PALACKÝ UNIVERSITY OLOMOUC
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Photonic switching for quantum information processing

a dissertation report

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Abstract

Photonic switches represent valuable tools in quantum technologies and quantum optics in general. In this Thesis, we discuss different platforms for photonic switching and address a wide scale of applications across all fields of quantum optics. We implement photonic switching experimentally via a Mach-Zehnder interferometer with embedded integrated electro-optic phase modulators. We reach versatile sub-ns low-latency switching with 26 dB extinction, convenient for a feedforward operation. To provide long-term stability of the interferometer, we implement active phase locking. The phase lock exploits external reference light operating on a different wavelength than the quantum signal. This solution enables stability of 0.05 degrees maintained over 15 hours. Further, we propose and demonstrate applications of the photonic switch. Firstly, we perform active time multiplexing via a loop configuration of the photonic switch. We achieve complete control over 4 time bins, allowing for qudit preparation or photon-number-resolving detection. Secondly, we theoretically investigate Fock state conversion with linear optics. The proposed protocol probabilistically converts m-photon state to n-photon state by subtracting $m - n$ photons at a sequence of feedforward-controlled beam splitters. We verify the feasibility of the protocol by experimental $|2\rangle$ to $|1\rangle$ conversion using an extended version of the photonic switch.

Keywords

Acknowledgments

I would like to express my deepest appreciation to Miroslav Ježek for his invaluable mentoring, insightful advice, and unwavering support throughout my Ph.D. I am extremely grateful to Jaromír Fiurášek for his patient guidance and valuable feedback throughout the preparation of this Thesis.

I am also thankful to all my collaborators and colleagues for their company, advice, and help whenever I needed it. Special thanks to Gleb Mazin being not only an enthusiastic cooperator but also my great friend. Many thanks to Martina Nováková as an outstanding leader at the beginning of my Ph.D. and during my master's and bachelor's studies. Thanks should also go to Jirka Fadrný, Pepa Hloušek, and Michal Dudka for exemplary cooperation. Without you, the research presented in this Thesis would not be possible. I am also grateful to QuantumFuture Research Group in Padova. Thank you for warm adoption into your wonderful team during my Ph.D. internship. Especially I would like to acknowledge Francesco Santaguistina for excellent collaboration and friendly companionship.

I would be remiss in not mentioning all my friends and musicians who have been supporting me and have been giving me joy that helped me to stay sane during my Ph.D. studies. Last but not least, I would like to extend my sincere thanks to my family for their continuous support and unconditional love giving me through my journey of life.

<div align="right">Vojtěch Švarc</div>

Declaration

I hereby declare I have written this Ph.D. Thesis by myself while being supervised by prof. Mgr. Jaromír Fiurášek, Ph.D. and RNDr. Miroslav Ježek, Ph.D. Also, I declare that every resource used is properly cited. I confirm this Thesis is based on original research, clarifying my personal contribution to individual projects in Author contribution. I agree with the Thesis being used for teaching purposes and being made available on the website of the Department of Optics.

Signed in Olomouc on ....

<div align="right">Vojtěch Švarc</div>

Author contribution

This Thesis is based on three publications where I act as a first author. Here, let me clarify my personal contribution to the individual research projects.

In work [1], I was responsible for the experimental implementation, measurements, and data processing, being supervised by Martina Nováková and Miroslav Ježek. Further, I participated in the manuscript preparation by writing a raw version, subsequently optimized by Miroslav Ježek. Gleb Mazin contributed to the time-multiplexing part by FPGA programming and driving the phase modulator via his hardware.

This work was further extended in publication [2], where we focused on the optimization of the active phase locking. The optimization to the current precision is predominantly a result of my own research, ideas, and experimental implementations. For example, I developed the concept of local setup detuning, limiting the long-term stability. Further, I optimized the experimental setup, performed all measurements, data analysis, and prepared the manuscript. Miroslav Ježek supported me with ideas and advice, and he also provided me with feedback on the manuscript. Michal Dudka contributed by assembling an improved version of the PID controller.

The project [3] can be divided into a theoretical section and an experimental section. The theoretical section, including the concept, theory, simulations, and an experimental proposal, was performed by Jaromír Fiurášek. My personal contribution in this part laid in a revision of his findings. The experimental section, consisting of the experimental implementation, measurements, and data evaluations, was predominantly performed by me. Josef Hloušek helped me with a coincidence unit and also shared with me a part of his experimental setup. Miroslav Ježek coordinated the theoretical and experimental parts. Regarding the manuscript preparation, Jaromír Fiurášek was the main coordinator. He prepared the theoretical part while I described the experimental part. Miroslav Ježek revised the manuscript.

[1] V. Švarc, M. Nováková, G. Mazin, and M. Ježek, "Fully tunable and switchable coupler for photonic routing in quantum detection and modulation," *Opt. Lett.* 44, 5844-5847 (2019)

[2] V. Švarc, M. Nováková, M. Dudka, and M. Ježek, "Sub-0.1 degree phase locking of a single-photon interferometer," *Opt. Express* 31, 12562-12571 (2023)

[3] V. Švarc, J. Hloušek, M. Nováková, J. Fiurášek, and M. Ježek, "Feedforward-enhanced Fock state conversion with linear optics," *Opt. Express* 28, 11634-11644 (2020)

Contents

1   Introduction

A century has passed since the fundamental principles of quantum theory were formulated. Quantum physics exhibits many counterintuitive properties with no equivalent in classical physics such as superposition principle, quantum interference, and non-locality. Although quantum physics was initially a theory with limited possibilities for experimental verification, experiments were eventually implemented to confirm its predictions. Later, applications utilizing the unique properties of quantum systems were proposed. Quantum communication can prevent leakage of secret information to an eavesdropper leading to inherently secure communication. Quantum metrology breaks classical limits for measurement precision enabling gravitional wave observation with the unprecedented sensitivity [4]. Quantum information protocols outperform classical computers in specific tasks [5]. The holy grail of quantum information processing, the universal quantum computing has a potential application in many fields. Large scale of combinatorics problems will be solved more efficiently, impacting advanced manufacturing, banking, and financial sector [6]. Also, quantum simulations for chemical engineering could be done much efficiently, massively improving the development of new materials. On the other hand, the advent of efficient quantum computing would threaten encryption methods used today. To implement quantum applications, various quantum protocols are investigated on different platforms such as atoms, ions, superconducting materials, and photons.

The photonic platform is capable of quantum communication, quantum metrology as well as universal quantum computing. However, there are huge technological demands for efficient single-photon generation, advanced quantum state processing, and efficient detection of photons to make the photonic-based protocols applicable in practice. Advanced quantum state processing often requires fast switching between two or more modes or their mixing. In some cases, we need to perform a specific operation depending on the result of a measurement. The operation is referred to as feedforward. Therefore, it is extremely useful to achieve fast photonic routing with low latency. Photonic switching is used in quantum cryptography [7], photonic simulations [8], scalable boson sampling [9–11], universal quantum computing [12, 13], entanglement synthesizing [14], and multi-mode quantum processing [15]. Further, fast photonic switching has facilitated a pioneering demonstration of postselection-loophole-free violation of Bell's inequality with genuine time-bin entanglement [16]. Fast switching also plays an important role in single-photon generation and photon counting. Specifically, in the last few years, high-efficiency single-photon generation has been demonstrated employing active time multiplexing [17–20]. In addition,

active time multiplexing was used to demonstrate a high-dynamic range photon-number-resolving detection [21].

