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Conditional Diffusion Model for One-Shot Metasurface Design in Scalable Ion-Trap Quantum Computing

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Abstract. Precise beam shaping is essential for many trapped-ion quantum computing architectures, where grating couplers are the conventional solution for delivering light from a photonic chip to an ion. The required beam properties, such as a Gaussian profile with a well-controlled beam waist, pure circular polarization, and steered in a specific direction, require a sophisticated design space. We replace standard grating structures with metasurfaces consisting of subwavelength pixels, transforming the problem into a complex inverse design challenge. Here, conventional multi-objective optimization methods require extensive computational resources and must be re-run for each new target parameter. We propose a hybrid deep learning-driven approach to accelerate the design process by integrating a surrogate-assisted optimization pipeline and generative models. Our approach significantly reduces computational cost while improving flexibility in beam engineering, making it a promising candidate for scalable ion-trap integration.

1 Introduction

Quantum experiments and applications have been brought to a more advantageous level with integrated on-chip light manipulation. For trapped-ion quantum computers, addressing ion transitions on a single chip enables scalability and higher performance of the entire system [1]. Traditional grating couplers have been shown to provide simple control over the beam waist and emission angle [2]. However, polarization control and an additional angle variation are more complicated functionalities to be implemented. To overcome these limitations, we replace standard gratings with metasurfaces composed of subwavelength pixels, enabling a higher degree of control over the emitted light field (see Fig. 1a). Optimizing such metasurfaces is inherently a multi-objective problem. Respective algorithms have been employed to iteratively refine metasurface topologies, but this approach is computationally expensive and impractical when the specific target properties change. By integrating surrogate modeling and generative models (see Fig. 1b), we aim to reduce the computational overhead associated with metasurface optimization while maintaining flexibility in beam shaping.

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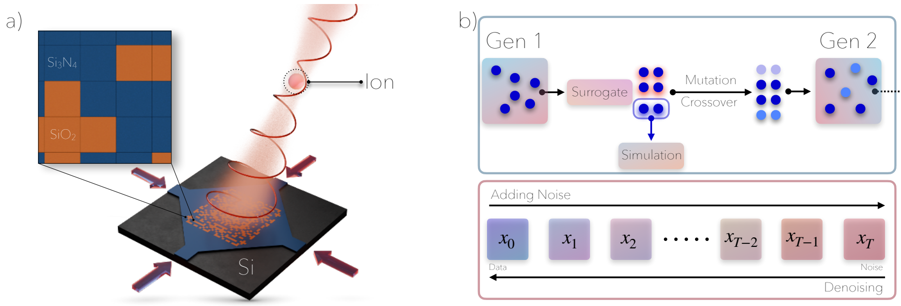

Figure 1. a) 4-port structure with the embedded metasurface to deliver CP light to the ion. b) Top: Our proposed hybrid optimization scheme features a surrogate model that evaluates designs (blue circles) and only passes promising designs (blue shaded) to the full-wave simulation before undergoing the typical steps of the genetic algorithm. Bottom: Latent diffusion model for one-shot inverse design.

2 Deep Learning Approach

The proposed approach begins with the collection of a diverse dataset consisting of both random and optimized metasurface designs. To improve efficiency, a surrogate model is trained to predict the beam properties from a given metasurface topology. This model is then used to accelerate the optimization process by pre-screening candidate designs before performing full-wave simulations. By that, only promising designs are subjected to computationally expensive simulations, significantly reducing the overall optimization time. This hybrid approach allows to generate a sufficiently large dataset that can be used to train a latent diffusion model to learn the inverse mapping from desired beam properties to metasurface topologies. This enables one-shot inverse design, where a metasurface fulfilling specific beam-shaping requirements can be generated without the need for iterative optimization.

3 Summary

The hybrid deep learning approach presented here offers a scalable and efficient framework for metasurface design in ion-trap quantum computing. By integrating surrogate modeling and generative design, we significantly reduce the computational challenge associated with conventional optimization techniques. The proposed framework has the potential to be extended beyond ion-trap applications to other areas requiring highly controlled optical fields, including quantum optics, nanophotonics, and beam steering technologies.

References

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