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RPPR Final Report
as of 10-Jul-2023

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Proposal Number: 69037MI **Agreement Number: W911NF-16-1-0086**

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STEM Degrees: 6 **STEM Participants:** 12

Major Goals: The overall aim of this project has been to develop and to demonstrate new tools for dimensional reduction of models for circuits/networks of coherently-coupled quantum dynamical systems. Such circuits/networks can be modeled straightforwardly in the limit of vanishing propagation time between components, using quantum stochastic differential equations. The overall dimension of the resulting models increases exponentially with component count, however, and prior to this project no optimized methods for incorporating time delays were known. The specific aims of this project are: 1) to apply manifold projection-based methods to develop componentwise dimensional reduction methods for quantum systems, 2) to apply machine-learning methods to develop component-wise dimensional reduction methods for quantum systems, 3) to explore strategies based on quantum measurement theory and quantum stochastic differential equations to develop dimension-reducing approximations in the way that we treat coherent coupling between components, 4) to develop and to demonstrate general-purpose methods for incorporating time delays in quantum circuit/network models, and 5) to demonstrate the utility of quantum dimensional reduction methods by simulating systems of interest for distributed quantum information processing.

Accomplishments: Over the full performance period of this award our research has progressed from origins in device and circuit modeling for single-mode quantum optics, to modeling and design of broadband (many-mode) quantum nonlinear photonic devices. The common underlying theme has been quantum dimensional reduction and we have explored several distinct technical strategies motivated by specific details of realistic physical models in these divergent regimes. Our most recent work has established unique foundations for emerging ideas in quantum nanophotonic engineering for ultrafast, ultra-low power beyond-classical information processing, which serve as an essential basis for continuing experimental work at Stanford supported by the NSF and NTT Research.

Our earliest work focused on the exploration of manifold-projection methods for dimensional reduction of quantum models for individual input-output devices. The results formalized previous intuitive ideas and provided a geometric picture of nonlinear model reduction for quantum systems. The methods we developed provided substantial theoretical insights but the corresponding codes we developed proved to be slow relative to ad hoc approaches to approximate simulation of device models of current interest. We hope that future work may revive these methods for use with more challenging quantum models and with optimized codes. In any case, the essential insights from this work have been carried forward into new work on systematic dimensional reduction for broadband quantum pulse propagation in nonlinear waveguides, which required a rigorous approach to yield physical insight into the classical-quantum crossover regime of current experimental interest. Early work in this award also generated new methods for treating time delays in feedforward/feedback networks of single-mode quantum optical devices. This work was mathematically illuminating and produced some significant technical results on approximate modeling of linear quantum stochastic delay-differential equations, which have not otherwise been effectively treated in the existing literature.

Experimental progress in quantum nonlinear photonics that occurred parallel to our work on this award motivated a shift of research emphasis towards broadband pulse propagation. With continuing focus on quantum model reduction, we shifted our emphasis from single-mode devices and circuits to highly multimode quantum devices. This shift allowed us to treat device designs that natively incorporate tens to hundreds-of-thousands of optical modes, corresponding to state-of-the-art experimental designs in nanophotonics with ultrafast laser sources. A dominant modeling challenge becomes the optimal identification of temporal “supermodes” that capture the most important coherent nonlinear dynamics occurring on relevant timescales, and that support an approximate “reservoir” treatment of remaining degrees of freedom. Our work on these systems has provided the first systematic development of system-reservoir separations in coherent nonlinear optics in the quantum regime, which has been a long-standing intuitive goal of theoretical work in this area.

One productive technical approach has incorporated the use of matrix product state representations borrowed from quantum information theory and quantum many-body physics. Such methods are powerful and accurate for quantum pulse propagation in nonlinear waveguides because the effective coherent coupling among optical field modes is essentially one-dimensional along the direction of pulse propagation. Using these methods we have been able to derive intriguing results on qualitative changes in the dynamics of canonical nonlinear-optical processes such as parametric downconversion and second-harmonic generation in the classical-quantum crossover regime, in which increasingly strong coherent coupling among optical modes leads to significant nonlinear dynamical effects on the few-photon energy scale. Our results underscore the importance of dispersion engineering as a design degree of freedom in quantum nonlinear photonics – the importance of linear dispersion for controlling nonlinear dynamical behaviors has been intuitively appreciated by experimentalists for some time, but our work has established rigorous guidelines and analyses for extending this control into the few-photon quantum regime.

