Laser-Written Waveguide Array Optimized for Individual Control of Trapped Ion Qubits in a Chain

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Abstract *We design and fabricate a waveguide array with custom mode size and pitch. We measure crosstalk values below -45 dB within the array and Gaussian emission profiles. This device enhances the performance of parallel addressing of individual ions compared to state-of-the-art methods using beam deflectors.*

Introduction

In quantum computing, information is encoded in a set of controllable energy levels of a quantum object such as the outer valence electron of an atomic ion. In equivalence to a bit in classical computing, two energy levels realize a quantum bit or qubit, a collection of which forms the building blocks of a quantum computer.

Qubits stored in the internal state of trapped atomic ions are one of the leading candidates for the realization of a large-scale quantum computer. Trapped ion qubits are identical by nature, thus they exhibit long coherence times and have been used to for high fidelity operations close to the quantum error correction threshold [1].

Ion qubits are trapped using static and radio-frequency electric fields, which generate three-dimensional confining potentials. Similarly, linear chains of ions are trapped together, where individual qubit manipulation is commonly achieved by illuminating individual ions successively with tightly focused laser beams. Currently, such laser beams are delivered using free space optical setups, where individual addressing of qubits is realized by electro- or acousto-optic deflectors and modulators that direct the light through large-NA custom-designed objective lenses.

These approaches suffer from a number of drawbacks: aside from the high sensitivity to optical alignment, free space optical addressing with acousto-optic [2,3] and electro-optic [4] deflectors is associated with laser frequency shifts and unavoidable beam drifts, respectively. Multi-channel acousto-optic modulators [5] and crossed acousto-optic deflectors setups [6] exhibit significant crosstalk inside the device or from the resulting beam pattern which affects neighbouring (spectator) ions, introducing errors in their quantum states and thereby reducing the overall operational fidelities.

Here, we propose and demonstrate the use of a waveguide array to create individual and misalignment-free Gaussian beams. These beams can be directly imaged onto an iso-spaced array of trapped ions, allowing for individual, resonant control of qubits within the chain. Importantly, for this application, the crosstalk between neighbouring waveguides needs to be as low as possible. We design and fabricate the waveguide array device by femtosecond laser writing. We measure very low device-intrinsic crosstalk below -45 dB and a Gaussian mode shape at the outputs. This waveguide array will significantly improve the stability of the ion addressing and thereby reduce the time required for calibration and beam realignment, leading to

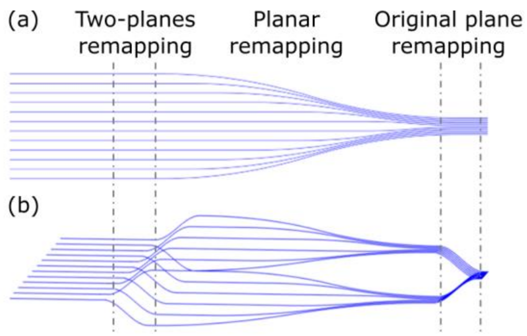

Fig. 1: Scheme of the 12-modes fabricated waveguide array device. (a) Top view. The waveguide pitch is reformatted from a value of 127 µm to 15 µm. (b) Side view of the optical circuit, showing the 3D design realized for reducing the crosstalk among the output waveguides.

an improved duty cycle with an expected increase in operational fidelities.

Waveguide array design and fabrication

The waveguide array, shown schematically in Fig. 1, has been properly designed to minimize both the crosstalk among the output modes and the overall insertion loss. The waveguides, initially arranged in a linear configuration, matching the input fiber array with a pitch of 127 µm, are gradually brought closer, reaching an output pitch of 15 µm.

For reducing the crosstalk, which at a pitch of 15 µm can be non-negligible due to the evanescent coupling between waveguides, we implement two different techniques. The first one consists in exploiting the 3D capability of femtosecond laser writing for reducing the interaction length of the waveguides. In detail, the odd and even waveguides are remapped in two different planes, with a vertical distance of 20 µm, where they are gradually brought closer to reach a planar pitch of 30 µm. Only after this transformation, the waveguides are remapped in the original plane, reaching the desired pitch of 15 µm in only hundreds of µm (Fig. 1b). The second implemented technique consists of using different inscription parameters for the even and the odd waveguides, thus inducing a detuning between their propagation constants, which further reduces their interaction in the final region.

