Photonic device

Design a single mode rib waveguide with zero birefringence

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1. Introduction

In photonic integrated circuits, silicon-on-insulator (SOI) rib waveguides are very important because they offer high refractive index contrast, strong mode confinement, low propagation loss, and full compatibility with CMOS (Complementary Metal-Oxide-Semiconductor) fabrication processes. Zero birefringence—making sure that the effective refractive indices of the fundamental transverse electric (TE) and transverse magnetic (TM) modes are equal (or nearly equal)—is one of the hardest parts of waveguide design, especially for devices that don't depend on polarization. This difference in index causes birefringence, which affects propagation based on polarization and can make the device less effective. In this document, we focus on designing a single-mode silicon rib waveguide with zero birefringence, optimizing its geometry to achieve polarization-independent operation. We studied some papers to better understand the concept of our task. The lists of these papers are in the reference section.

Objective:

The goal of this project is to design a single-mode rib waveguide on an SOI platform that exhibits negligible birefringence. The "starting dimensions" are:

- Core (Si) index $n_{Si} \approx 3.45$ (at λ=1.55 μm)
- Cladding (SiO2) index $n_{SiO2} \approx 1.45$.
- Total silicon device layer thickness: 260 nm
- Slab thickness: 170 nm
- Rib thickness: 90 nm
- Waveguide width: w

We seek:

1. Single-mode behavior for both TE and TM polarizations.
2. Zero (or minimal) birefringence, $\Delta n_{eff} = n_{effTE} - n_{effTM}$

2. Theoretical Background

2.1 Rib Waveguide Geometry

A typical SOI rib waveguide cross-section is shown schematically in Fig. 1. The silicon device layer is partially etched, forming a "rib" of height H_{rib} above a remaining "slab" of height H_{slab}.

The sidewalls define a waveguide width w. The buried oxide (BOX) layer beneath has an index ≈1.45.

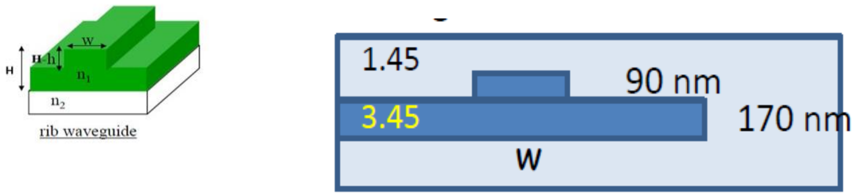

Fig.1. Rib Waveguide Geometry

2.2 Single-Mode Operation

A waveguide is a single mode for a given polarization if only the fundamental mode can propagate at the wavelength of interest. For rib waveguides, the effective index method or a 2D mode solver can be used to check whether higher-order modes are cut off.

2.3 Birefringence in Rib Waveguides

Birefringence Δn_{eff} arises when the TE and TM polarizations see different mode confinement or different boundary conditions, leading to distinct effective indices. By carefully choosing rib height H and width w, the waveguide can be made nearly polarization-independent, i.e., $\Delta n_{eff} \approx 0$.

3. Design Approach

1. **Parameter:**
    - Total Silicon Thickness, H
    - Slab Thickness, h
    - Rib Etch Depth: $H_{etch} = H - h$
    - Ratio $r = h / H$
    - Waveguide Width W
2. **Mode Solver / Simulation:**
    - EIMS Mode solver for 2-D multilayer waveguides, variational effective index approximation (https://www.computational-photonics.eu/eims.html)
3. **Zero Birefringence Condition**
    - $\Delta n_{eff} = n_{effTE} - n_{effTM}$

