University of Pécs

Doctoral School of Physics

Quantum Optics and Quantum Information Programme

Optimization of periodic single-photon sources

PhD Theses

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Pécs, 2020

1. Introduction

Construction of periodic single-photon sources is an important research topic in quantum optics owing to the numerous applications such as optical quantum computing [1, 2], quantum key distribution [3, 4], quantum communication [5, 6], quantum teleportation [7, 8], tests of nonlocality [9, 10], boson sampling [11–13], and the generation of coherent state superpositions [14–18].

Among many possible physical systems that can be used to produce single-photon states, photon pair sources based on spontaneous parametric down-conversion (SPDC) have proven to be promising candidates. In these sources the detection of one member of the correlated photon pair heralds the presence of the other photon which can be used for the desired purpose.

Ideal operation can be approached via spatial or time multiplexing of the sources in these devices. In the lossless case, multiplexing of probabilistic sources would lead to a perfect single-photon source, however, losses proportional to the number of applied optical elements deteriorate the expected single-photon probability in both multiplexing systems. Spatially and time-multiplexed sources known from the literature already have a unified theoretical description which takes all relevant loss mechanisms into consideration. The detailed statistical analysis reveals the existence of an optimal system size in both multiplexing schemes. Maximal single-photon probability is achieved with multiplexed sources used with the optimal system size. In my thesis I discuss two methods which can improve multiplexed single-photon sources. First, I propose a single-photon source based on combined multiplexing which merges spatial and time multiplexing in a single setup. I perform a full statistical analysis of the proposed combined setup. In the second part I optimize single-photon sources operated with photon-number-resolving detectors (PNRD). I show that the single-photon source based on the bulk time multiplexing setup operated with photon-number-resolving detectors has the highest single-photon probability.

2. Aims and Objectives

Development of multiplexed single-photon sources is a relatively young field of quantum optics, less than 20 years have passed since the first ideas were published. Ádám et al. published a mathematical framework in 2014 which is capable of describing spatially or time-multiplexed single-photon sources operated with threshold detectors. They showed that these devices can be optimized in order to achieve maximal single-photon probability [19]. This result forms the basis of my research.

The aim of my research is to develop new methods that contribute to the construction of almost ideal single-photon sources. I develop a general statistical description for all proposed methods. I perform the optimization of the devices over a broad range of loss parameters. The statistical analysis can be used to determine all parameters required for the optimal operation of the multiplexed single-photon sources, and also the expected maximal single-photon probability. At the same time, the full statistical treatment reveals all characteristics of multiplexed single-photon sources, the detailed analysis helps to understand the operation of these complex devices.

The first goal of my research is to develop a scheme that merges spatial and time multiplexing in a single setup. My further goal is to develop the full statistical framework of the proposed scheme, and to optimize the device over a broad range of experimentally feasible loss parameters.

In most experiments so far, idler photons are detected by threshold detectors which are not capable of determining the number of detected photons. In view of new research results regarding the development of high-efficiency PNRDs, my aim is to analyze the effect of these more advanced devices on the single-photon probability of multiplexed single-photon sources. My goal is to develop a mathematical model that is capable of describing the output photon statistics of multiplexed single-photon sources operated with PNRDs. My further goal is to compare the expected single-photon probabilities of multiplexed single-photon sources operated with threshold and number resolving detectors over a broad range of loss parameters with the help of a selected multiplexing arrangement. The more advanced detector type enables the realization of different detection strategies. My goal is to determine the optimal detection strategy over the considered range of parameters. Finally, my goal is to determine the maximal single-photon probability of time multiplexed single-photon sources operated with PNRDs.