A convenient way to achieve fast photonic switching with low latency is to employ a Mach-Zehnder interferometer with an integrated phase modulator. In this case, 100 GHz response is feasible [22] and thanks to the low-voltage control of the modulator, low latency and high repetition rate are provided. A major drawback lies in the environmental phase sensitivity of the Mach-Zehnder interferometer. Although inherently stable configurations exist, they are not free of issues and do not fit all applications. Therefore, commonly the long-term stability of the Mach-Zehnder interferometer requires active phase locking. Active phase locking at a single-photon level is feasible but extremely challenging due to Poissonian photodetection noise. As a consequence, the typical precision of single-photon phase locking is a few degrees, and the response is slower than 0.1 s [23, 24]. An efficient strategy to overcome this issue is to lock the phase via a bright reference light co-propagating with the signal photons [2, 25–27].

In this Thesis, we present experimental research in the field of photonic switching for single-photon applications with an emphasis on quantum information processing. We have implemented an ultra-fast photonic switch by using a Mach-Zehnder interferometer with an embedded integrated electrooptic modulator. Also, we provided the Mach-Zehnder interferometer with continuous active phase locking by adding a reference beam to the setup. We achieved stability of 0.05 degrees for 15 hours which is an unprecedented result within actively stabilized single-photon interferometers. Further, we present applications of photonic switching: Firstly, the photonic switch can perform temporal multiplexing by using a loop configuration. Specifically, we demonstrate temporal multiplexing for photon-number-resolving detection and qudit preparation. Secondly, we present a theoretical and experimental protocol for Fock state conversion with linear optics. The protocol transforms arbitrary m-photon state to n-photon state by subtracting $m - n$ photons at feedforward-controlled photonic switches. Our approach uses within each subtraction step the results of all previous subtraction steps enabling the conversion with maximal probability. We use the photonic switch for experimental proof-of-principle conversion from a two-photon state to a single-photon state.

2 Active phase locking

Single-photon interferometers locked to a specific phase are widely used in many fields of photonics research and technology, such as quantum information processing [28, 29], quantum metrology [4, 30, 31], quantum communication [25–27, 32, 33], and tests of fundamental physics [3, 16, 34]. Phase locking at a single-photon level is demanding, though, and the speed and precision are limited due to the shot noise of the detected photons. These limitations can be overcome by employing an auxiliary light acting as a phase reference. This approach enables continuous stabilization with high precision, operating independently of the quantum signal. To address the signal and the reference individually, they must differ in a selected parameter, such as the wavelength.

Here, we demonstrate continuous sub-0.1 degree phase locking of a single-photon Mach-Zehnder interferometer (MZI) in the dual-wavelength configuration. To lock the phase, we use spectrally stable 1.5 nW reference light adaptively corrected for intensity fluctuations, and as a result, we reach exceptional phase stability of 0.05 degrees for 15 hours demonstrated for the signal.

The phase lock is carried out by an active feedback loop consisting of a detector, a proportional-integral-derivative (PID) controller, and a phase modulator. The principle is the following: A phase fluctuation is imprinted to the detected light as an intensity fluctuation. Subsequently, the produced electronic signal is evaluated by the PID controller, and an appropriate voltage is fed into the phase modulator in order to compensate for the initial phase fluctuation. The precision and speed of this approach depend on noise, frequency response, and dynamic range of the feedback loop. However, maintaining high phase precision in the long term also requires the optimization of the optical part of the setup. Firstly, it is necessary to avoid relative phase drift between the signal and the reference, which implies their perfect spectral stability. Secondly, the phase lock has to be immune to fluctuations of the reference intensity. To achieve this feature, we adaptively adjust the phase-locking setpoint to follow the intensity fluctuations. However, there is another deteriorating effect, which we refer to as local setup detuning. If one arm (or output) of the interferometer is detuned, the phase estimation of the reference becomes biased, and consequently, we observe *relative phase drift* between the signal and the reference. In this work, we aimed to reduce all these undesired effects and optimize the control electronics in order to achieve the best possible phase-locking performance.

The experimental setup is depicted in Fig. 7. To achieve intensity and spectrally stable sources, we use fiber-coupled light-emitting diodes with additional spectral and polarization filtering. The signal and the reference are merged and co-
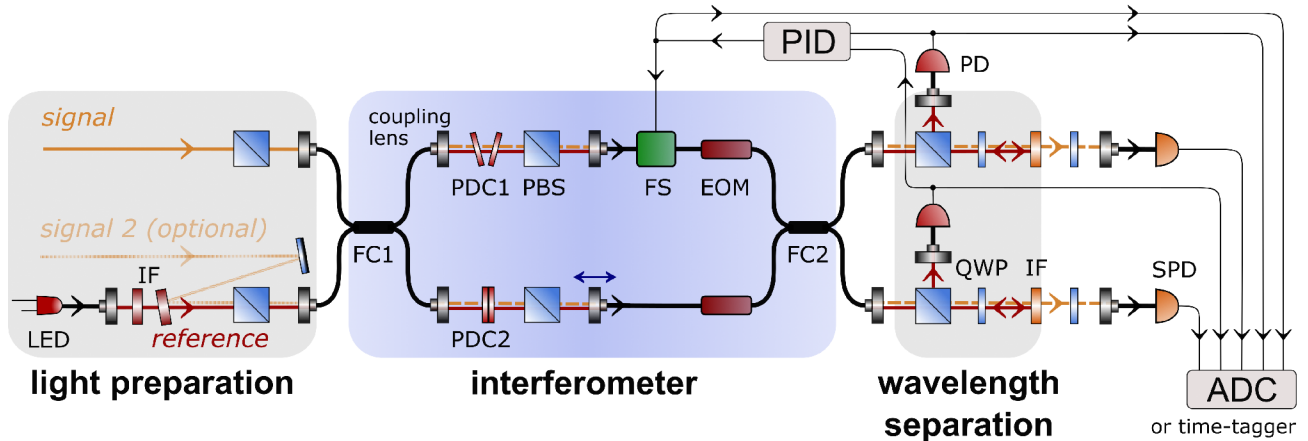
Figure 1: Experimental setup for an interferometer with active phase locking. The signal and the reference are injected into the interferometer and co-propagate through 8 m of fibers and 0.5 m of free space in each arm. The interferometer is assembled to maximize interference visibility for a broad spectrum and simultaneously provide fast phase switching. At the interferometer outputs, the signal and the reference are separated and detected. The detected reference is processed by a PID controller, and consequently, the phase is locked via a fiber stretcher. Legend: light-emitting diode (LED), interference filter (IF), polarizing beam splitter (PBS), fiber coupler (FC), phase dispersion compensator (PDC), fiber stretcher (FS), electro-optic phase modulator (EOM), quarter-wave plate (QWP), photodiode (PD), sensitive photodiode or single-photon detector (SPD), proportional-integral-derivative controller (PID), analog-to-digital convertor (ADC).

propagate through the MZI. We can tune a relative phase between the signal and the reference, allowing us to lock the phase to the most stable point of $\frac{\pi}{2}$ while operating the signal at an arbitrary phase. To achieve this ability, we developed a component called phase dispersion compensator. At each MZI output, the wavelengths are demultiplexed via a dichroic optical isolator assembled from a polarizing beam splitter, a quarter-wave plate, and an interference filter. We reach negligible crosstalk of 30 photons/s from the reference to the signal, equivalent to extinction better than 80 dB. To reduce air flux and temperature instabilities, we cover the whole setup with styrofoam plates during all measurements. The main benefit of the passive protection is in suppressing the local setup detuning.