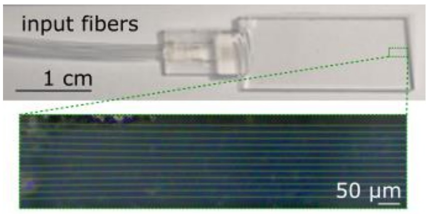

Fig. 2: Photo of the waveguide array device (rectangular glass chip) with input fibers. The inset shows a dark field microscopy image of the waveguide array.

The inscription of the optical circuit is performed by focusing a femtosecond laser beam (wavelength 1030 nm, repetition rate 1 MHz, pulse duration 170 fs, pulse energy 310 nJ, focusing objective 20x NA 0.5) into an Eagle XG borosilicate substrate, which is translated with a speed of 15 mm/s for the inscription of the even waveguides, and 25 mm/s for the odd ones. The fabrication method is described in detail elsewhere [7, 8]. In this way, waveguides with comparable performances (propagation loss of 0.2 dB/cm, bending loss of 0.1 dB/cm for a radius of 30 mm) can be achieved, showing however a remarkable detuning value of 40 cm^{-1} between their propagation constants,[1] much higher than the evanescent coupling coefficient at 15 µm, equal to 0.05 cm^{-1}.

Characterization of the waveguide array output

The fabricated waveguides array device with 12 waveguides and 12 fiber inputs is shown in Fig. 2. We test the beam output in a custom-built microscope shown and described in Fig. 3.

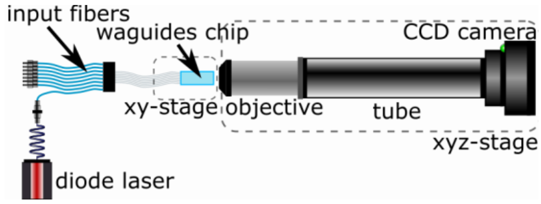

Fig. 3: Schematic of the microscope setup measuring the output of the waveguide array device. The camera-objective assembly and the waveguides array chip are mounted independently on multi-axis stages. The light from a diode laser (wavelength 729 nm) is coupled to each waveguide through input fibers in a V-groove assembly. The output of each waveguide is imaged with a CCD camera using a high NA objective (NA = 0.95).

We show in Fig. 4 the Gaussian intensity profile of three neighbouring waveguides located in the middle of the array. We observe a Gaussian beam output (Fig. 4, inset) with a waist of 1.5 µm. Furthermore, we confirm the designed 15 µm array pitch in the overlap of the intensity profiles, shown in Fig. 4.

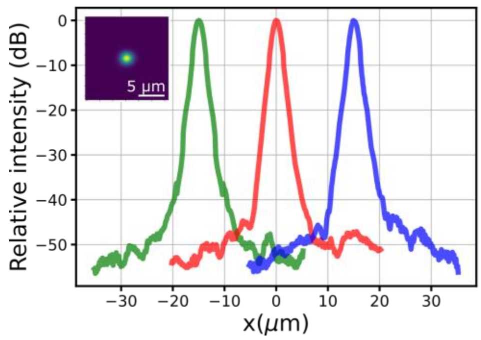

Fig. 4: Intensity profile for three neighbouring waveguides along the axis passing through the center of the waveguides. Inset: Image of one waveguide output measured with the setup in Fig. 3.

Next, we determine the crosstalk to the neighbouring waveguides by creating a high dynamic range (HDR) intensity profile. For this, we measure the output of the same waveguide for increasing exposure time, where the longest exposure time is 5000 times higher than the shortest exposure time. We overlap the HDR

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[1] The propagation constant, given by $\frac{2\pi}{\lambda}\Delta n$ (Δn is the index contrast between the waveguide and the medium, with typical values of $10^{-3} - 10^{-2}$) is here estimated to 50-100 cm^{-1}.

intensity profiles (Fig. 4) and check the intensity of the beam at the position of the next waveguide. We conclude that the crosstalk values are below -45 dB. We note that this value is limited rather by the performance of the setup. Thus, we successfully fabricate a waveguide array device with remarkably low crosstalk, which provides the required contrast for high fidelity operations with trapped ions in a chain.

Discussion and outlook

In a next step, we plan to improve the dynamic range of the measurement, which can be achieved in two possible ways. One option is to cover the output of a waveguide with a reflective layer. Thus, the output of the neighbour waveguide can be measured with higher dynamic range due to the absence of the intense output of the covered waveguide. The device with the covered waveguide output is currently being fabricated. The second option is to use an additional relay lens and perform a knife edge measurement.

