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SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

Design and fabrication of an integrated photonic circuit for the generation of heralded three-photon entangled states

Laurea Magistrale in Engineering Physics - Ingegneria Fisica

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1. Introduction

The research to develop a quantum computer started more than twenty years ago and it is still going on today. Many different solutions have been proposed in terms of different candidates as qubits, the quantum equivalent of classical bits. One of the possibility is exploiting photons. Their strengths are: having high coherence, allowing for room temperature operations and the scalability provided by integrated optics. On the other hand photons hardly interact between them, so this makes the creation of two-qubit gates very difficult. To overcome this issue a solution called *one-way quantum computing* has been proposed. It relies on only single-qubit gates, already demonstrated also in integrated photonics.

To achieve that, an entangled state of many photons has to be built before the beginning of the computation, called *cluster* state. If this can be obtained, then it has been demonstrated that every algorithm can be implemented by using only linear optical elements, acting on this particular state. To create the cluster state, the basic building block is a state composed by three entangled photons: the Greenberger-Horne-Zeilinger (GHZ) state [3]. This is the most critical part of the protocol for the realization of a photonic quantum computer [5].

The goal of this work is to obtain an integrated photonic circuit for the generation of GHZ states. This kind of state has already been generated probabilistically with post selection, but this leaves the issue of having to measure the state to ensure its generation. Here the heralders come into play. They provides a mechanism to recognize the correctness of the generated state without perturbing it. Our device will accept as inputs six identical photons and will provide as outputs three photons to form the entangled state and three photons as the heralders. If the latter are measured in a particular state, they ensure the generation of the GHZ state made by the other three photons.

In this work, such a circuit was fabricated by *Femtosecond laser micromachining* (FLM) [4]. It consist on focusing ultrashort laser pulses in a glass substrate. This induces a permanent modification of the glass itself, through phenomena like multi-photon absorption and avalanche ionization. Optical waveguides and directional couplers can be fabricated with this technique and these are the optical elements exploited in our circuit. Many irradiation and material parameters play a role in the final result of the fabrication.

Regarding the glass substrate, an initial work has been carried out with Borofloat glass, because it recently showed promising waveguide insertion losses. The second part of the work employed EagleXG as a substrate, a more established glass. We discarded it at the beginning for its higher propagation losses, but the design of the final device we reached allowed us to fabricate it with low insertion losses in this glass.

2. Photonic circuit layout

The circuit layout has been adapted from [1] and it is reported in Figure 1. The lines are waveguides, the rectangles represent 50/50 directional couplers. All the inputs are labeled, the boxes highlight the modes where the six single photons are injected. The semicircles at the output are the detectors for the heralders (output labeled as H_i). The labels Q_j indicate the qubits. The GHZ state is generated after the first two stages, the last one is needed to perform quantum state tomography. In the qubit notation the general GHZ state is defined as

$$|GHZ\rangle = \frac{1}{\sqrt{2}}(|000\rangle + e^{i\phi}|111\rangle) \tag{1}$$

It can be demonstrated that such a state is generated, if for every pair of detectors one and only one clicks. High generation rate single photon sources will be employed by this device, developed by the research group Pascale Senellart at Univeristy Paris-Saclay. Their edge technology, based on quantum dots, is capable of producing single photons at a wavelength of 925nm.

The blue circles represent the thermal phase shifters [2]. Thermo-optic effect is exploited to control the phase of some modes. They are realized by depositing a conductive layer on top of the glass. By flowing a current in it, the glass is heated by Joule effect. To ensure that only the waveguide beneath the phase shifter suffers the heating, trenches are fabricated exploiting FLM, to isolate that portion of the guide from the rest of the sample.