The active phase lock is carried out by a feedback loop composed of the photodiodes, PID controller, and a fiber stretcher. The reference with the power of 1.5 nW impinges silicon photodiodes with NEP=9 fW/$\sqrt{\text{Hz}}$ and 2 kHz bandwidth. The resulting electronic signals are processed by an in-house developed
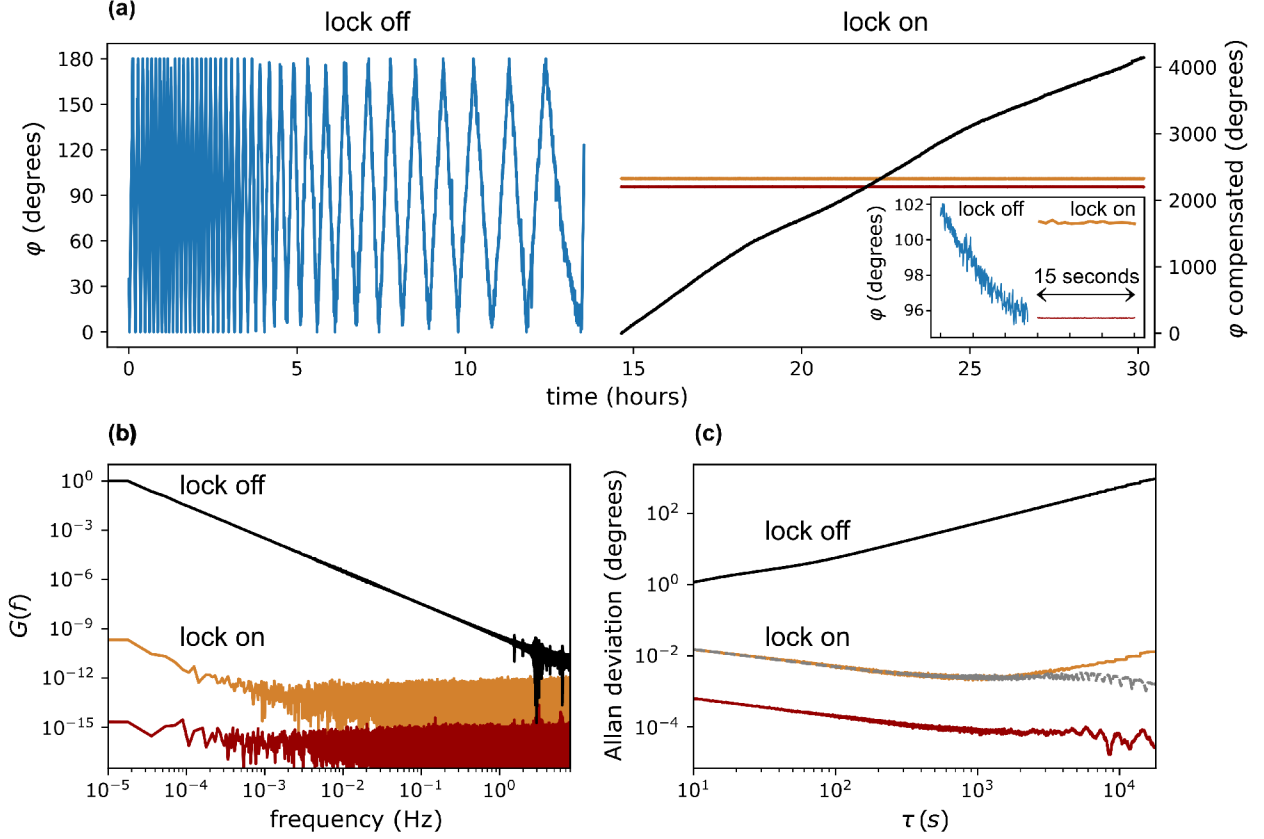
Figure 2: Comparison of stabilized and non-stabilized MZI. In stabilized MZI, the reference and the signal are represented by the red line and the orange line, respectively. (a) Stability in the time domain. The blue line represents the phase in non-stabilized MZI and the black line corresponds to the phase drift compensated during the phase locking (see the right vertical axis). The inset shows the stability in the short term. (b) Spectral power density G of the phase noise. (c) Allan deviation of the phase noise. The gray line illustrates the noise level of the signal acquisition.

analog PID controller. Compared to a conventional PID controller, the circuit is provided with the adaptive setpoint, which corresponds to the correct phase regardless of the intensity fluctuations of the reference. The PID controller is fine-tunable in each parameter via 10-turn precision potentiometers. As a result, the target phase is set with high accuracy. To provide correct phase estimation for the adaptive setpoint, we include additional tunability to cancel out detection offsets and to balance detection efficiencies. The PID controller is designed to drive a custom-made fiber stretcher with 7.2 μF capacitance, 1 kHz bandwidth, a half-wave voltage of 0.11 V, and a dynamic range of ± 275 μm [35].

Now, let us present the results of the phase stability. We compare the performance of the MZI with and without the active stabilization and present the

phase stability in three ways: in the time domain, in the frequency domain, and via the Allan deviation. The results in the time domain are depicted in Fig. 2(a). The typical phase drift of non-stabilized MZI is shown on the left side. On the right side, we show phase noise for stabilized MZI (orange and red lines) and the phase compensated during the stabilization process (black line). The inset represents a detailed view of the phase noise. While the phase lock is active, a phase drift of 4000 degrees per 15 hours is virtually eliminated. In terms of standard deviation accumulated over a typical single-photon sampling frequency of 1 Hz, we reach 0.05 degrees for the signal and 0.002 degrees for the reference within a 15-hour interval.

Further, we analyze the spectral power density of the phase noise shown in Fig. 2(b). During the stabilization process, the phase noise is suppressed by 9 orders of magnitude for frequencies in the range 10^{-3} to 10^{-5} Hz. For frequencies above 10^{-3} Hz, the phase noise is primarily given by detection noise. Furthermore, we evaluate the Allan deviation of the phase noise depicted in Fig. 2(c). For the signal, we reach Allan deviation below 2×10^{-2} degrees for time intervals from 10 s to more than 5 hours. The minimum value 2×10^{-3} degrees is achieved for 10^3 s. Allan deviation of the reference is evaluated to be smaller than 10^{-3} degrees.

3 Photonic switch

Fast splitting, switching, and routing of light are critical tools of photonic technology in the rapidly developing fields of optical communication and optical information processing. We present a low-latency switchable coupler employing a high-visibility fiber MZI. We demonstrate fast switching of the coupler by changing its operation between any splitting ratios in a fraction of nanosecond. The splitting ratio is controlled using low-voltage electronic signal compatible with the output of the majority of photodetectors, which is crucial for utilization of the coupler in optical feedback and feedforward circuits. We show outstanding performance of the reported device in two demanding applications, namely a balanced time-multiplexed device for photon-number-resolving detectors and an active preparation of a photonic time-bin encoded 4-level state with time-bin separation in the range of tens of nanoseconds.

The developed coupler is based on a fiber MZI where the splitting ratio can be switched by changing an optical phase using an integrated waveguide EOM, see Fig. 3. The MZI was implemented to have high interference visibility resulting in high extinction ratio, exceptional phase stability enabling a long-
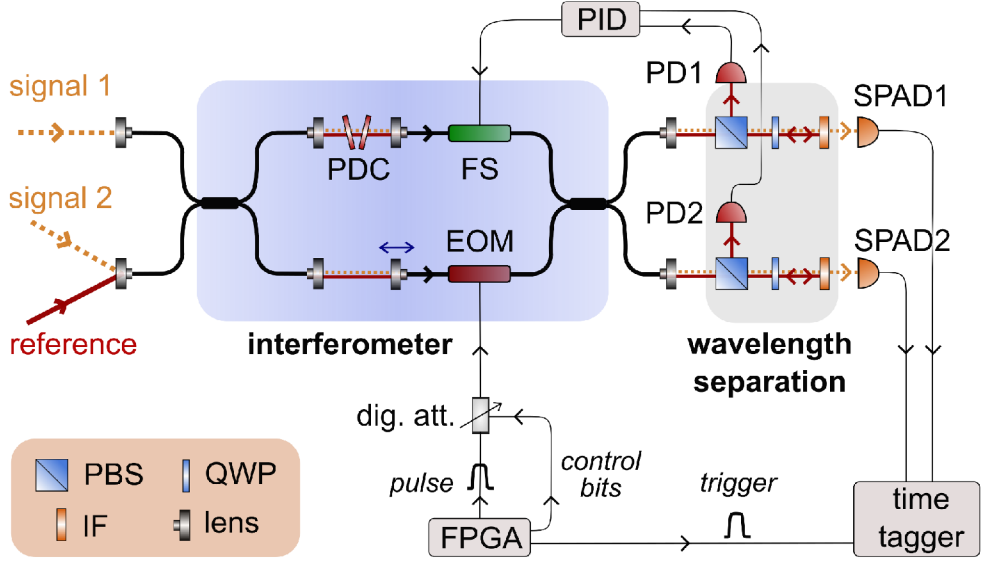
Figure 3: Simplified experimental scheme of the switchable coupler showing the signal and reference beams entering the MZI and being separated at its output. Phase dispersion compensator (PDC) and fiber stretcher (FS) are used to lock the MZI phase based on the reference detection at the photodiodes (PD1,2). Integrated electro-optic modulator (EOM) driven by FPGA based electronics is employed for switching the coupler between arbitrary splitting ratios. The output signals are detected by single-photon avalanche diodes (SPAD1,2).

term continuous operation (already discussed in the previous chapter), and fast modulation with low overall latency between a control electronic signal and the response of the switching. In what follows we will discuss these design goals and the corresponding features of the presented solution.

