Si_xN_y plasma etching; *f* – deposition of SiO_2

The second step is the plasma chemical deposition of a silicon dioxide (SiO_2) film (Figure 2*b*). The wafer is loaded into the working chamber of the STEICP200D unit. SiO_2 deposition is performed in a monosilane (SiH_4) and nitrous oxide (N_2O) atmosphere. The gas flow ratio is 120/20 cm³/s, and the chamber pressure is 1.7 Pa. The inductive coupled plasma source power is 600 W. The deposition occurs at 300 °C for 4870 s, resulting in a two µm thick SiO_2 film.

The third step involves the deposition of silicon nitride (Si_xN_y) (Figure 2*c*). SixNy deposition is conducted in situ, following the silicon dioxide (SiO_2) deposition, in a monosilane (SiH_4) and nitrogen (N_2) atmosphere. The gas flow ratio is 170/5.5 cm³/s, and the chamber pressure is 3.7 Pa. The inductive coupled plasma source power is 600 W, and the RIE source power is 50 W. The deposition occurs at 270 °C for 2000 s, producing an 800 nm thick Si_xN_y film.

The fourth step is the 3D photolithography process to obtain an asymmetric ridge structure (Figure 2*d*). The wafer is calcined at 200 °C for 5 min. Then, AZ1505 photoresist is applied by centrifugation on an OPTI Spin SB20 at 1600 rpm with 400 acceleration. This creates an 800±10 nm thick resist layer. The resist is dried at 100 °C for 4 min. Then, it is exposed under specific parameters.

The fifth step is the plasma chemical etching of Si_xN_y on the STEICP200E unit (Figure 2*e*). The wafer is loaded into a chamber at 23 °C. Si_xN_{y}-etching is performed in an SF6 atmosphere with a gas flow rate of 50 cm³/s. The chamber pressure is 2.1 Pa, and the reactive ion etching source power is 34 W. Etching occurs for 800 s, monitored by an interferometer. This ensures the complete removal of Si_xN_y in the opened field area and the resist. This process has a selectivity of $S = 1$.

The sixth step is similar to step 2 (Figure 2*f*).

The abovementioned method represents the technological approach to realising silicon nitride on insulator-based integrated optical converters. These technological operations can also be employed to fabricate other silicon nitride on insulator-based photonic devices.

Results

Input/Output waveguides

To achieve maximum efficiency (100 %) in polarisation rotation and output power (100 %), the design of the input rib waveguide must ensure that the confinement factor for the TE mode (Γ^{TE}) is 100 % and for the TM mode (Γ^{TM}) is 0 %. Additionally, the design of the polarisation rotation section (asymmetric rib waveguide) must ensure that Γ^{TE} and Γ^{TM} are each 50 % for their respective modes. A modal analysis of a single-mode rib waveguide was conducted for various crest widths (w), with the height (h) equal to w (Figure 3).

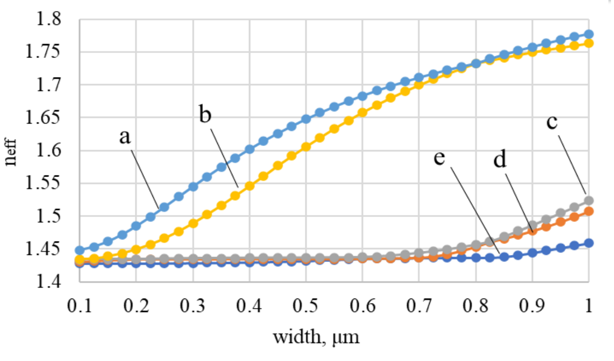

Figure 3 – Dependence of the effective refractive indices n_{eff} of various modes on the waveguide side width w: a – TE_0; b – TM_0; c – TE_1; d – TM_1; e – TE_2

The modal analysis results indicate that the effective refractive indices of the TE_0 and TM_0 modes converge at crest widths (w) and heights (h) of the waveguide starting from 800 nm. However, due to the maximum silicon nitride film thickness being limited to 800 nm by the technological capabilities of the Nanotechnology Research and Educational Center at TUSUR, further studies were conducted with $h = 800$ nm. The impact of the waveguide crest width (w) on the confinement factors of the TE_0 and TM_0 modes was investigated. The results showed that $\Gamma^{TE} = 100$ % and $\Gamma^{TM} = 0$ % are achieved with a crest width of $w = 850$ nm.

Polarisation Rotation Section

Subsequently, the impact of the geometric parameters of the asymmetric rib waveguide on the efficiency of polarisation rotation, facilitated by the transfer of optical power from the TE_0 to the TM_0 mode, was investigated. The geometric parameters of the rotation section that maximise polarisation rotation efficiency were determined. The cross-sectional geometric parameters of the asymmetric waveguide are demonstrated in Figure 4. The calculation results are presented in Table.