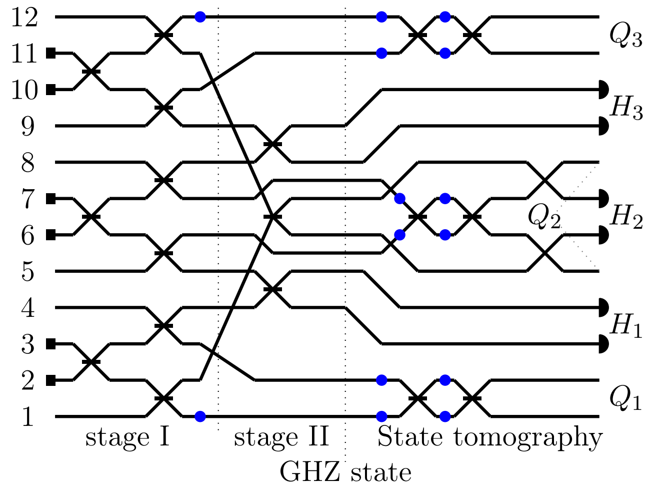

Figure 1: Scheme of the photonic circuit.

3. Fabrication and characterization setup

FLM does not need a clean room or a controlled environment to be performed. The setup consists in a moed-locked laser, which generates ultrashort pulses at an operationg wavelength of 1030nm. The beam undergoes some reflections on different dielectrical mirrors, to be guided up to the objective, that will focus it in the glass sample. The fabrications in Borofloat were carried out in air, while in EagleXG we exploited water immersion, to reduce the refractive index mismatch between the glass and the environment, therefore also the optical aberrations. A CCD camera placed behind a mirror captures the image of the focal point, allowing to a precise alignment of the sample. In the actual fabrication, the sample is moved in the horizontal plane and the objective on the vertical axis, by the *Aerotech FIBER-Glide 3D* motion system (feedback mechanism with 2nm resolution and maximum acceleration of 20m/s^2). A scheme of the setup is reported in Figure 2. With this we are able to fabricate complex three dimensional devices on centimeter long glass samples.

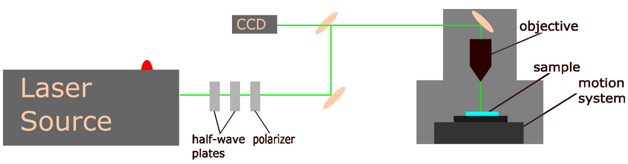

Figure 2: Fabrication setup scheme.

To control the movement of the samples, a pro-

gram has to be written in G-code and loaded into the software controlling the slits. To simplify and improve this process, an open source Python library developed by a researcher of the group has been employed. It is called *femto*. All the fabrications have been planned with this tool. After the fabrication the sample must undergo an annealing process, to achieve the desired guiding structures.
After the fabrication the samples are inspected visually with a microscope. The slightly change in the refractive index of the glass of the fabricated waveguides makes them visible. The glass is then polished, to minimize the coupling losses, and then characterized with the setup reported in Figure 3. A laser diode, emitting at a wavelength of 925nm, is focused in a single mode optical fiber. The fiber is coupled to the waveguides of the sample exploiting a two hexapods system (H-811.F2 by PI-Physik Instrumente) with 100nm precision. The output radiation is collected by an objective and focused on a powermeter (or a CCD camera) to measure the power and so calculate the losses (or acquire the modes of the waveguide and verify that it is monomodal). Placing half-wave plates and a polarized filter in the laser path, it is possible to inject H- or V-polarized light and measure the dependence of the device properties on the polarization direction.

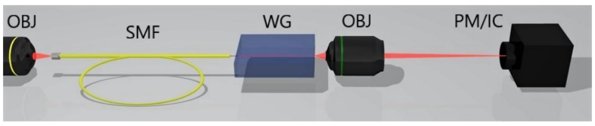

Figure 3: Characterization set-up scheme.

4. Borofloat glass

The initial part of this thesis work was performed with Borofloat glass. Nevertheless the procedure followed will be the same applied to EagleXG too. The data gathered from each fabrication are used to plan the next one, up to the realization of the final device.

4.1. Waveguide optimization

The initial process has been an optimization of the waveguides, to find the one with the lowest possible losses and single mode at 925nm. We acted on different parameters to achieve the result: laser output power, number of scan, velocity of a single scan, minimum radius of curvature, depth. Multiple fabrications were needed to try different combination of these parameters. The critical feature of the device is a waveguide that bends out of plane (3DWG in Figure 4), it is the one with the highest expected losses of the device, so the main focus of our optimization. Following this protocol we obtained a suitable set of parameters for our waveguide. The insertion losses of the highest average curvature waveguide were 0.87dB over 5cm length.

