

Low-Loss Broadband Parabolic Dielectric Reflector in Silicon-on-Insulator

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Abstract. In this work, we designed a spot-size converter based on parabolic dielectric reflector that couples light from a 0.5 μm -wide waveguide to a 285 μm -wide waveguide, i.e. has an expansion factor of $\times 570$. We assessed its behavior on the silicon-on-insulator commercial platform. We experimentally report insertion losses of less than 0.35 dB in an unprecedented bandwidth of more than 380 nm. We also provide a full analytical design method for arbitrary expansion factors, which does not require any simulation.

Keywords: Integrated Photonics, Silicon-on-insulator, Spot-size Converter, Dielectric Reflector.

1 Introduction

Spot-size converters (SSCs) are essential for coupling waveguides of different sizes, especially for feeding gratings that direct light into fibers or free space. In the latter, spot-size expansions to hundreds of micrometers are needed, which traditional adiabatic tapering cannot achieve efficiently [1].

Silicon-nitride (SiN) platforms use evanescent couplers for large gratings [1], but they suffer from wavelength-dependent propagation angles, causing unwanted variations in radiation. Silicon-on-insulator (SOI) SSCs based on Bragg deflectors also have strong wavelength dependence [2-4], while integrated lenses have been limited to smaller mode-field diameters (MFDs) [5-6].

We here prove that using parabolic dielectric reflectors in SOI are encouraged when extreme conversion with low losses and broad bandwidth are required. Employing the approach here presented, we design a SSC that couples light from a 0.5 μm waveguide to a 285 μm waveguide with losses below 0.35 dB over a 380 nm bandwidth. In terms of the bandwidth \times expansion figure of merit, this corresponds to a 98-fold improvement over the previous parabolic dielectric design proposed in [7].

2 Design and Fabrication

From the classical theory of antennas, we know that parabolic antennas are fed through a small antenna located at the focus of the parabolic reflector. The device presented in Fig. 1 has an analogous operation to an offset parabolic antenna, where the dielectric interface acts as a parabolic reflector with a focal length of F , which follows the equation [7]:

$$y = \frac{x^2}{4F}. \quad (1)$$

Light is injected at port P1, where a taper of length L adiabatically adapts the mode of a single mode waveguide to that of the fundamental mode of a waveguide of width W_{ap} . From this aperture, which acts as the feeder antenna of our parabolic SSC, light diffracts with a divergence angle θ_{div} and finally reaches the output waveguide port P2 after totally reflecting at the parabolic interface. The choice of the aperture size is crucial, as it governs the divergence angle θ_{div} of the diffracting beam in the free space propagating region. The divergence angle is given by the equation:

$$\theta_{\text{div}} = \frac{2.35\lambda_0}{W_{\text{ap}}n_{\text{slab}}}, \quad (2)$$

where λ_0 is the central wavelength and n_{slab} is the effective index of the mode traveling through the propagation region. This angle defines the angular range of rays that will impinge on the parabolic interface. The focal length F required for the beam to be coupled effectively into the output waveguide is then [7]:

$$F = \frac{W_{\text{out}}}{4 \tan(\theta_{\text{div}}/2)}. \quad (3)$$

To minimize losses, all rays need to satisfy total internal reflection, which imposes a lower bound on the divergence angle. This condition is expressed as:

$$\theta_{\text{div}} < \pi - 4 \arcsin\left(\frac{n_c}{n_{\text{slab}}}\right). \quad (4)$$

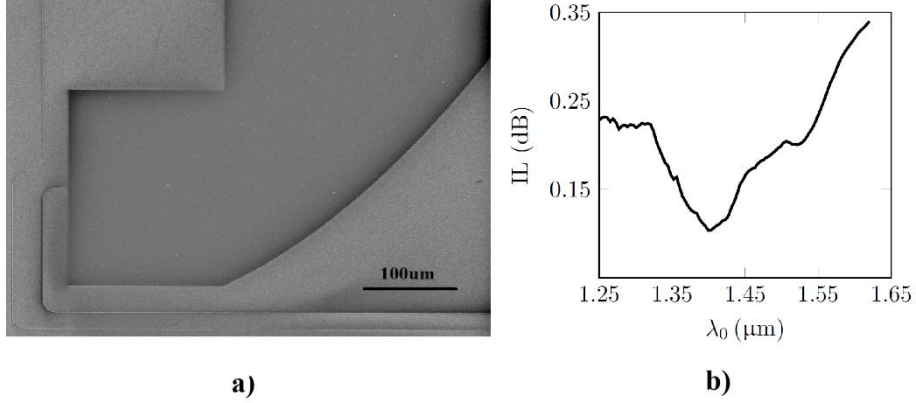
From equations (2) and (3), we find the condition required to fulfill total internal reflection:

$$W_{\text{ap}} > \frac{2.35\lambda_0}{n_{\text{slab}}(\pi - 4 \arcsin(n_c/n_{\text{slab}}))}. \quad (5)$$

The design method proposed here is based on equations (1), (2), (3) and (5), where we first confirm total internal reflection for the fundamental TE mode of the standard SOI platform of 220 nm core height ($n_{\text{slab}} = 2.85$ at $\lambda_0 = 1.55 \mu\text{m}$). This gives $W_{\text{ap}} > 1.3 \mu\text{m}$. When choosing $W_{\text{ap}} = 1.5 \mu\text{m}$, we meet the total internal reflection condition with a certain margin, and we are ready to design a SSC for any arbitrarily wide output waveguide width W_{out} . Finally, aided by Fig. 1, the parabolic reflector is fully defined when selecting $L = 1.2y_b$, with y_b the ordinal coordinate of the upper point in the parabolic interface represented in Fig. 1, with coordinates $[x_b, y_b]$ given by eq. (1)

Table 1. Dimensions (in microns) of the designed SSC.

W_{in}	L_t	W_{ap}	W_{out}	F	L	x_{out}	L_{cb}	L_{ct}	L_{cv}
0.5	10	1.5	285	157.5	455	318	203	23	74.6

**Fig. 2.** Fabricated extreme parabolic SSC with Applied Nanotools foundry. a) SEM of the device. b) Insertion losses measurement of a nominal flavor single device.**Table 2.** Comparison with state-of-the-art SSCs in SOI

Ref.	W_{in} (μm)	W_{out} (μm)	Magnification	IL (dB)	BW_{1dB} (nm)	FoM (μm)
[2-4]	0.5	57	114	0.3	N/A	N/A
[5]	0.5	15	30	0.6	130	3.9
[6]	0.5	10	20	0.8	220	4.4
[7]	0.45	10	22.2	0.15	>100	>2.2
This work	0.5	285	570	0.23	>380	>216.6

3 Conclusions

We have demonstrated that parabolic dielectric interfaces enable highly efficient large spot-size conversions. Using the approach here proposed, we achieved a magnification factor of up to $\times 570$ while maintaining ultra-low losses (below 0.35 dB) over a broad 380 nm bandwidth, leveraging the total internal reflection condition. The design can be fully analytical with minimal impact on insertion loss, making it a strong candidate for integration into a Process Design Kit (PDK).

Acknowledgements. We acknowledge funding through project TED2021-130400B-I00/AEI/10.13039/501100011033/ Unión Europea NextGenerationEU/PRTR and project PDC2023-145833-I00/ Ministerio de Ciencia, Innovación y Universidades.

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