3. New Scientific Results

1. I have proposed a scheme of a periodic single-photon source based on combined multiplexing, where the outputs of several time multiplexers are spatially multiplexed. I have developed a statistical description of single-photon sources based on the proposed combined multiplexing scheme in which all relevant loss mechanisms are taken into consideration. The proposed single-photon source based on combined multiplexing can be optimized with the statistical model in order to achieve maximal single-photon probability. [S1,E1]

2. I have carried out the optimization of the proposed single-photon source based on combined multiplexing assuming experimentally feasible loss parameters. I have determined the optimal system size and the optimal number of input mean photon number for which the single-photon probability is maximal. I have shown that the maximal single-photon probability of optimized standalone spatially or time-multiplexed sources can only be enhanced in rather special cases, when combined multiplexing is applied. I have also shown that the number of multiplexed time windows and the number of multiplexed nonlinear sources can be reduced via the application of combined multiplexing, while maintaining a relatively high single-photon probability. [S1,E1]

3. I have developed a general statistical description of multiplexed periodic single-photon sources operated with photon-number-resolving detectors. The model includes all relevant loss mechanisms. All possible detection strategies that can be realized only by photon-number-resolving detectors can be analyzed with the proposed statistical description. With the presented mathematical framework, multiplexed single-photon sources with photon-number-resolving detectors can be optimized in order to achieve maximal single-photon probability. [S2,P1,P2,P3]

4. I have optimized single-photon sources based on symmetric spatial multiplexing operated with photon-number-resolving detectors over a broad range of parameters assuming Poissonian and thermal input photon statistics. I have determined the range of parameters where single-photon sources operated with photon-number-resolving detectors outperform single-photon sources with threshold detectors. I have shown that higher single-photon probabilities are achievable with either the same or less multiplexed units when the sources are operated with photon-number-resolving detectors regardless of the input photon statistics. I have determined the optimal detection strategy over the whole parameter range under consideration for both photon statistics. [S2,P1,P2,P3]

5. I have carried out the optimization of storage loop based and binary time multiplexing based time-multiplexed single-photon sources operated with photon-number-resolving detectors. I have found that the optimized binary time multiplexing based single-photon source can achieve the highest single-photon probability among all presented results. [S2,P1,P2,P3]

4. List of Publications

Own publications related to the dissertation

Publications in peer-reviewed journals

S1 **Ferenc Bodog**, Peter Adam, Matyas Mechler, Imre Santa, Mátyás Koniorczyk, *Optimization of periodic single-photon sources based on combined multiplexing*, Phys. Rev. A, **94**, 033853, (2016)

S2 **Ferenc Bodog**, Matyas Mechler, Mátyás Koniorczyk, Peter Adam, *Optimization of multiplexed single-photon sources operated with photon-number-resolving detectors*, Phys. Rev. A, **102**, 013513 (2020)

Presentations

E1 **Ferenc Bodog**, Peter Adam, Matyas Mechler, Imre Santa, and Matyas Koniorczyk *Optimization of periodic single-photon sources based on combined multiplexing*, 5th Work Meeting on Quantum Optics & Information 28-29. April 2017, Pécs, Hungary (2017)

Posters

P1 **Ferenc Bodog**, Peter Adam, Matyas Mechler, *Analysis of multiplexed single-photon sources operated with photon-number-resolving detectors*, 24th Central European Workshop on Quantum Optics 26-30 June 2017, Kongens, Lyngby, Denmark (2017)

P2 **Ferenc Bodog**, Matyas Mechler, Peter Adam, *Enhancing the performance of multiplexed single-photon sources with photon-number-resolving detectors*, Quantum Optics IX 17 - 23.09.2017, Gdańsk, Poland (2017)

P3 **Ferenc Bodog**, Matyas Mechler, Peter Adam, *Enhancing the expected single-photon probability of multiplexed single-photon sources via optimized detection strategy*, „Kvantumelektronika 2018: VIII. Szimpózium a hazai kvantumelektronikai kutatások eredményeiről", 2018. június 15., Budapest (2018)

Other publications

K1 **Ferenc Bodog**, Matyas Mechler, Peter Adam, *Enhancing the performance of spatially multiplexed single-photon sources with optimized heralding strategy*, 25th Central Eu-

ropean Workshop on Quantum Optics, 21-25 May, University of the Balearic Islands, Spain (2018)

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