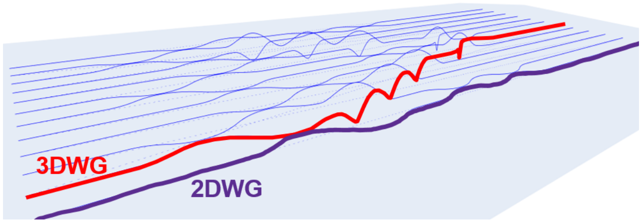

Figure 4: 3D plot of the final device.

4.2. Directional coupler optimization

After having found the parameters of the waveguide we proceeded with the optimization of the directional couplers. For the device are needed couplers with a splitting ratio of 50%, so that they act as balanced beam splitters, splitting the incoming power into two equal parts. To minimize the dimension of the device we chose to fabricate couplers with zero coupling length, so the parameter left to adjust the splitting ratio is the coupling distance. A fabrication of thirteen couplers with different coupling distances has been carried out. The gathered data on the splitting ratio allowed us to calculate, by performing a numerical fit and knowing the shape of the function ruling the coupling, the coupling distance corresponding to a 50% splitting ratio. Its value was 6.5μm.

4.3. Complete device and conclusions on Borofloat

We had all the elements we need, so we proceeded with the fabrication of the complete device. The measured losses were much higher than what we had found during the optimization procedures. We performed other optimization to fine tune the parameters of the fabrication. We also tried to optimized the design of the device, changing the geometry of the 3D bent waveguides. In the end the best device obtained has the insertion losses reported in Figure 5. To calculate such losses, the power has been measured at each output, injecting light in the same input. The values are summed together and compared to the reference power at the input of the chip.

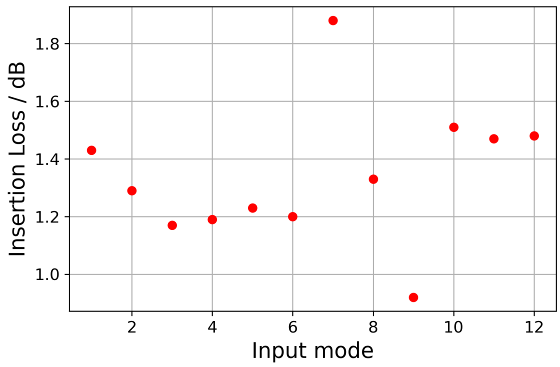

Figure 5: Insertion losses of each mode of the final device obtained in Borofloat glass.

The losses are still higher than the ones found during the optimization procedure. Moreover the average splitting ratio of the couplers was around 46% for this device.
Borofloat has proven to be able to sustain waveguides with propagation losses lower than 0.1dB/cm, but it has some drawbacks. We could only demonstrate waveguides with viable bending losses for curvature radii of at least 40mm. It is very sensible to the fabrication parameters, in particular the fabrication depth. Changes of few micrometers produce a completely different outcome, this is probably due to the spherical aberration of the glass, not well compensated by the objective employed. In the end the major issue for Borofloat is the reproducibility. In the future high performance devices may be fabricated in this glass, but before that further study is needed, to find a consistent fabrication recipe.

5. EagleXG glass

In EagleXG glass, waveguides with lower radius of curvature with respect to Borofloat are demonstrated. This opened up the possibility to try this glass. Its higher propagation losses could be compensated by the reduction of the total length of the device thanks to the higher bending.

5.1. Waveguide optimization

Being EagleXG a glass substrate widely used by our research group, an in-house very robust fabrication recipe for single mode waveguides at 925nm was already known. Since they are typically less preponderant parameters, we kept the number of scans and the velocity from the recipe fixed and performed a single optimization crossing 13 powers and 3 radii of curvature. We fabricated straight waveguides, in plane and out of plane bent waveguides (respectively 2DWG and 3DWG in Figure 4). We found a set of optimal fabrication parameters, which gave the lowest measured losses for all the three different waveguides.
The insertion losses for this 3D bent waveguide are 1.026dB for a sample length of 4cm. This is an 18% increase with respect to the value found with Borofloat.