High interference visibility operation requires perfect indistinguishability of interfering optical signals at the output of the MZI in all relevant degrees of freedom, namely path, spatial mode, polarization, time, and frequency. The path information is reduced by making the signals in both arms of the MZI of the same intensity by slight tuning of losses. Also, the splitting ratio of the output fiber splitter has to be close to 50:50. Spatial indistinguishability is inherent in single-mode fiber implementation. Polarization-maintaining fibers are utilized throughout the setup to keep the polarization constant in time and the same for both the MZI arms. All connector splices are made to minimize polarization crosstalk between the fiber axes, and additional polarization filtering is also included. The MZI arms are carefully adjusted to have the same optical path length using tunable air gaps. The difference between the MZI arms is further minimized by placing the components symmetrically in both the arms. This

is particularly important for the components exhibiting strong dispersion such as integrated EOMs and dispersion compensators. Having all these degrees of freedom under control and precisely adjusted, we have reached the interference visibility of 99.55% in the optical bandwidth of 3 nm around 810 nm (equivalent to spectral bandwidth of 1.3 THz and pulse length down to 300 fs). It results in switching with the extinction ratio of 26 dB for continuous as well as pulsed optical signals.

The response time, also termed latency, of the realized switchable coupler is given by the propagation delay of the optical signal from the input to the output of the device and, also, by the response of the phase modulator employed. The coupler is approximately 9 m long, which corresponds to the delay of 45 ns. It can be decreased below 10 ns easily by reducing the pigtail length of the constituent components and shortening the fiber stretcher sacrificing its dynamic range. The waveguide integrated LiNbO$_3$ EOM features 10 GHz bandwidth with negligible impact on the overall latency. The modulator is controlled by voltage signals within $0 - 2.2$ V using electronic pulse generator with 3.5 ns pulse width and 0.4 ns rise time for the response characterization, and a field-programmable gate array (FPGA) with 10 ns clock period to control complex measurement protocols. The FPGA was supplemented with a GaAs FET 6-bit digital attenuator with the 0.5 dB step to generate pulse sequences used for switching the coupler between arbitrary splitting ratios.

The time response was evaluated by setting a fixed initial splitting ratio and sending an electronic control pulse to the coupler. The switching process was observed at the output ports while the single-photon level signal was injected in the first input port of the device. The accumulated photon-counting histograms are shown in Fig. 4(a) for various initial and target splitting ratios to demonstrate arbitrariness of the switching. The data are depicted without corrections, except for SPAD afterpulses subtraction (maximum 1% of the signal) and normalization, to show the temporal evolution of the transmittance and reflectance. The switching speed determined as the rise time (10%-90%) of the measured histograms is 0.7 ns, though the actual response of the coupler switching is much faster due to measurement imperfections (e.g. detection jitter).

The input optical pulse can be multiplexed in many time bins when reflected part of the signal is fed from the output of the coupler to its input to create a loop, as shown in Fig. 4(b). Electronic control pulses applied to the EOM have to be synchronized with the optical pulse repeatedly passing the coupler. This scheme follows the proposal of a time-multiplexed device for photon-number-resolving detectors [36]. The reported switching protocol can be generalized to
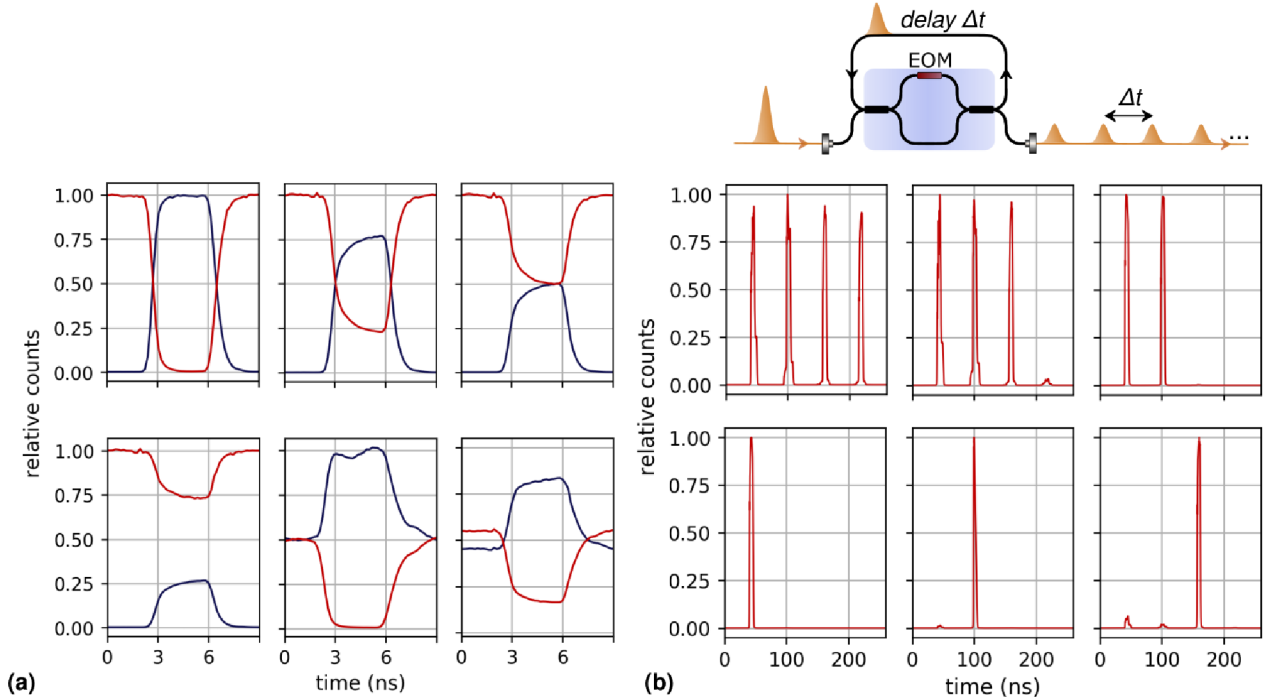
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Figure 4: (a) Examples of fast switching. Red and blue data points correspond to two outputs of the interferometer. (b) Loop-based temporal multiplexing using the reported switchable coupler: scheme of the experiment (up) and various configurations of time-bin encoded 4-level photonic signal (down).

arbitrary time multiplexing. We demonstrate full control over the amplitude of the individual time bins with the mean fidelity of 98.9%. Several examples of time-bin encoded 4-level optical system are depicted in Fig. 4(b). The tunable routing of the input signal to the resulting time bins can be complemented by their arbitrary phase modulation using EOMs in both the MZI arms. Starting from single photon input, such the routing represents an efficient way of preparing a photonic multi-level system (qudit). A second switchable coupler would be needed for the qudit analysis at the receiver.