4. Simulation Results and Discussion

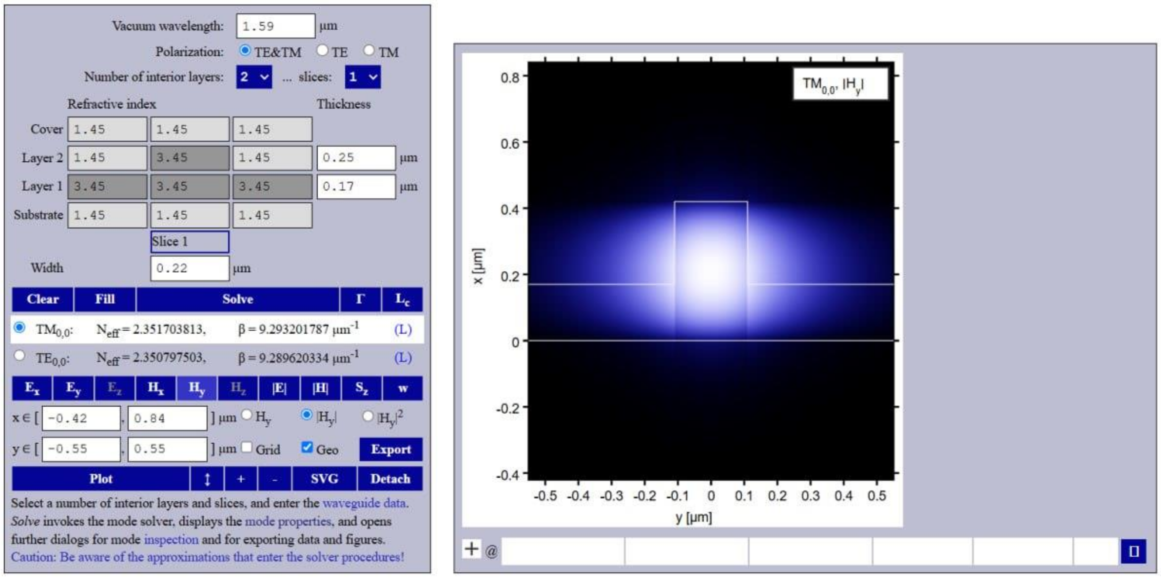

Fig.2. Simulation of the best result.

Table.1. Numerical Results.

λ(nm)	W(nm)	H(nm)	h(nm)	H – h	r	n_{effTE}	n_{effTM}	Δn_{eff}	Single Mode?
1550	200	260	170	90	0.6538	2.5603	1.81	0.7502	Yes
1550	300	260	170	90	0.6538	2.6361	1.9180	0.718	Yes
1550	400	260	170	90	0.6538	2.7024	2.0158	0.6866	Yes
1550	500	260	170	90	0.6538	2.7536	2.471	0.2825	No
1550	200	370	170	200	0.4594	2.3982	2.2384	0.1598	Yes
1550	300	370	170	200	0.4594	2.6089	2.4330	0.1758	Yes
1550	400	370	170	200	0.4594	2.7681	2.5602	0.2079	No
1550	200	420	170	250	0.4047	2.3421	2.3224	0.1960	Yes
1550	210	420	170	250	0.4047	2.3685	2.35	0.0185	Yes
1550	300	420	170	250	0.4047	2.5930	2.5586	0.0343	No
1590	210	420	170	250	0.4047	2.3263	2.3238	0.0025	Yes
1590	220	420	170	250	0.4047	2.351703813	2.350797503	**0.00090631**	Yes
1600	210	420	170	250	0.4047	2.3174	2.3158	0.0016	Yes
1600	220	420	170	250	0.4047	2.3441	2.3411	0.003	Yes
1550	200	220	130	90	0.5909	2.3377	1.5463	0.7913	Yes
1550	300	220	130	90	0.5909	2.4425	1.6273	0.8152	Yes
1550	400	230	140	90	0.6086	2.5811	1.7755	0.8055	Yes

This report presented a numerical simulation and parametric study to design a single-mode silicon rib waveguide structure that achieves zero birefringence (polarization independence). The goal was to identify the optimal waveguide width that minimizes the difference in effective refractive indices between fundamental TE and TM modes.

At a wavelength of 1590 nm, with waveguide width W = 220 nm, H = 420 nm, h = 170 nm, and H-h = 250 nm, the minimum birefringence Δn_{eff} was achieved. This indicates almost perfect polarization independence (TE and TM modes have nearly identical effective indices). This configuration yields zero birefringence (practically polarization-independent) and guarantees single-mode propagation, which is essential for integrated photonic circuits where polarization independence and mode stability are critical.

Several waveguide configurations were tested for single-mode conditions. Notably, the optimal waveguide dimension identified (W=220 nm) meets the single-mode requirement. Waveguides marked as "No" (highlighted in red) did not fulfill single-mode criteria and hence were unsuitable for practical single-mode applications.

References

1. Soref, Richard A., Joachim Schmidtchen, and Klaus Petermann. "Large single-mode rib waveguides in GeSi-Si and Si-on-SiO/sub 2." IEEE Journal of Quantum Electronics 27.8 (1991): 1971-1974. “Waveguides and Couplers,” *Slides on Waveguides*, Politecnico di Milano, 2025.
2. Yusof, Nor Roshidah, et al. "Zero birefringence condition in lithium niobate on insulator rib waveguides." Advanced Theory and Simulations 7.3 (2024): 2300853.