5.2. Directional coupler optimization

The second fabrication performed in this glass was of 13 direction couplers with zero coupling length, always to keep the device as compact as possible, and with coupling distances ranging from 3μm to 9μm. The gathered data were used to numerically reconstruct the function ruling the splitting ratio and find the coupling distance for it to be 50%. The result of this procedure is shown in Figure 6.

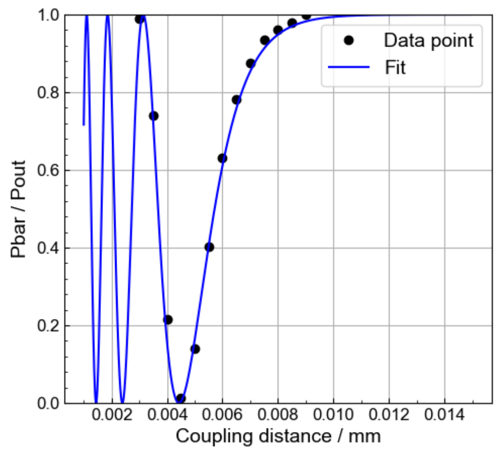

Figure 6: Splitting ratio as a function of the coupling distance for the couplers fabricated in EagleXG.

5.3. Complete device and trenches fabrication

Having found the writing and geometrical parameters, we fabricated the full device. Five devices, with five different coupling distances for the couplers, are fabricated in the same chip, to account for possible fabrication inaccuracies and obtain one device with splitting ratio close to 50% for all couplers. The full device is shown in Figure 7. The optical circuit (in dark blue) is topologically equivalent to the one in Figure 1. The grey polygons are deep isolation trenches, used to thermally isolate a guide from the neighboring one. They consist of hollow structures, also realized with FLM, by irradiating with a lower repetition rate: 20KHz, with respect to 1MHz used for the waveguides. Since the device is only trenched in a successive fabrication with respect to the optical circuit, the black crosses in Figure 7 are used as a reference to realign the sample for this second fabrication. They are laser ablation made on the bottom facet of the sample, during the circuit fabrication. After the fabrication the device has been cut and polished, its final length is 3.3cm.

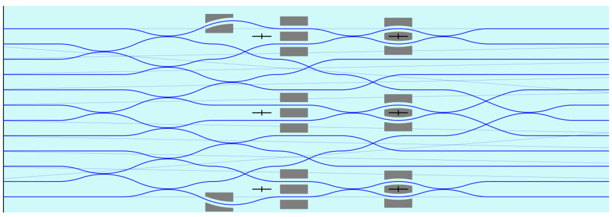

Figure 7: Design of the GHZ state factory generated with *femto*. The dashed lines help to visualize the correspondent output of each input mode.

6. Optical validation of the full device

The five fabricated devices were firstly characterized in terms of splitting ratios, used as the selection criterion. An average splitting ratio of 50.54% ± 0.88% was measured for the elected device, which was then mapped (Figure 9). The data gathered confirmed that each mode has insertion losses lower than 1.25dB, as shown in Figure 8. The couplers splitting ratio is between 48.76% and 51.20% for all but one, which has a splitting ratio of 46.49%. The measurements were performed also with linearly polarized light, in two orthogonal directions, to ensure that there was no dependence of the insertion losses or the coupling ratios with the polarization. The data obtained confirmed that the device sensitivity to the polarization direction is negligible.

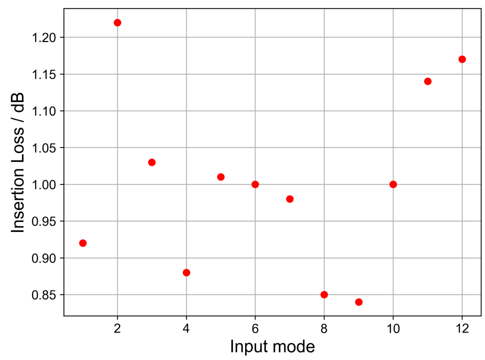

Figure 8: Insertion losses of each mode of the final device, for incident horizontally polarized light.

