UNIVERSITY OF PÉCS

Doctoral School of Physics

Quantum Optics and Quantum Information Program

Generation of Nonclassical states by Coherent-state superpositions

PhD Theses

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1. Introduction

Generation of various nonclassical states of light is still an important topic in quantum optics owing to the numerous applications. The one-dimensional coherent-state superpositions along a line and on a circle are good represenations of the nonclassical states [1–4]. It has been shown that superpositions of even a small number of coherent states placed along a straight line or on a circle in phase space can approximate nonclassical field states with a high degree of accuracy [5–7]. We consider quantum state engineering on an ellipse and on a specific lattice in phase space. We show, by using an efficient numerical optimization method, that the superpositions of a small number of coherent states in these geometries can approximate certain nonclassical states with a high accuracy. For certain states and parameter ranges the approximation is better than the corresponding one on a circle or along a line.

The nonclassical states of light including Schrödinger-cat states have already been prepared in several traveling wave experiments [8–12]. Quantum state engineering has also been extensively studied with the general aim of the preparation of a variety of different nonclassical states in traveling fields in the same single experimental scheme [13, 14]. For realizing this task various methods have been developed, such as repeated photon additions, photon subtractions and the application of the superpositions of these processes. It is a characteristic property of such schemes that the number of the optical elements is generally proportional to the amount of number states involved in the photon number expansion of the target state. This implicates that an increase in the number of the constituent photon number states of the target state leads to a decrease in the success probability and even to that in the fidelity of the generation.

In the dissertation we propose two experimental schemes containing only a small number of linear optical elements and homodyne measurements that can be used for producing coherent-state superpositions along a line and on a lattice in phase space. These superpositions can approximate various nonclassical states in traveling optical fields. The succes probabilities these schemes are higher than the ones presented in the literature.

2. Aims and methods

Inspired by the results of the approximation of the nonclassical states by discrete coherent-state supeprositions, we consider approximation of special nonclassical states by coherent-state superpostions on an ellipse and on a lattice in phase space. As the ellipse fits to the shape of the Wigner function of certain states, we expect that for such states we can obtain an approximation superior in quality to the one based on the one-dimensional coherent-state representation of the state, that is, constructed from states along a line in phase space. My aim is to study the approximation of displaced squeezed number states by coherent-state superpositions on an ellipse in phase space and the approximation of other nonclassical states by experimentally realizable superpositions on a 3×3 lattice in phase space. My aim is to develop a numerical method for finding the optimal discrete coherent-state superpositions approximating a given nonclassical state.

It is a characteristic property of quantum state engineering schemes that the number of the optical elements is generally proportional to the amount of number states involved in the photon number expansion of the target state. This implicates that an increase in the number of the constituent photon number states of the target state leads to a decrease in the success probability and even to that in the fidelity of the generation. The solution of these problems is a scheme contains fixed number of optical elements and measurements independently of the amount of states involved in the photon number expansion of the target states. My aim is to propose experimental schemes containing only a small number of linear optical elements and homodyne measurements that can be used for producing coherent-state superpositions along a line and on a lattice in phase space. My aim is to propose a numerical method to determine the optimal parameters of the schemes. My aim is to study the generation of special nonclassical states such as amplitude squeezed states, binomial states, squeezed cat states, and various photon number superpositions.

3. Theses

1. I have proved that the squeezed and displaced photon number states can be approximated with a high accuracy by discrete coherent-state superpositions on an ellipse in phase space. I have determined the parameters of the ellipse and the coefficients of the coherent-state superposition by a numerical method so that the misfit of the approximation should be minimal for a given target state. I have proved that the approximation by a discrete coherent-state superposition on an ellipse has a higher accuracy than the one along a straight line for the considered states. [S1]

2. I have proved that amplitude-squeezed states, squeezed photon number states, and photon number states can be approximated with a high accuracy by discrete coherent-state superposition on an equidistant 3x3 lattice in phase space. I have determined the parameters of the lattice and the coefficients of the coherent-state superposition by a numerical method so that the misfit of the approximation should be minimal for a given target state. I have proved that the approximation by a discrete coherent-state superposition on an equidistant 3x3 lattice has higher accuracy than the one on a circle for the considered states for certain

parameters. [S1]

3. I have proposed two experimental quantum state engineering schemes for high-fidelity conditional generation of various nonclassical states of practical relevance in traveling optical fields. The first scheme contains three beam splitters and three homodyne measurements while the simplified scheme contains only two of them. The input states of the schemes are experimentally generable coherent-state superpositions and a squeezed vacuum state in the case of the simplified scheme. The output states of the two proposed schemes are discrete coherent-state superpositions along a straight line and on a lattice in phase space. [P1,P3,P4,S2]

4. I have developed a numerical method for the optimization of the proposed optical systems. During the optimization of the method I have determined the parameters of the input states and the parameters of the homodyne measurements so the misfit of the generation should be minimal for a given target state. I have also determined the succes probability of the generation for all the considered states. I have shown that amplitude-squeezed states, binomial states, Schrödinger-cat states and squeezed Schrödinger-

cat states, and special photon number superpositions and resource states can be prepared with a high accuracy by the proposed schemes. I have found that the considered states can be generated with the same range of accuracy with both of the schemes, but the succes probability for the simplified scheme is greater than the one for the first scheme. I have shown that the achievable succes probabilities in the proposed schemes are higher than the ones that can be achieved in the quantum state engineering schemes known in the literature. [P1,P3,P4,S2]

4. List of Publications

Own publications related to the dissertation

Publications in a peer-reviewed journal

S1 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)

S2 **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)

Presentations

E1 **Molnár Emese**, Mogyorósi Gábor, Varga Árpád, Mechler Mátyás, és Ádám Péter: *„A fény nemklasszikus állapotainak haladó hullámú 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 **Molnár Emese**: *„A fény nemklasszikus állapotainak haladó hullámú előállítása”*,

IV. Fizikus Doktoranduszok Konferenciája. Helyszín: Balatonfenyves, Magyarország, 2015. 06. 11–14.

Posters

P1 **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.

P2 **Emese Molnar**, Arpad Varga, Gabor Mogyorosi, Peter Adam, *„Quantum state engineering with linear optical tools”*,P-63, 21th Central European Workshop on Quantum Optics. Helyszín: Burssels, Belgium, 2014. 06. 23–27.

P3 **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)

P4 **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)

Other publications

K1 Adam P., Mechler M., Szalay V., **Molnar E.**, Koniorczyk M., *„Intelligent states for number operator-annihilation operator uncertainty relation"* P-63, 21th Central European Workshop on Quantum Optics. Helyszín: Burssels, Belgium, 2014. 06. 23–27.

K2 Adam P., Mechler M., Szalay V., **Molnar E.**, Koniorczyk M., *„Intelligent states for number operator-annihilation operator uncertainty relation"*, Kvantumelektronika 2014: VII. szimpózium a hazai kvantumelektronikai kutatások eredményeiről. Helyszín: Budapest, Magyarország, 2014. (2018)

K3 Gabor Mogyorosi, Peter Adam, **Emese Molnar**, and Matyas Mechler,
„Single-step quantum state engineering in traveling optical fields", Phys. Rev. A **100**, 013851 (2019)

K4 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)

K5 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)

K6 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.

K7 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.

K8 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.

K9 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)

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