UNIVERSITY OF PÉCS

Doctoral School of Physics

Quantum Optics and Quantum Information Program

Generation of nonclassical states of light in traveling optical fields

PhD Theses

Gábor Mogyorósi

supervisor:
Péter Ádám
associate professor

Pécs, 2020

1 Overview

Nonclassical states of light play an essential role in numerous applications in optical quantum information processing, quantum-enhanced metrology, and fundamental tests of quantum mechanics. In the generation of nonclassical states two main research areas can be distinguished. One of them is the generation in optical resonators, cavities, the other is the generation of states in traveling optical fields. Most of the developed methods can be used to generate a particular quantum state. Special attention has been paid to producing nonclassical states of light in traveling optical fields due to their practical relevance [1–6].

A way of generating states in traveling optical fields is producing them in nonlinear optical processes with a possible inclusion of a feedback. The other method is the conditional generation of quantum states that consists in the measurement of one of the modes of a bipartite correlated state, thereby projecting the state of the other mode to the desired one.

The generation of a broader class of relevant nonclassical states requires a more general approach to quantum state engineering, especially for states lacking a specialized preparation scheme. The aim of these general protocols is the preparation of a large variety of states in the same experimental setup [7–14]. In such schemes, the number of the optical elements and detection events is generally proportional to the amount of number states involved in the photon number expansion of the target state. This property obviously leads to a decrease in the success probability and even to that in the fidelity of the preparation of states involving larger photon number components. The high fidelity and success probability are important for practical applications.

2 Aims and methods

The previous results regarding the quantum state generation motivated me to propose an experimental quantum state engineering scheme for the high-fidelity conditional generation of various nonclassical states of practical relevance in traveling optical fields. My aim is to reduce the number of optical elements to minimum in the proposed experimental scheme. I intend to analyze the performance of the system equipped with homodyne measurement and photon-number-resolving detection. My further goal is to determine the output state of the experimental system using photon-number-state and coherent-state representations. I intend to show that the developed single-step conditional generation scheme using separately prepared squeezed coherent states as inputs can be applied for preparing several types of nonclassical states with high fidelity and success probability.

In my dissertation I develop a numerical method based on a genetic algorithm for the optimization of the proposed optical system. During the optimization, the variable parameters of the system are determined so that the accuracy of the generation should be maximal. I analyze in detail the generation of binomial states, negative binomial states, special photon number superpositions, amplitude-squeezed states, photon number states, squeezed photon number states, Schrödinger-cat states and squeezed Schrödinger-cat states.

Finally, I consider the sensitivity of the method to the precision of the parameters of the input states and to the nonunit quantum efficiency of the measurements.

3 Theses

1. I have proposed a traveling-wave experimental scheme for high-fidelity generation of nonclassical states of light, which includes a beam splitter and a measurement, and the input states are independently prepared squeezed coherent states with variable parameters. The measurement can be a homodin measurement or a single- or N-photon detection. The output state of the proposed optical system was determined in a photon number state and coherent state representation
[S1, S2].

2. I have developed a numerical method to optimize the proposed experimental scheme. During the optimization of the developed procedure, the parameters of the proposed optical system and the input states were determined so that the target function of the method, the misfit should be minimal for the target state. The probability of generation was determined for each target state. I have also analyzed a numerical optimization which simultaneously optimizes the misfit and probability of generation [S1, S2].

3. I have proved that the proposed experimental scheme with single and N-photon detection can generate binomial and negative binomial states, special photon number state superpositions, photon number, squeezed photon number and displaced squeezed photon number, amplitude-squeezed, Schrödinger cat states with high accuracy and high probability. I have analyzed for each quantum state how the accuracy and probability of generation changes depending on the parameters of the states [S1, P1, P2].

4. I have proved that certain binomial and negative binomial states, photon number state superpositions and amplitude-squeezed states that are close to a Gaussian state can be generated by homodyne measurement with high accuracy and high probability [S1, P3, P4].

5. I have found that several optimal solutions exist for various parameters for several nonclassical states. I came to the conclusion that some of the input parameters can be chosen freely in certain ranges without the significant deterioration of the fidelity. Thus, in the experimental implementation, several different nonclassical states can be generated with the proposed experimental scheme without significant modification of the input states and the parametric device that generates them [S1, S2].

6. I have examined the efficiency of the proposed optical system in relation to the accuracy of the input states and the efficiency of the non-ideal detectors. I have shown that the nonclassical states can still be generated with high accuracy at experimentally feasible error values [S1, S2].

4 List of publications related to the thesis

[S1] **Gabor Mogyorosi**, Peter Adam, Emese Molnar, and Matyas Mechler, *"Single-step quantum state engineering in traveling optical fields"*, Phys. Rev. A **100**, 013851 (2019)

[S2] **Gabor Mogyorosi**, Emese Molnar, Matyas Mechler, and Peter Adam, *"Single-Step Traveling-Wave Quantum State Engineering in the Coherent State Representation"*, J. Russ. Laser Res. **39**, 448 (2018)

[E1] **Mogyorósi Gábor**, Molnár Emese, Varga Árpád, Mechler Mátyás, és Ádám Péter: *„Fotonszám-állapot szuperpozíciók haladóhullámú előállítása"*, IV. Interdiszciplináris Doktorandusz Konferencia.
Helyszín: Pécs, Magyarország, 2015. 05. 14–15., Pécsi Tudományegyetem Állam- és Jogtudományi Kar, ISBN: 978-963-642-830-3 (2015)

[E2] **Mogyorósi Gábor**: *„Fotonszám-állapot szuperpozíciók haladóhullámú előállítása”*,
IV. Fizikus Doktoranduszok Konferenciája. Helyszín: Balatonfenyves, Magyarország, 2015. 06. 11–14.