4   Fock state conversion

Preparation and controlled manipulation of nonclassical states of light lies at the heart of quantum optics and represents a key tool for the rapidly developing optical quantum technologies. Since the class of experimentally available deterministic unitary operations on quantum states of light is rather limited, it is

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extremely useful and fruitful to consider also probabilistic conditional operations that significantly extend the scope of quantum states that could be prepared, and transformations that could be implemented. The prime examples of such operations are the conditional single-photon addition and subtraction [37–44].

Here we study the model problem of conversion of a Fock state $|m\rangle$ to a Fock state $|n\rangle$ with $n < m$ by subtraction of $m - n$ photons. We consider a scheme involving k elementary photon subtraction blocks and we demonstrate that the success probability of the scheme is maximized if we actively and adaptively choose a suitable transmittance of the beam splitter in jth subtraction block depending on the measurement outcomes of all the previous blocks. We experimentally demonstrate this feedforward-based protocol for the conversion of a two-photon Fock state $|2\rangle$ to the single-photon state $|1\rangle$ using an electronically controlled variable fiber beam splitter formed by a Mach-Zehnder interferometer with electrooptics modulators placed in its arms [1]. Our measurement results clearly confirm the potential advantage of the feedforward-based photon conversion scheme.
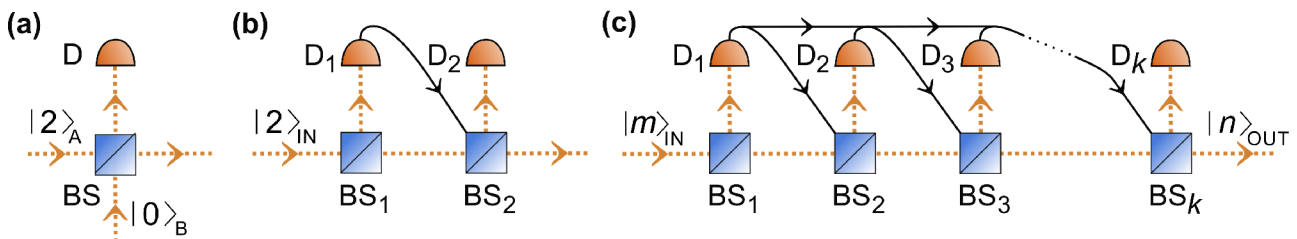

Figure 5: Fock state conversion schemes. (a) The simplest way of $|2\rangle \rightarrow |1\rangle$ conversion utilizing single beam splitter. (b) Feedforward-enhanced $|2\rangle \rightarrow |1\rangle$ conversion using two beam splitters. (c) Generic scheme for $|m\rangle \rightarrow |n\rangle$ conversion exploiting k beam splitters.

Let us illustrate the protocol principle on a simple case of $|2\rangle$ to $|1\rangle$ conversion. The most straightforward scheme uses one beam splitter and a photon-number-resolving detector, as depicted in Fig. 5(a). The conversion is successful if one photon is subtracted at the beam splitter and one photon reaches the output. This occurs maximally in 50% cases for the beam splitter transmittance $T_1 = 0.5$. Now consider we add a second beam splitter with feedforward-controlled transmittance T_2 as shown in Fig. 5(b). If no photon is subtracted at BS$_1$, we repeat the subtraction attempt with BS$_2$ set to $T_2 = 0.5$. However, if one photon is subtracted at BS$_1$, we activate the feedforward to steer the remaining photon directly to the output ($T_2 = 1$). Indeed, another possibility is that both photons are subtracted at BS$_1$, leading to unsuccessful conversion. For this reason, T_1 in two-step conversion has to be higher than in single-step conversion to reach the

maximal probability of success. Specifically, for $T_1 = \frac{2}{3}$, the success probability for the two-step $|2\rangle \rightarrow |1\rangle$ conversion is maximized to 66.7%.
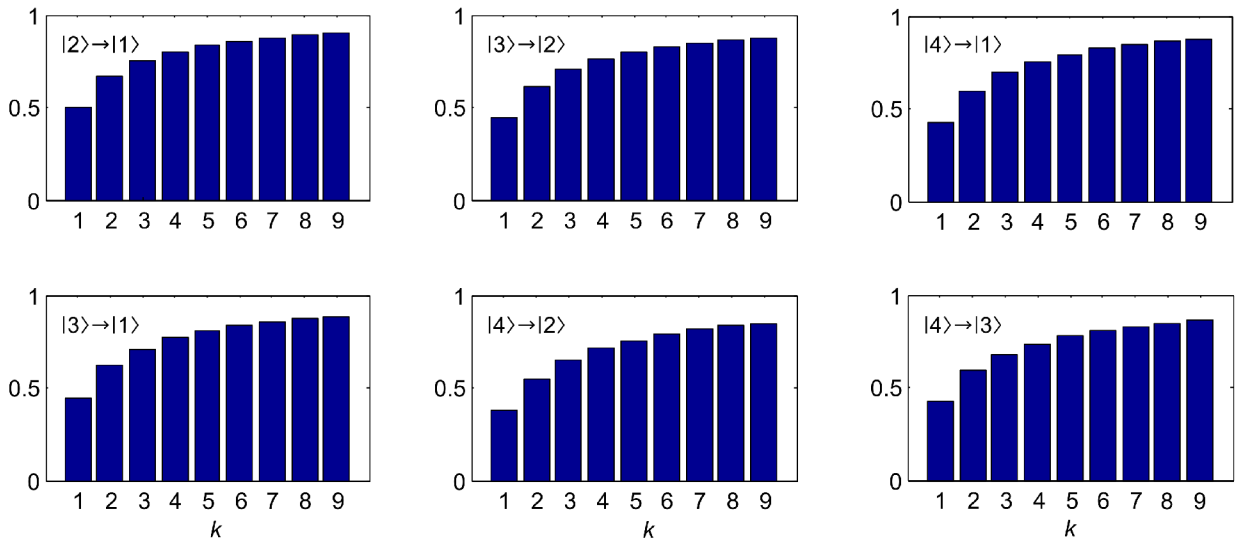

Figure 6: Optimal photon conversion probabilities $P_{\max}(m, n|k)$ are plotted for 6 combinations of m and n.

We can extend the scheme to arbitrary $|m\rangle \rightarrow |n\rangle$ conversion using k subtraction steps. The generic scheme depicted in Fig. 5(c) uses all measurement outcomes to optimally set beam splitter transmittances T_j. The following explanations illustrate the principles of calculating conversion probabilities. However, for full understanding, we refer the reader to the publication below. The equation describing the probability of success $P(m, n|k)$ reads

$$P(m, n|k) = \sum_{j=0}^{m-n} \binom{m}{j} T_1^{m-j} (1 - T_1)^j P_{\max}(m - j, n|k - 1). \tag{1}$$