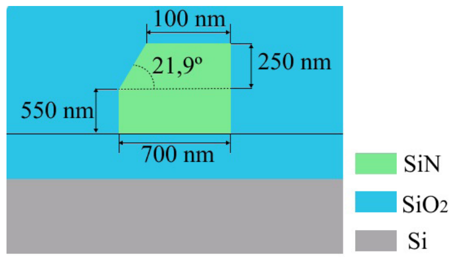

Figure 4 – Geometric parameters of the polarisation conversion section with maximum efficiency

Table

Polarisation converter parameters using geometry for maximum efficiency

Γ^{TE}, %	Γ^{TM}, %	P, %	L, μm	TE_0 to TM_0, %
50	50	98.32	57	96.3

Despite the developed integral optical converter design's high polarisation rotation efficiency (96.3 %) and output power (98.32 %), the technological assessment revealed this geometry's reproducibility tolerance is ±60 nm. Exceeding this tolerance significantly reduces the device's efficiency. To expand the range of technological error, the length of the conversion section was doubled, and

25 % of the length of the asymmetric waveguide was mirrored (Figure 5).

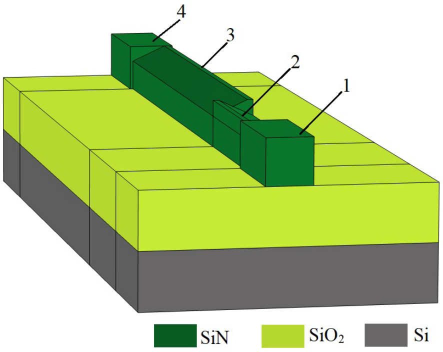

Figure 5 – Scheme of a model of an integrated optical converter with a mirror-reflected asymmetric waveguide: 1 – input rib rectangular waveguide; 2 – mirror-reflected asymmetric waveguide; 3 – asymmetric waveguide; 4 – output rectangular waveguide

Using the mirrored section, the allowable technological error increased to 215 nm, maintaining a polarisation conversion efficiency of 96.3 % and an output power of 98.32 %. The length of the polarisation converter section (L) was 114 µm.

Discussion

The study aimed to optimise the design of a polarisation converter in an integral optical waveguide system, achieving both high polarisation rotation efficiency and output power. The results indicate that specific geometric configurations of the waveguide are crucial in attaining these goals.

Polarisation Rotation Efficiency and Output Power

The modal analysis on the single-mode rib waveguide demonstrated that the effective refractive indices for the TE_0 and TM_0 modes converge at a crest width (w) and height (h) starting from 800 nm. This convergence is critical for ensuring effective mode confinement and polarisation rotation. Our findings suggest that a crest width of 850 nm and a height of 800 nm optimise the confinement factors, with Γ^{TE} reaching 100 % and Γ^{TM} falling to 0 %. This configuration effectively isolates the TE mode, minimising TM mode confinement, which is essential for maintaining high polarisation purity and minimising losses.

Technological Tolerance and Reproducibility

A critical aspect of the design is its manufacturability within the technological constraints of available fabrication processes. The initial design, with a tolerance of ±60 nm, posed significant challenges for consistent production, as slight deviations could drastically reduce efficiency. To address this, we proposed a design modification by extending the length of the polarisation conversion section and incorporating a mirrored segment.

The mirrored segment works by reversing the slope direction of the rib waveguide, altering the phase relationship between the TE and TM modes. This reversal creates an additional phase shift, allowing the gradual accumulation of polarization rotation over the extended waveguide length. By redistributing the phase mismatch along a longer interaction region, the mirrored segment compensates for geometric variations caused by fabrication errors. As a result, the extended length to 114 µm, with 25 % of it mirrored, increases the allowable technological error to ±215 nm while maintaining a polarisation conversion efficiency of at least 95 % and preserving output power.

This adjustment ensures that the device remains effective even with variations in fabrication, enhancing reproducibility and practical applicability.

Conclusion

This study successfully developed a design method and fabrication technology for polarization converters based on silicon nitride-on-insulator material. The research identified and optimized the key geometric parameters of the asymmetric rib waveguide, achieving a polarization rotation efficiency of 96.3 % and an output optical power of 98.32 %. These results highlight the importance of precise waveguide geometry in maintaining high conversion efficiency.

A major innovation of this work is the incorporation of a mirrored section into the polarization converter. This section reverses the slope direction in the comb-like rib waveguide, configured as 25 % straight section and 75 % mirrored section relative to the OY plane in the cross-section. The mirrored section modifies the polarization rotation direction by altering the phase relationship between the transverse electric and transverse magnetic modes. This change increases the variation in the effective refractive index within the waveguide structure by approximately 30 %. While the total device length increased by 15 %, the design significantly improved fabrication robustness. The fabrication tolerance expanded from ±60 nm to ±215 nm, maintaining a minimum polarization rotation efficiency of 95 %.

The silicon nitride-on-insulator platform further distinguishes this work by offering compatibility with widely used integration technologies, such as silicon-on-insulator and indium phosphide. This compatibility allows the polarization converters to integrate seamlessly into modern photonic circuits. The compact size, high efficiency, and enhanced manufacturability make the proposed design highly suitable for dense wavelength division multiplexing systems and other advanced photonic applications.

Future research should prioritize experimental validation of the proposed theoretical findings and explore new materials to enhance the polarization converter's performance. Additionally, extending the design to support broader fabrication tolerances and additional waveguide platforms could enable its adoption in diverse areas of integrated photonics.

This study establishes a foundation for future advancements in photonic integration, paving the way for the development of reliable, cost-effective, and high-performance optical devices for telecommunications and related domains.

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