Characterization of On-Chip Waveguide Loss

Research Paper for Labs in Photonics Research

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***Abstract*—This study characterizes transmission losses in on-chip waveguides and bends using laser measurements on waveguides with varying lengths and bends. By isolating coupling and bend losses, we identify key mechanisms such as scattering from surface roughness, absorption, and radiation in straight waveguides, as well as mode mismatch and radiation in bends. These insights validate design models and underscore the importance of optimizing waveguide geometries and fabrication processes in integrated photonics.**

I. Introduction

Waveguide optics is foundational to integrated photonics, enabling compact and efficient devices for optical communication and sensing. These photonic circuits often incorporate curvilinear geometries, such as waveguide bends, to route light effectively. However, these bends can introduce additional transmission losses, particularly if bend radius is too small. During the afternoon session of Module 5 on waveguide optics, we measured the transmission losses of on-chip waveguides, including bends, using a 1550 nm laser source and manual fiber alignment with micrometric stages. This paper analyzes these losses to explore scattering, absorption, and bend-induced mechanisms, critical for validating design models and optimizing fabrication processes.

II. Theoretical Background

Transmission losses in on-chip waveguides and bends arise from multiple physical mechanisms, impacting the performance of integrated photonic circuits. The total loss in straight waveguides is modeled as ($L_{\text{total}} = \alpha \cdot l + L_{\text{fixed}}$), where (α) is the propagation loss (dB/mm), (l) is the length, and (L_{fixed}) includes coupling losses. During light propagation in straight waveguides, the interaction between light and dielectric materials results in absorption. Additionally, deviations from ideal guidance lead to scattering and radiation losses [1]. Understanding these loss mechanisms is crucial for designing efficient photonic circuits and validating theoretical models.

In bends, the phase-front rotates around a center of curvature. Because the group velocity of the phase fronts cannot exceed the local speed of light ((c/n)), there is a point where the phase front bends, causing the mode to shift outward and resulting in radiation losses [1]. Furthermore, mode mismatch at transitions between straight and curved sections introduces additional losses. The annular geometry of bends is well-suited for analysis in polar coordinates, often employing conformal transformations [2] to accurately model field distributions.

These mechanisms collectively determine the performance of routing components in photonic circuits.

III. Experimental Setup

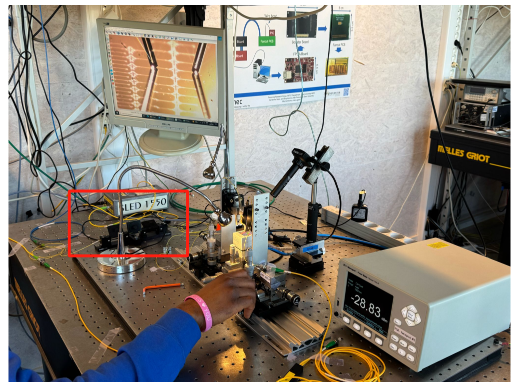

Fig. 1: Measurement setup

The measurement setup, as illustrated in Figure 1, consisted of a 1550 nm laser source with an input power set to 0 dBm. A **polarization rotator** was used to adjust the polarization due to the polarization sensitivity of the grating couplers. The light was coupled into the device under test via a coupling fiber tilted at 12°, and grating couplers were employed for both input and output coupling. To optimize the coupling efficiency, the input fiber was aligned using manual micrometric stages to maximize the output power measured by the photodetector. The output power was then recorded using a photodetector.

IV. Measurement and Characterization

A. Measurement and Analysis

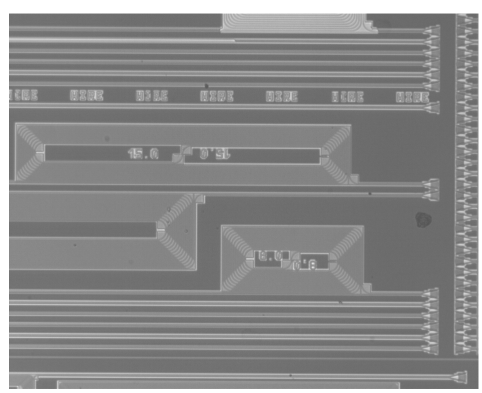

Fig. 2: Microscopy of waveguides being measured

TABLE I: Measured output power for different waveguide lengths (each with 42 bends)

Waveguide Length (mm)	Measured Power (dBm)
8	-15.04
15	-15.80
30	-17.44
60	-19.70

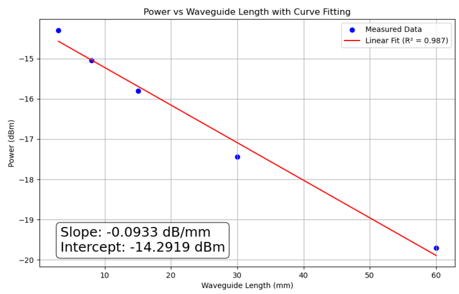

Fig. 3: Fitting for loss versus waveguide length

The output power levels for waveguides of different lengths, each incorporating 42 waveguide bends and coupled through grating couplers, are summarized in Table I. Additionally, the output of a $3\,\mathrm{mm}$ straight waveguide (without bends) coupled through grating couplers was measured at $-14.30\,\mathrm{dBm}$. The laser output, obtained by directly connecting the laser to the output power meter, yields a reading of $-5.523\,\mathrm{dBm}$, indicating an insertion loss of $5.523\,\mathrm{dB}$ attributed to the connection components.