where $P_{\max}(m, n|k)$ denote the maximum achievable conversion probability. $P_{\max}(m, n|k)$ can be solved by finding roots of the $\frac{d}{dT_1}$ derivative of Eq. 1. The whole process of finding $P_{\max}(m, n|k)$ is iterative, starting from the simplest cases of conversion. In Fig. 6, we show maximal conversion probabilities depending on the number of subtraction steps. For 9 conversion steps, the probability of success varies around 85%, depending on the conversion type. Increasing the number of subtraction steps leads to asymptotically deterministic conversion. However, in practice, detection efficiency is finite, and the scheme is affected by losses. As a consequence, the probability of success is smaller than optimal, and the produced output state becomes a mixture of Fock states. Despite these facts, we
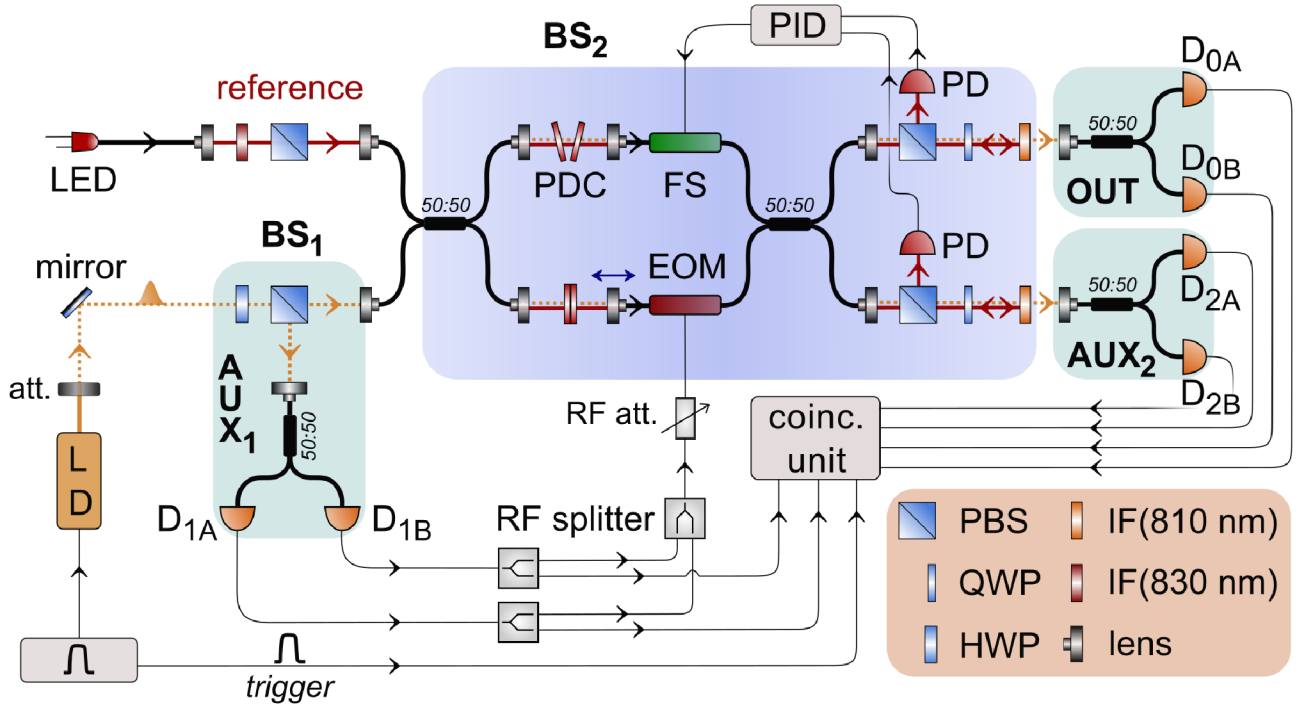
Figure 7: Experimental setup for feedforward-enhanced $|2\rangle \rightarrow |1\rangle$ conversion. The main optical parts of the setup include a variable beam splitter BS_1 and an electro-optically switchable beam splitter BS_2 implemented as Mach-Zehnder interferometer. The feedforward control of BS_2 is triggered by detection of a photon in the output port AUX_1. Legend: laser diode (LD), half-wave plate (HWP), polarization beam splitter (PBS), phase dispersion compensator (PDC), fiber stretcher (FS), electro-optic phase modulator (EOM), quarter-wave plate (QWP), photodiode (PD), single-photon detector (D), interference filter (IF).

found out that the scheme remains beneficial even for inefficient detection and for a certain amount of losses. Details are included in the publication below.

Now let us describe a proof-of-principle experimental demonstration of feedforward-enhanced $|2\rangle \rightarrow |1\rangle$ Fock state conversion as sketched in Fig. 5(b). The main aim of our experiment is to verify the feasibility of feedforward-controlled photon subtraction and demonstrate the potential advantage of feedforward-based scheme in comparison to the elementary single-step photon subtraction block in Fig. 5(a). The experiment is therefore designed such as to emulate a perfect lossless setup for both schemes. We overcome the optical losses and finite detection efficiency by effectively balancing the losses in all channels and measuring two-photon coincidence events that indicate either success or failure of the Fock state conversion. We thus postselect only the cases when both input photons reach the single photon detectors and are detected. In this approach,
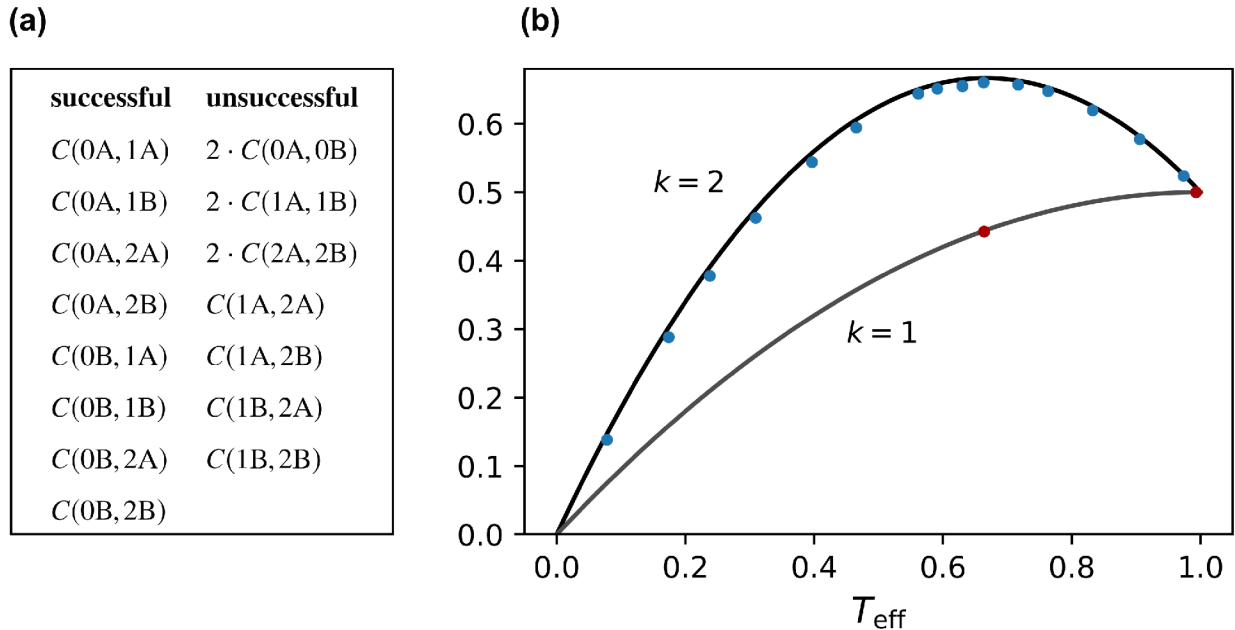
(a)

successful	unsuccessful
$C(0A, 1A)$	$2 \cdot C(0A, 0B)$
$C(0A, 1B)$	$2 \cdot C(1A, 1B)$
$C(0A, 2A)$	$2 \cdot C(2A, 2B)$
$C(0A, 2B)$	$C(1A, 2A)$
$C(0B, 1A)$	$C(1A, 2B)$
$C(0B, 1B)$	$C(1B, 2A)$
$C(0B, 2A)$	$C(1B, 2B)$
$C(0B, 2B)$	

(b)

Figure 8: (a) Table of coincidence tagging, where $C(i, j)$ denotes a coincidence event between detector D_i and D_j. For neighbouring detectors an event is counted twice, because if two photons reach the same output port AUX_1, AUX_2 or OUT, they trigger the coincidence event only with 50% probability. (b) Experimental results of conversion probability $P_{\mathrm{exp}}(2, 1|k)$ for $k = 1, 2$ depending on effective spitting ratio T_{eff}. Blue dots representing data of feedforward-enhanced conversion $k = 2$ are plotted against the single beam splitter conversion $k = 1$ shown as red dots. Black and grey lines represent upper bounds for the ideal conversion. Error bars are smaller than the point size.

the overall losses are factored out and cancelled in the calculation of the effective success probabilities of both schemes, that are determined as ratios of the measured two-photon coincidence counts. Additionally, the projection onto the two-photon subspace enables us to emulate the two-photon source with a highly attenuated coherent state.