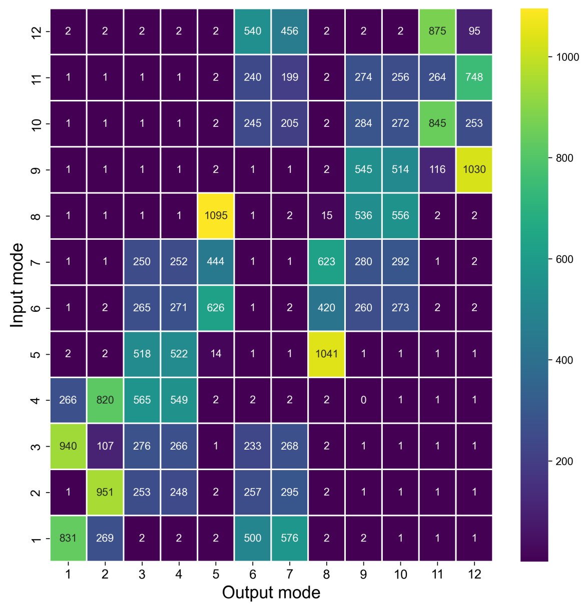

Figure 9: Power distribution map of the final device.

In Figure 9 is reported the power collected at each output mode from any input. It is colour coded for an easier visualization. It should be symmetric with respect to its main diagonal, if the couplers have splitting ratio around 50% and the guides have comparable losses. This symmetry is clearly visible, so another confirm that the device is working properly. The only asymmetric outputs are the ones connected to the

Mach-Zenhder interferometers, but this was expected, since the characterization is passive and the arms' relative phase is random.
Fourteen thermal phase shifters are present on the device. The resistances and metal contacts that constitute them have been deposited by a lithographic procedure. The test carried out on the resistances confirmed their stability. After the pigtailing procedure (connection of the inputs and outputs of the chip with a fiber array with 12 optical fibers), the device will be tested, to find the currents needed to flow through the resistances to get the desired phase shifts, to obtain the desired state at the output.

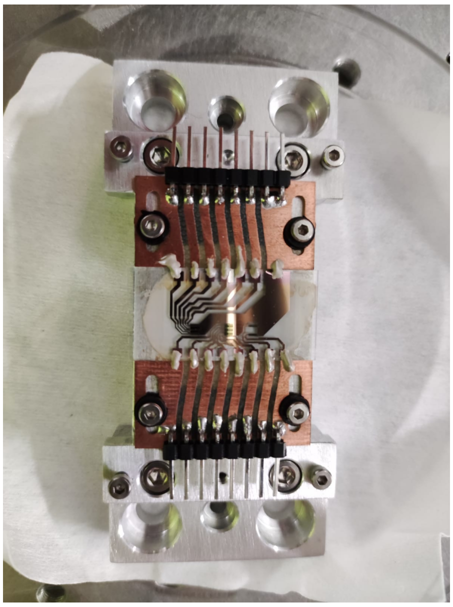

Figure 10: Final device fabricated in EagleXG glass. On top of it are visible the conductive layers deposited.

7. Conclusions

The initial work done with Borofloat glass did not allow us to achieve a minimal loss device due to irreproducibility. On the contrary, EagleXG is an already established glass, with typically higher propagation losses, that in the end were mitigated by the more compact layout allowed by the lower bending losses. The work done has culminated in a device for the generation of heralded GHZ states, validated by different characterizations. The insertion losses of each mode are lower than 1.25dB. The couplers' splitting ratio measured were of 50% $\pm$ 1%, except for one coupler with 46.49%. A final tuning procedure for the thermal phase shifters has yet to be performed. A picture of the final device with the phase shifters and the electrical contacts is reported in Figure 10. Then the chip will be tested with single photon sources for the actual generation of a GHZ state, usable in further experiments.

8. Acknowledgements

First of all I want to thank Professor Roberto Osellame that allowed me to join its awesome group and work on this very stimulating argument on my thesis. I want to thank a lot Hugo, my supervisor, who has been available in any moment to help me, has taught me how to perform all the procedures precisely and also to enjoy the life in the laboratory. I want to thank all the members of the research group, everyone was always supportive and willing to help me. Last but not least I wish to thank my family for the support they gave me through all these year, that led to this great conclusion.

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