Diffusion Model-Driven Optimization of High-Efficiency Wavelength-Scale Microring Lasers

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Bottom-up grown InP/InAsP III-V multi-quantum-well (MQW) microring lasers, fabricated via Selective Area Epitaxy (SAE), are promising candidates for fully integrated photonic and optoelectronic circuits, offering tunable emission in the telecommunication O-band and lower lasing thresholds compared to top-down approaches. These advantages stem primarily from the smooth sidewalls achieved during growth, which reduce optical losses [1]. Optimizing these lasers requires identifying the key geometric factors—such as shape, radius, and waveguide width—that govern lasing threshold and wavelength, while simultaneously refining growth parameters to enhance material quality. This is critical, as lasing threshold depends on the interplay between optical gain and propagation losses, both of which are strongly influenced by microring geometry and material properties [1, 2, 3].

To address this challenge, we propose leveraging recent advancements in generative diffusion models, which have surpassed traditional generative adversarial networks (GANs) and variational autoencoders (VAEs) in image generation tasks [4, 5]. Our approach utilizes a multimodal dataset of approximately 5,000 optical images of microrings, each paired with corresponding lasing thresholds, emission wavelengths, geometric parameters (e.g., diameter, pitch, height), and growth conditions. By training a diffusion model on this dataset, we aim to generate optimized microring designs that minimize lasing thresholds while ensuring emission remains within the target O-band.

Further insight can be brought from computational models based on Finite-Difference Time-Domain (FDTD) approaches, which are commonly used to calculate the quality factor (Q factor) from geometric conditions. The approach of combining generative diffusion models with FDTD simulations provides both predictive accuracy and physical insight, paving the way for significant advancements in microring laser technology for next-generation high-density photonic circuits.

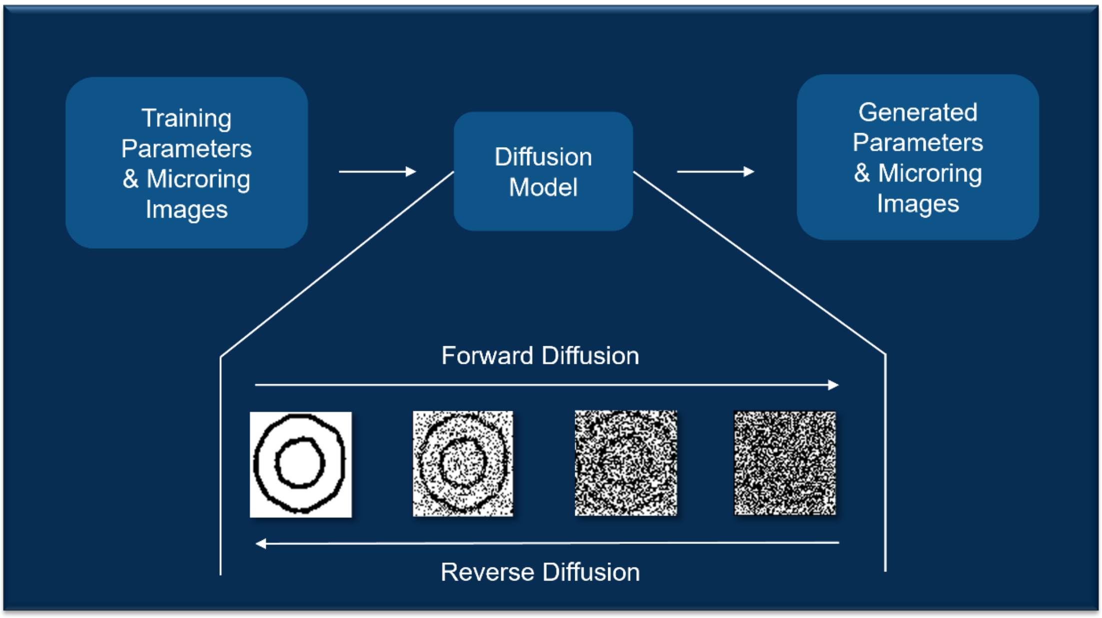

Fig. 1: Schematic representation of the diffusion model process for optimizing microring laser geometries. The model is trained using microring images and parameters (left), undergoes forward diffusion to introduce noise, and reverse diffusion to generate optimized microring images and parameters (right), enabling the design of low-threshold, telecommunication-wavelength microring lasers.

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References

[1] Wong, W. W.; Wang, N.; Esser, B. D.; Church, S. A.; Li, L.; Lockrey, M.; Aharonovich, I.; Parkinson, P.; Etheridge, J.; Jagadish, C.; Tan, H. H. *Bottom-up, Chip-Scale Engineering of Low Threshold, Multi-Quantum-Well Microring Lasers*. ACS Nano 2023, 17, 15065–15076.

[2] Wong, W. W.; Su, Z.; Wang, N.; Jagadish, C.; Tan, H. H. *Epitaxially Grown InP Micro-Ring Lasers*. Nano Letters 2021, 21, 5681–5688

[3] Athavale, M. R., Al-Abri, R., Church, S., Wong, W. W., Low, A. K., Tan, H. H., Parkinson, P. *Accelerated Design of Microring Lasers with Multi-Objective Bayesian Optimization*. arXiv preprint 2024 arXiv:2411.04487.

[4] Vivekananthan, S. *Comparative analysis of generative models: Enhancing image synthesis with VAEs, GANs, and stable diffusion*. arXiv preprint 2024 arXiv:2408.08751.

[5] Dhariwal, P., & Nichol, A*. Diffusion models beat gans on image synthesis*. Advances in neural information processing systems 2021, 34, 8780-8794.