Our experimental setup is depicted in Fig. 7. An attenuated laser diode periodically driven by 1 ns pulses at 2 MHz repetition rate produces signal photons at 810 nm. The signal passes through a tunable beam splitter BS_1 realized as a sequence of a half-wave plate and a polarization beam splitter. Subsequently, the signal enters a switchable beam splitter BS_2 implemented as a Mach-Zehnder interferometer described in the previous chapter. To provide the projection into a two-photon subspace, we need to discriminate at least between Fock states $|2\rangle$ and $|1\rangle$ at each output. We simplify generic photon-number-resolving detection by splitting the signal between two silicon avalanche

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photodiodes with detection efficiencies around 65%. To trigger the feedforward control of BS_2, electronic pulses generated by D_{1A} and D_{1B} are utilized. The pulses are merged, set to $\pi/2$ modulation voltage, and fed into an EOM.

Results of feedforward-enhanced $|2\rangle \to |1\rangle$ conversion are shown in Fig. 8(b). For comparison, we include data of single beam splitter conversion achieved by deactivation of the feedforward. Our results show that the proposed protocol can work experimentally with nearly ideal performance. Extension to arbitrary $|m\rangle \to |n\rangle$ conversion is possible, provided additional detection multiplexing is implemented. To improve the probability of success, an extension of the experimental setup up to k beam splitters would be necessary. A resource-efficient approach would be reusing single beam splitter for k times in a loop [45, 46]. Although our fiber-based experimental setup is not suitable for cascading due to a high amount of loss, an alternative approach using free-space electrooptic modulator-based switches would be convenient. The loss can be reduced below 10% per cycle, making it practical even without a coincidence basis.

5 Conclusions

This Thesis represents an overview of photonic switching methods and their applications in quantum protocols. The research presented here compiles the results published in three articles: Firstly, we implemented a Mach-Zehnder interferometer with ultra-fast phase switching and demonstrated loop-based time multiplexing for qudit preparation and photon-number-resolving detection [1]. Secondly, a phase stabilization technique was developed, allowing for the stabilization of a single-photon interferometer and interferometric networks with ultra-high precision [2]. Thirdly, a protocol for probabilistic conversion between Fock states was proposed and implemented using a Mach-Zehnder interferometer with feedforward operation [3].

The first part of the Thesis discusses common methods of photonic switching and compares them in the context of quantum technology. The fastest response is enabled by interferometric schemes utilizing an integrated electro-optic modulator, while the lowest losses are achieved using polarization switching with Pockels cells. Possible approaches to active phase stabilization of single-photon interferometers are also discussed. The following chapter provides a brief overview of the theoretical and experimental tools used in the research. A detailed analysis of the Mach-Zehnder interferometer is performed with an emphasis on the phase estimation under real conditions. Further, technical aspects of phase stabilization and phase modulation are described. Additionally, detection, data

processing, and basic tools of quantum optics relevant to our research are described. The subsequent chapters are focused on individual research projects.

In the work [1], we present a fast single-photon switch using phase modulation in a Mach-Zehnder interferometer. We aimed to achieve fast operation, high visibility, and full tunability. Therefore, we used a hybrid configuration of the Mach-Zehnder interferometer, including fiber and free space. The fiber part allows for fast phase control via an integrated electro-optic phase modulator with a 10 GHz bandwidth, while the free-space part allows for precise balancing of the interferometer together with dispersion compensation, polarization filtering, and dispersion-based phase tunability. With this approach, we achieved sub-nanosecond switching with an extinction of 26 dB for an optical bandwidth of 1.3 THz. Further, using a loop configuration of the photonic switch, we performed temporal multiplexing. The incident pulse is trapped into a loop, and during each roundtrip, a fraction is split to the output depending on the switched phase. Using this approach, we demonstrate full control over four time bins with a mean fidelity of 98.9%. The potential applications are photon-number-resolving detection and qudit encoding. Although the presented switch is impractical for the applications due to 7 dB of loss, a low-loss polarization-based switch enabling practical temporal multiplexing is being developed.

In the work [2], we focused on optimizing the phase stabilization of a single-photon Mach-Zehnder interferometer with fast phase switching [2]. A typical problem of interferometers is their phase instability caused by environmental fluctuations. To stabilize the interferometer, we use an auxiliary light acting as the phase reference. The reference is operating on a different wavelength than the quantum signal. The advantage of this approach is in continuous operation and the independence of the quantum signal. Additionally, a strong reference can be used, achieving much greater speed and precision of phase stabilization compared to a single-photon reference. However, to achieve maximum precision in the long term, additional requirements must be satisfied. Firstly, the spectral stability of the reference and signal beams must be ensured to exclude their mutual phase shift. Secondly, phase stabilization must be independent of the overall intensity of the reference beam. In this work, we discuss these problems and propose their solutions, e.g., by using adaptive setpoint. Furthermore, we discuss other sources of errors in phase stabilization, namely local detuning in the interferometer. The experimental implementation of phase stabilization utilizes an active feedback loop with a 1 kHz response, consisting of an analog PID controller, a fiber phase modulator, and sensitive photodiodes. Thanks to a thorough optimization of the interferometer and stabilization over all available parameters, we achieved

exceptional phase stability of 0.05 degrees for 15 hours, exceeding any previous results in the field of single-photon interferometer stabilization by 1 or 2 orders of magnitude. Moreover, due to the low power of the reference (1 nW) and efficient wavelength separation, crosstalk from the reference to the single-photon signal is negligible.

In the work [3], we proposed and experimentally implemented a probabilistic protocol for the conversion between Fock states. Fock state conversion enables the preparation of highly non-classical states, which can serve as resources for quantum information protocols. In our approach, photon subtraction is used to transform a state with a higher photon number into a state with a lower photon number. In each subtraction step, the results of all previous subtraction steps are considered, enabling the conversion with maximal probability. This task is implemented by a sequence of beam splitters with feedforward-controlled splitting ratios. The theoretical analysis shows that the probability of successful conversion is around 85% (depending on the type of conversion) using a sequence of nine splitters. We also investigate the influence of losses and limited detection efficiency on the protocol. The analysis reveals that the protocol can offer an advantage over passive conversion if the losses on the switchable beam splitter are lower than the losses during detection. We experimentally demonstrated a model case of $|2\rangle \to |1\rangle$ conversion using a sequence of two splitters. This was achieved using a Mach-Zehnder interferometer with feedforward operation and a passive tunable beam splitter. By measuring on a coincidence basis, we replicated the theoretical predictions of a 66.6% conversion success rate.

Currently, we have been developing a polarization-based photonic switch with the aim to minimize the loss while keeping the speed moderate. Together with the switch, we develop an ultra-low-loss optical delay line based on multiple reflections between plane mirrors. Apart from the loss, we aim for a high stability of the delay line and to reduce beam aberrations. So far, we have implemented a switch-delay-line setup with 6.5% of roundtrip loss, a 60 ns switching window, and 25 partially dependent switching levels. Especially in terms of the switching levels, our results are unique. However, the development of the setup is still in progress thus further improvements are possible. As a first application of the prototype switching setup, we plan to realize a photon-number-resolving detector. Combining multiplexing in time and space, we aim for more than 30 balanced detection channels.

Fast photonic switching and precise phase stabilization are essential building blocks in quantum information processing as well as in quantum communication. The conversion of Fock states enables the preparation of highly non-classical

states and the realization of a wide range of quantum operations. Therefore, we believe that our results will contribute to the development of quantum optics and quantum technologies.

