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QR-Code Structure for Beam Shaping and Polarization Control via Machine Learning for Chip-Integrated Quantum Applications

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Abstract. While many research fields are driven to higher levels of performance with photonic integrated circuits, the forward design of these systems faces certain limitations. This paper presents a machine learning based approach to design binary metasurfaces to facilitate beam shaping, angle, and polarization state. We implement Lumerical FDTD and Non-Dominated Sorting Genetic Algorithm III (NSGA-III) to optimize the topology of the outcoupling structure composed of subwavelength pixels, allowing a higher degree of control over the emitted light field. The generated pattern is shown to maintain the desired beam shape and angle while modulating the right/left circular and linear polarization states, allowing scalability of the design for different wavelengths without large distortion of the field properties and promising low fabrication complexity.

1 Introduction

Bringing light to an on-chip scale has led to significant breakthroughs in quantum applications. In the context of trapped-ion quantum computing, addressing optical transitions in ions from photonic integrated trap chips facilitates scalability and increases the performance of the overall system. The field of integrated photonics has been actively developing towards various grating couplers and metasurfaces with conventional and advanced functionalities [1, 2]. Conventional grating couplers have been shown to provide simple control of beam waist and emission angle. However, implementing polarization control and additional angle variation is more challenging. The use of inverse design techniques provides elegant solutions with higher degrees of freedom and complex

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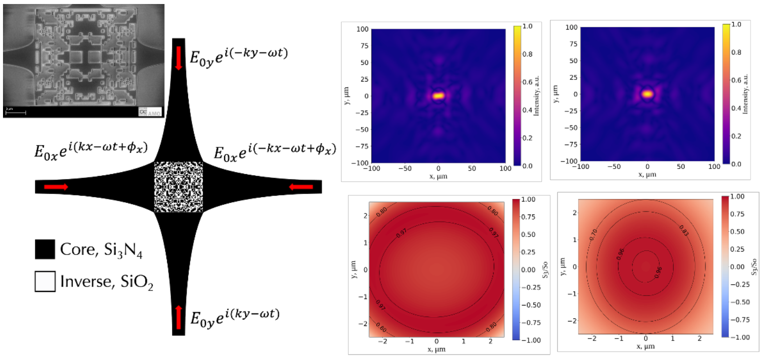

a) b)

Figure 1. a) Schematic representation of a QR code with a 4-port waveguide system, accompanied by a fabricated exemplar. b) Produced far-field pattern evaluated 100 µm above the QR-code structure for 760 nm and 855 nm wavelength with the corresponding polarization map of the beam.

functionality. This study presents the inverse-design of QR-code-like metasurfaces that promise reasonably low fabrication complexity while allowing precise control for fixed beam waist, angle, and polarization state.

2 Metasurface design and optimization method

The designed metasurface consists of subwavelength elements arranged in a QR-code-like pattern, integrated with a four-port waveguide configuration that incorporates a modulated phase shift at two x-ports (see Fig. 1a). Each element of this metasurface has a fixed size of 150 nm, with a random distribution of 16 square regions, symmetrically mirrored to form a 32 x 32 element grid. The optimization is performed using the Non-dominated Sorting Genetic Algorithm III (NSGA-III) [3], combined with Lumerical FDTD simulations for 760 nm wavelength within a Si_3N_4/SiO_2 material system. The metasurface's performance is evaluated based on three key metrics. Efficiency is evaluated based on the fraction of incident power forming the desired beam. Gaussianity is verified by comparing the simulated field distribution with an ideal 2D Gaussian intensity map, including a two-step check that assesses beam quality and background noise suppression. Polarization control is analyzed through Stokes parameters, ensuring the output maintains a well-defined polarization, averaged over a 5 µm x 5 µm region. After only 50 generations, the optimized design successfully produces a well-defined Gaussian beam profile, while enabling polarization control, including circular (right- and left-handed) and linear polarization, via modulation at the x-ports. Moreover, the design maintains similar functionality at 855 nm, demonstrating its adaptability across a broader wavelength range (see Fig. 1b).

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