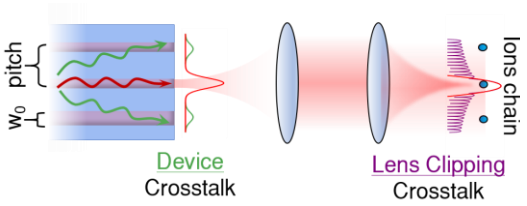

Fig. 5: Schematic showing the sources of crosstalk at the position of the trapped ions chain due to the waveguide array device and the lens clipping.

In a final step, we plan to characterize the waveguide array performance in a setup containing the optical components used on the ions trap itself. This setup consists of a lens and a custom objective. These components, shown schematically in Fig. 5, have the functions of de-magnifying the waveguides output to match the ions distance of ~5 µm and to focus the beams on the ion positions. This measurement is important because it shows the second source of crosstalk to the spectator ions, caused by the clipping of the Gaussian beams passing through the objective. In Fig. 5, we show a schematic of the beam clipping appearing as an interference pattern along the ions chain.

Conclusions

We designed and fabricated a waveguide array device by femtosecond laser writing and performed its optical characterization. The device has a custom pitch of 15 µm and very low crosstalk below -45 dB between neighbouring waveguides due to an optimized design, as confirmed by our measurements. Next, the beam profiles in the ion trap optical setup will be experimentally determined. Using this approach, we expect to extend the waveguides array device for individually addressing of ions chains with as many as 50 ions while improving the stability and the fidelity due to the reduced crosstalk. Moreover, by integrating active elements, switches or waveguides with more complex modes with the waveguide array, the footprint of the assembly required for trapped ions qubits can be significantly reduced.

Acknowledgements

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References

[1] G. Popkin, "Quest for qubits," *Science*, vol. 354, no. 6316, pp. 1090–1093, Dec. 2016, doi: 10.1126/science.354.6316.1090.

[2] P. Jurcevic, B. P. Lanyon, P. Hauke, C. Hempel, P. Zoller, R. Blatt, C. F. Roos, "Quasiparticle engineering and entanglement propagation in a quantum many-body system," *Nature*, vol. 511, no. 7508, pp. 202–205, Jul. 2014, doi: 10.1038/nature13461.

[3] C. Hempel, "Digital quantum simulation, Schrödinger cat state spectroscopy and setting up a linear ion trap," University of Innsbruck, Innsbruck, Austria, 2014. Accessed: May 04, 2022. [Online]. Available: https://quantumoptics.at/images/publications/dissertation/hempel_diss.pdf

[4] P. Schindler, D. Nigg, T. Monz, J. T. Barreiro, E. Martinez, S. X. Wang, S. Quint, M. F. Brandl, V. Nebendahl, C. F. Roos, "A quantum information processor with trapped ions," *New J. Phys.*, vol. 15, no. 12, p. 123012, Dec. 2013, doi: 10.1088/1367-2630/15/12/123012.

[5] S. Debnath, N. M. Linke, C. Figgatt, K. A. Landsman, K. Wright, and C. Monroe, "Demonstration of a small programmable quantum computer with atomic qubits," *Nature*, vol. 536, no. 7614, pp. 63–66, Aug. 2016, doi: 10.1038/nature18648.

[6] I. Pogorelov, T. Feldker, Ch. D. Marciniak, L. Postler, G. Jacob, O. Krieglsteiner, V. Podlesnic, M. Meth, V. Negnevitsky, M. Stadler, B. Höfer, C. Wächter, K. Lakhmanskiy, R. Blatt, P. Schindler, and T. Monz, "Compact Ion-Trap Quantum Computing Demonstrator," *PRX Quantum*, vol. 2, no. 2, p. 020343, Jun. 2021, doi: 10.1103/PRXQuantum.2.020343.

[7] G. Corrielli, S. Atzeni, S. Piacentini, I. Pitsios, A. Crespi, and R. Osellame, "Symmetric polarization-insensitive directional couplers fabricated by femtosecond laser writing," *Opt. Express*, vol. 26, no. 12, p. 15101, Jun. 2018, doi: 10.1364/OE.26.015101.

[8] F. Hoch, S. Piacentini, T. Giordani, Z.-N. Tian, M. Iuliano, C. Esposito, A. Camillini, G. Carvacho, F. Ceccarelli, N. Spagnolo, A. Crespi, F. Sciarrino, R. Osellame, "Boson Sampling in a reconfigurable continuously-coupled 3D photonic circuit," *arXiv:2106.08260 [quant-ph]*, Jun. 2021, Accessed: May 10, 2022. [Online]. Available: http://arxiv.org/abs/2106.08260