Shrnutí výsledků práce v češtině

Tato disertační práce se zabývá experimentální realizací jednofotonového fotonického spínání pomocí interferometrů s rychlým fázovým spínáním a dopřednou vazbou, které jsou následně využity pro experimenty a techniky související s kvantově informatickými protokoly. Zaprvé, pomocí Mach-Zehnderova interferometru s rychlým fázovým spínáním a plnou fázovou laditelností byl demonstrován princip přípravy vícedimenzionálních kvantových stavů pomocí rozdělení vstupního pulsu do několika časových oken [1]. Zadruhé, byla vyvinuta technika fázové stabilizace, umožňující stabilizovat jednofotonový interferometr a interferometrické sítě s vysokou přesností po dobu desítek hodin [2]. Zatřetí, pomocí Mach-Zehnderova interferometru s dopřednou vazbou byl realizován protokol pro probabilistickou konverzi mezi Fockovými stavy [3].

V první části práce jsou diskutovány různé metody fotonického spínání a porovnánány v kontextu kvantové technologie. Nejrychlejší odezvu umožňují interferometrická schémata využívající integrovaný elektro-optický modulátor, zatímco nejnižší ztráty představuje polarizační spínání pomocí Pockelsových cel. Dále jsou diskutovány možné přístupy k aktivní fázové stabilizaci jednofotonových interferometrů. Další kapitola obsahuje stručný přehled teoretických a experimentálních nástrojů, které byly využity v rámci výzkumu. Je proveden detailní rozbor Mach-Zehnderova interferometru a nastíněny technické aspekty fázové stabilizace a fázové modulace. Dále je popsána detekce, zpracování dat a základní nástoje kvantové optiky relevantní pro tuto práci. Následující kapitoly se zabývají jednotlivými výzkumnými projekty.

V práci [1] je prezentován rychlý jednofotonový přepínač využívající fázovou modulaci v Mach-Zehnderově interferometeru. V našem přístupu jsme se zaměřili primárně na rychlé fázové spínání a vysokou vizibilitu. Rychlé fázové spínání je zajištěno pomocí integrovaného elektro-optického modulátoru s 10 GHz šířkou pásma. Kromě vláknových prvků však interferometr obsahuje i objemové elementy, což umožňuje přesné srovnání ramen interferometru a umístění disperzních elementů pro kompenzaci disperze a dosažení plné fázové laditelnosti. Díky tomuto přístupu jsme dosáhli libovolného sub-nanosekundového spínání s extinkcí 26 dB pro šířku optického spektra 1.3 THz. Dále jsme demonstrovali dvě aplikace fotonického spínače. Propojením jednoho výstupu se vstupem interfero-

metru jsme dostali takzvanou smyčkovou konfiguraci, díky níž mohl být interferometr využit několikanásobně. Zaprvé jsme demonstrovali rozdělení vstupního pulsu do čtyř časových oken, což v závislosti na obsazenosti oken odpovídá různým kvantovým stavům s dimenzí 4. Zadruhé, ve speciálním případě, kdy jsou všechna okna stejně obsazena a na výstup umístíme jednofotonový detektor, dostáváme zařízení rozlišující počet fotonů.

V článku [2] jsme se zaměřili na dosažení co nejlepší fázové stabilizace Mach-Zehnderova interferometru s rychlým fázovým spínáním [2]. Typickým problémem interferometrů je totiž jejich fázová nestabilita způsobena fluktuacemi prostředí. Aby bylo zamezeno spontánnímu fázovému driftu v interferometru, je třeba jej stabilizovat. Náš přístup spočíval ve využití dvou vlnových délek – na jedné vlnové délce je nesen kvantový signál a druhá vlnová délka slouží jako fázová reference. Výhodou tohoto přístupu je, že fázová stabilizace je prováděna kontinuálně a nezávisle na kvantovém signálu. Navíc je možné použít relativně silný referenční svazek, a tím dosáhnout mnohem větší rychlosti a přesnosti fázové stabilizace než by tomu bylo v případě jednofotonového referenčního svazku. Pro dosažení maximální přesnosti i v dlouhočasové škále je však třeba zajistit další požadavky. Zaprvé je třeba zajistit spektrální stabilitu referenčního a signálního svazku, a tím vyloučit jejich vzájemné fázové rozposunutí. Zadruhé, fázová stabilizace musí být nezávislá na celkové intenzitě referenčního svazku. V práci tyto problémy diskutujeme a navrhujeme jejich řešení. Dále diskutujeme další zdoje chyb fázové stabilizace, a to lokální fluktuace intenzity v interferometeru. Experimentální realizace fázové stabilizace využívá aktivní zpětnovazební smyčku s 1 kHz odezvou složenou z analogové PID regulace, vláknového fázového modulátoru a citlivých fotodiod. Díky důkladné optimalizaci interferometru i stabilizace přes všechny dostupné parametry jsme byli schopni dosáhnout výjimečné fázové stability 0,05° po dobu 15 hodin, což je o 1-2 řády lepší výsledek než jaké byly dosud dosaženy v oblasti stabilizace jednofotonových inferferometrů. Navíc, díky nízkému výkonu referenčního svazku (1 nW) a kvalitní separaci vlnových délek jsou přeslechy z referenčního svazku do jednofotonového signálu zanedbatelné.

V článku [3] jsme navrhli a experimentálně realizovali probabilistický protokol konverze mezi Fockovými stavy. Konverze Fockových stavů umožňuje připravit vysoce neklasické stavy, jež mohou být zdrojem pro kvantově-informatické protokoly. V našem případě navrhujeme konverzi směrem dolů, tedy měníme stav s vyšším počtem fotonů na stav s nižším počtem fotonů. K tomu využíváme síť děličů svazku, jejichž dělicí poměr je ovládán pomocí dopředné vazby. Z teoretické analýzy vyplývá, že pravděpodobnost úspěšné konverze je okolo 85%

(v závislosti na typu konverze) při použití sekvence 9 děličů. Dále vyšetřujeme vliv ztrát a omezené detekční účinnosti na protokol. Z analýzy plyne, že protokol může nabídnout jistou výhodu oproti pasivní konverzi pokud jsou ztráty na spinatelném děliči nižší než ztráty při detekci. Dále jsme experimentálně demonstrovali modelový případ $|2\rangle \rightarrow |1\rangle$ konverze pomocí sekvence 2 děličů. Toho jsme docílili pomocí Mach-Zehnderova interferometru s dopřednou vazbou a pasivního laditelného děliče svazku. Při měření v koincidenční bázi jsme dokázali zreplikovat teoretické predikce úspěšnosti této konverze 66,6%.

Nyní pracujeme na nové generaci fotonického spínače, který je optimalizován na ztráty. Společně se spínačem vyvíjíme nízkoztrátovou zpožďovací linku umožňující realizaci komplexních kvantových protokolů využívajících časové multiplexování. Náš přístup využívá polarizační spínání ve volném prostoru a optickou zpožďovací linku pomocí několikanásobného odrazu na zrcátcích. Celý systém má 6.5% ztrát na oběh, délku spínacího okna 60 ns a 25 částečně závislých hladin. Zejména co se týče počtu hladin, jsou naše parametry unikátní. Celý systém je však stále ve vývoji a další zlepšení v budoucnu jsou možná. Nejbližší plánovaná aplikace fotonického spínače je realizace detektoru rozlišujícího počet fotonů. Využitím časového i prostorového multiplexingu plánujeme zrealkizovat více než 30 vyvážených detekčních kanálů.

Věříme, že výsledky našeho výzkumu rozšiřují dostupné metody fotonického spínání a obohacují pole kvantové optiky a kvantových technologií. Rychlé fotonické spínání i přesná fázová stabilizace jsou důležitými stavebními bloky nejen v kvantovém zpracování informace, ale i kvantových komunikacích. Konverze Fockových stavů umožňuje přípravu vysoce neklasických stavů a realizaci široké škály kvantových operací.

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