A linear fit of the measured output power (in dBm) versus waveguide length (in mm) is displayed in Figure 3. From this fit, the propagation loss coefficient α is determined to be $0.0933\,\mathrm{dB/mm}$. Using this value, the loss induced by two grating couplers can be calculated as follows:

$$L_{\text{grating pair}} = P_{\text{out, straight}} - \alpha \cdot l - P_{\text{laser}} = 8.497\,\mathrm{dB}$$

Thus, the loss per grating coupler is $4.249dB$, this value aligns with typical grating coupler losses, which range from $3\,\mathrm{dB}$ to $5\,\mathrm{dB}$.

The loss per bend is determined using the output power of a waveguide with 42 bends and a length of $8\,\mathrm{mm}$, measured at $-15.04\,\mathrm{dBm}$. The total loss is:

$$L_{\text{total}} = P_{\text{laser}} - P_{\text{out, bends}} = 9.517\,\mathrm{dB}$$

The loss due to propagation and grating couplers is:

$$L_{\text{propagation}} + L_{\text{grating pair}} = (\alpha \cdot l) + L_{\text{grating pair}} = 9.2434\,\mathrm{dB}$$

Thus, the total bend loss for 42 bends is:

$$L_{\text{bends}} = L_{\text{total}} - (L_{\text{propagation}} + L_{\text{grating pair}}) = 0.2736\,\mathrm{dB}$$

The loss per bend is:

$$L_{\text{bend}} = \frac{0.2736}{42} = 6.51 \times 10^{-3}\,\mathrm{dB/bend}$$

This result is consistent with the previously reported bend loss of $6.43 \times 10^{-3}\,\mathrm{dB}$ per bend.

B. Waveguide loss mechanisms

Transmission losses in straight waveguides stem from three primary mechanisms: scattering, absorption, and radiation. Absorption losses arise from several processes, including nonlinear absorption (e.g., multi-photon absorption) and free carrier absorption, where electrons in the conduction band absorb additional photons, exciting them to higher energy states.

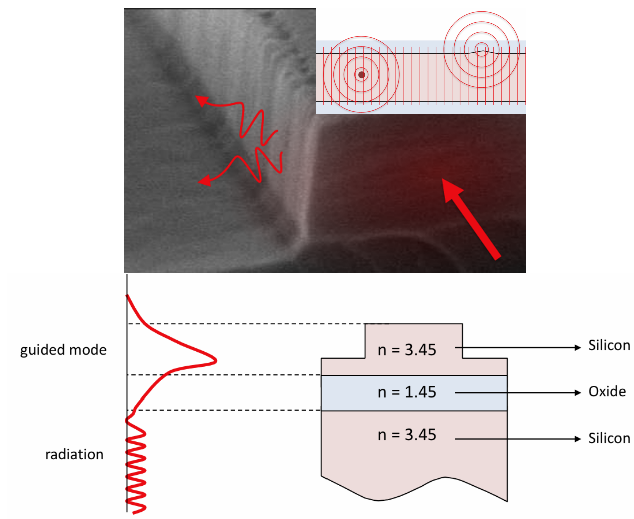

Fig. 4: Waveguide loss mechanisms: a) surface and volumetric scattering; b) radiation [3]

Silicon waveguides exhibit significantly higher propagation losses compared to optical fibers, as evidenced by previous fitting results. This disparity is partly due to the high refractive index contrast between the core and cladding in silicon waveguides. While this strong contrast enables compact geometries and tight mode confinement, it also increases susceptibility to scattering losses. These losses include volumetric scattering from spatial fluctuations in the refractive index and surface roughness scattering from sidewall roughness (see Figure 4 (a)). Surface roughness scattering primarily occurs at two interfaces: the bottom surface between grown layers and the sidewalls due to etching irregularities. Thus, the higher propagation losses in silicon photonic systems represent a trade-off for the benefits of high index contrast.

Another fundamental loss mechanism is radiation due to imperfect waveguide guiding, as shown in Figure 4 (b). In silicon photonics, this primarily manifests as mode leakage into the substrate. The electric field, which tends to concentrate in regions of higher refractive index, extends the exponential tail of the waveguide's eigenmode into the silicon substrate, resulting in significant power loss. This phenomenon is analogous to quantum mechanical tunneling of charged particles through a potential barrier [1].

