High-Performance Thin-Film Lithium Niobate Modulators for Advanced Photonic Integrated Circuits: A Statistical Congruence Analysis

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Abstract: Thin-film lithium niobate (TFLN) has emerged as a promising platform for integrated photonics due to its large electro-optic coefficient and strong confinement. However, scaling TFLN modulators to large-scale photonic integrated circuits (PICs) requires rigorous analysis of manufacturing variations. This paper presents a comprehensive study of TFLN modulator performance, focusing on the statistical congruences observed across wafer-scale fabrication. We identify key correlations between geometric parameters and electro-optic bandwidth, providing a framework for yield prediction and robust circuit design.

1. Introduction

The demand for high-bandwidth, low-power optical interconnects has driven significant interest in thin-film lithium niobate (TFLN). Unlike bulk lithium niobate, TFLN allows for tight optical confinement and velocity matching between optical and detailed microwave fields, enabling bandwidths exceeding 100 GHz. Despite these advantages, the sensitivity of TFLN devices to fabrication tolerances remains a critical challenge for large-scale integration.

2. Device Design and Fabrication

We designed Mach-Zehnder modulators (MZMs) on a 600 nm X-cut TFLN platform. The waveguides were defined using electron-beam lithography and etched into the lithium niobate layer. Ground-signal-ground (GSG) electrodes were deposited to facilitate high-speed modulation. The interaction length was varied from 5 mm to 20 mm to study the trade-offs between $V\pi$ and bandwidth.

3. Statistical Congruences

To evaluate manufacturing reliability, we characterized 500 devices across a 4-inch wafer. We observed a strong statistical congruence in the distribution of insertion loss and $V\pi L$ product. The standard deviation in $V\pi$ was found to be less than 5%, indicating high uniformity. However, bandwidth variations showed a bimodal distribution, which we attribute to local variations in the thickness of the buffer oxide layer. By applying a multivariate regression model, we established a predictive correlation between the electrode gap deviation and the frequency response roll-off.

4. Conclusion

Our statistical analysis of TFLN modulators reveals that while DC performance metrics exhibit high wafer-level uniformity, RF performance is more sensitive to specific fabrication parameters. These findings underscore the importance of precision process control and provide a pathway towards high-yield manufacturing of TFLN-based photonic circuits.

References

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