[P1] **Gabor Mogyorosi**, Peter Adam, and Emese Molnar, *“Conditional generation of superpositions of photon number states of traveling fields”*, 24th Central European Workshop on Quantum Optics. Helyszín: DTU Lyngby, Dánia, 2017. 06. 26–30.

[P2] **Gabor Mogyorosi**, Peter Adam, and Emese Molnar, *“Conditional generation of nonclassical states of traveling fields”*, Quantum Optics IX. Helyszín: Gdańsk, Lengyelország, 2017. 09. 17–23.

[P3] **Gabor Mogyorosi**, Emese Molnar, Matyas Mechler, and Peter Adam, *“Quantum state engineering via optimized photon subtraction in traveling optical fields”*, 25th Central European Workshop on Quantum Optics. Helyszín: University of the Balearic Islands, Mallorca, 2018. 05. 21–25.

[P4] **Gábor Mogyorósi**, Emese Molnár, Mátyás Mechler, Péter Ádám, *"Single step quantum state engineering in traveling optical fields"*, P11, Kvantumelektronika 2018: VIII. szimpózium a hazai kvantumelektronikai kutatások eredményeiről. Helyszín: Budapest, Magyarország, 2018. 06. 15., ISBN: 978-963-429-250-0 (2018)

5 Other list of publications

[K1] Emese Molnar, Peter Adam, **Gabor Mogyorosi**, and Matyas Mechler, *"Quantum state engineering via coherent-state superpositions in traveling optical fields"*, Phys. Rev. A **97**, 023818 (2018)

[K2] Emese Molnár, **Gábor Mogyorósi**, Mátyás Mechler, Péter Ádám, *"Quantum state engineering via coherent-state superpositions in traveling optical fields"*, P12, Kvantumelektronika 2018: VIII. szimpózium a hazai kvantumelektronikai kutatások eredményeiről. Helyszín: Budapest, Magyarország, 2018. 06. 15., ISBN: 978-963-429-250-0 (2018)

[K3] P. Adam, E. Molnar, **G. Mogyorosi**, A. Varga, M. Mechler, and J. Janszky, *"Construction of quantum states by special superpositions of coherent states"*, Phys. Scr. **90**, 074021 (2015)

[K4] **Mogyorosi G**, Adam P, Molnar E, Varga A, Mechler M, and Janszky J, *"Construction of quantum states by special superpositions of coherent states"*, P13, Kvantumelektronika 2014: VII. szimpózium a hazai kvantumelektronikai kutatások eredményeiről. Helyszín: Budapest, Magyarország, 2014. 11. 28., ISBN: 978-963-642-697-2 (2014)

[K5] Molnar E, Varga A, **Mogyorosi G**, and Adam P, *"Quantum state engineering with linear optical tools"*, P14, Kvantumelektronika 2014: VII. szimpózium a hazai kvantumelektronikai kutatások eredményeiről. Helyszín: Budapest, Magyarország, 2014. 11. 28., ISBN: 978-963-642-697-2 (2014)

[K6] Molnar E, Varga A, **Mogyorosi G**, and Adam, P, *„Quantum state engineering with linear optical tools"*, Lézer Tea 2014. Konferencia helye, ideje: Szeged, Magyarország, 2014. 04. 23.

References

[1] J. S. Neergaard-Nielsen, B. M. Nielsen, K. Hettich, C. Mølmer, and E. S. Polzik, Phys. Rev. Lett. **97**, 083604 (2006).

[2] A. Ourjoumtsev, H. Jeong, R. Tualle-Brouri, and P. Grangier, Nature **448**, 78 (2007).

[3] H. Takahashi, K. Wakui, S. Suzuki, M. Takeoka, K. Hayasaka, A. Furusawa, and M. Sasaki, Phys. Rev. Lett. **101**, 233605 (2008).

[4] T. Gerrits, S. Glancy, T. S. Clement, B. Calkins, A. E. Lita, A. J. Miller, A. L. Migdall, S. W. Nam, R. P. Mirin, and E. Knill, Phys. Rev. A **82**, 031802 (2010).

[5] J. Etesse, M. Bouillard, B. Kanseri, and R. Tualle-Brouri, Phys. Rev. Lett. **114**, 193602 (2015).

[6] K. Huang, H. Le Jeannic, J. Ruaudel, V. B. Verma, M. D. Shaw, F. Marsili, S. W. Nam, E. Wu, H. Zeng, Y.-C. Jeong, R. Filip, O. Morin, and J. Laurat, Phys. Rev. Lett. **115**, 023602 (2015).

[7] S. Szabo, P. Adam, J. Janszky, and P. Domokos, Phys. Rev. A **53**, 2698 (1996).

[8] M. Dakna, L. Knöll, and D.-G. Welsch, Opt. Commun. **145**, 309 (1998).

[9] M. Dakna, J. Clausen, L. Knöll, and D.-G. Welsch, Phys. Rev. A **59**, 1658 (1999).

[10] J. Fiurášek, R. García-Patrón, and N. J. Cerf, Phys. Rev. A **72**, 033822 (2005).

[11] C. C. Gerry and A. Benmoussa, Phys. Rev. A **73**, 063817 (2006).

[12] E. Bimbard, N. Jain, A. MacRae, and A. I. Lvovsky, Nat. Photonics **4**, 243 (2010).

[13] J. Sperling, W. Vogel, and G. S. Agarwal, Phys. Rev. A **89**, 043829 (2014).

[14] K. Huang, H. Le Jeannic, V. B. Verma, M. D. Shaw, F. Marsili, S. W. Nam, E. Wu, H. Zeng, O. Morin, and J. Laurat, Phys. Rev. A **93**, 013838 (2016).