C. Bend loss mechanisms

Figure 5 shows how mode profiles and bend losses vary with bend radius. Smaller bend radii lead to exponentially higher losses and an outward shift in the mode profile. This shift occurs because the outer part of the mode experiences a longer effective path length than the inner part, causing phase differences that distort the mode and excite higher-order and radiation modes. As a result, the effective index changes, and the increased field intensity near the outer edge makes the mode more sensitive to sidewall roughness, leading to higher scattering and reflection losses [3].

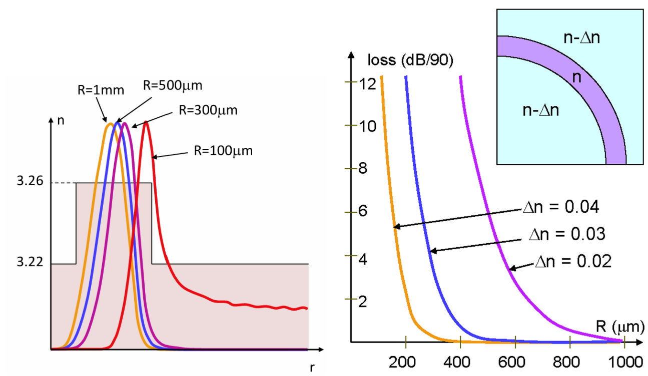

Fig. 5: a)Mode profile versus bend radius plot [3]; b)mode loss versus bend radius and refractive index contrast [1]

Analyzing the eigenmodes and leakage in waveguide bends requires solving the Helmholtz equation for the bend geometry. Due to the complexity, a conformal transformation is used [2], defined as ($w = R_2 \ln \frac{z}{R_2}$), where (R_2) is the outer radius of the bend. The transformed Helmholtz equation is:

$$\frac{\partial^2 \psi}{\partial u^2} + \frac{\partial^2 \psi}{\partial v^2} + k_0^2 T^2(u,v) n^2(u,v)\psi = 0$$

where ($T = \frac{r}{R_2} = \exp \frac{u}{R_2}$). The transformed refractive index is ($n_t(u) = n(u) \exp \frac{u}{R_2}$), as shown in Figure 6. This transformation helps explain the observed mode behavior: as the bend radius decreases, the transformed index gradient increases, causing stronger index variation within the core. Since light tends to concentrate in higher index regions, the mode shifts outward, increasing the electric field near the outer edge (By further reducing the bend radius such that the inner edge no longer contributes to modal propagation, the bend width becomes irrelevant, resulting in modes known as whispering-gallery modes.). Moreover, the exponential index growth in the outer cladding can surpass the core index, allowing energy to tunnel into the cladding, which accounts for the intrinsic radiation loss in bends [2].

To mitigate bend losses, various strategies are used. One method is to introduce a controlled offset between bent and straight waveguides to better align the modal peaks. More recent approaches include using bends with gradual transitions, such as spline bends, hybrid wire/rib structures, or Euler bends [3].

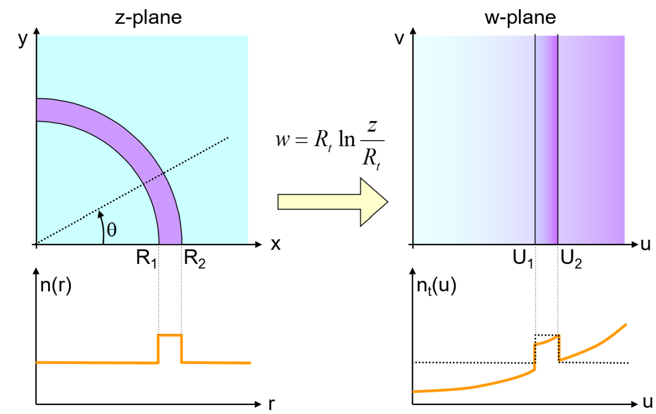

Fig. 6: Conformal transformation of waveguide bend[2]

V. Conclusion

This study characterized transmission losses in on-chip waveguides and bends using measurements and theoretical analysis. The discussions indicate that total loss comprises propagation losses proportional to waveguide length and fixed losses from coupling elements. A linear fit of output power versus waveguide length allowed us to quantify grating coupler losses at 4.249 dB each and bend losses at $6.51 \times 10^{-3} dB$ per bend, values consistent with established silicon photonic benchmarks, affirming the accuracy of the methods. The exploration of loss mechanisms highlighted scattering due to the high refractive index contrast in silicon waveguides—a trade-off for their compact design—as well as radiation and mode mismatch in bends, elucidated via conformal transformation. These insights are vital for designing efficient photonic circuits. While this work focused on specific waveguide configurations, future research could investigate a wider range of bend radii and advanced structures, such as gradual transition bends or hybrid waveguides, to further minimize losses. By applying established theory to a specific waveguide configuration, this study contributes to the optimization of integrated photonic devices.

References

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[2] Peter Bienstman. *Mathematics for Photonics*. 2024.
[3] Wim Bogaerts. *Photonic Integrated Circuits*. 2025.