We subsequently returned to ideas stemming from our early work on manifold projection, to develop a new “gaussian interaction frame” approach for accurate simulation of emergent non-gaussian effects in the classical-quantum crossover regime. This work targets a parameter regime of primary focus in contemporary experimental work, corresponding to the stronger coherent coupling becoming newly accessible with state-of-the-art materials (principally thin-film lithium niobate) and nanofabrication methods. In this regime, familiar coherent nonlinear-optical phenomena that could traditionally be treated using simple gaussian approximation starts to deviate from classical formulae, and non-gaussian effects begin to emerge that could be harnessed for quantum information processing and related aims. The gaussian interaction frame method uses a kind of theoretical “feed-forward” in which the leading-order gaussian effects are displaced into simplified mean-field equations and residual quantum equations of motion are derived relative to these displacements. If done correctly, the residual quantum equations can be simulated with high accuracy using truncated Fock spaces that require far fewer dynamical variables than ab initio simulation. We have used these methods to make surprising predictions regarding both leading-order non-Gaussian effects and higher-order Gaussian corrections that should occur in simple squeezing experiments with strong coupling.

Our work for this award reached a final frontier of leveraging new insights regarding system-reservoir separations in quantum nonlinear photonics, to launch new ideas regarding the design of devices that minimize system-reservoir couplings as a way to minimize decoherence associated with Hilbert-space “leakage.” Our proposal for temporal trapping provides the first known practically feasible approach to circumventing a no-go theorem for quantum optical quantum information processing identified by Shapiro in 2006. Our result shows that rigorous analysis of quantum model reduction – and in particular rigorous analysis of the conditions for reduction of complex multi-mode quantum models to coherent few-mode models – can provide concrete guidelines for engineering quantum devices and architectures with minimized decoherence. Our continuing theoretical work in this area will build upon these seminal results to explore a broader range of strategies for purifying useful quantum phenomena in the classical-quantum crossover regime of nonlinear nanophotonics.

Training Opportunities: Two postdoctoral scholars and ten graduate students have received interdisciplinary research training over the course of this award, six of whom have successfully completed their Ph.D. degrees largely on the basis of work for this award. All of this research training has included both theoretical and computational work, including pursuit of goals stemming both from fundamental physics questions and applied computational mathematics. Some of this work has been set in the context of quantum engineering and advanced nanophotonics, while other aspects have related strongly to contemporary research in dynamical systems theory, nonlinear feedback control, and non-convex optimization.

Results Dissemination: During the final period of this award Hideo Mabuchi delivered an online presentation at the NSF-FET Panel on Ising Machines (9 May 2022). Ryotatsu Yanagimoto also presented a paper titled "Towards an engineering framework for ultrafast quantum nonlinear optics" at SPIE Ultrafast Phenomena and Nanophotonics XXV on 5 March 2021.

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PARTICIPANTS:

Participant Type: PD/PI
Participant: Hideo Mabuchi
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Edwin Ng
Person Months Worked: 1.00 **Funding Support:**
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Date Submitted: 10/4/18 12:00AM Date Published: 12/1/17 8:00AM
Publication Location:
Article Title: Low-dimensional manifolds for exact representation of open quantum systems
Authors: Nikolas Tezak, Nina H. Amini, Hideo Mabuchi
Keywords: quantum, dimensional, manifold, projection, reduction
Abstract: Weakly nonlinear degrees of freedom in dissipative quantum systems tend to localize near manifolds of quasiclassical states. We present a family of analytical and computational methods for deriving optimal unitary model transformations that reduce the complexity of representing typical states. These transformations minimize the quantum relative entropy distance between a given state and particular quasiclassical manifolds. This naturally splits the description of quantum states into transformation coordinates that specify the nearest quasiclassical state and a transformed quantum state that can be represented in fewer basis levels. We derive coupled equations of motion for the coordinates and the transformed state and demonstrate how this can be exploited for efficient numerical simulation. Our optimization objective naturally quantifies the nonclassicality of states occurring in some given open system dynamics. This allows us to compare the intrinsic complexity of different open quant
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Date Submitted: 10/4/18 12:00AM Date Published:
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Article Title: Factorization of linear quantum systems with delayed feedback
Authors: Gil Tabak, Ryan Hamerly, Hideo Mabuchi
Keywords: quantum, feedback, delay, dimensional reduction
Abstract: We consider the transfer functions describing the input-output relation for a class of linear open quantum systems involving feedback with nonzero time delays. We show how such transfer functions can be factorized into a product of terms which are transfer functions of canonical physically realizable components. We prove under certain conditions that this product converges, and can be approximated on compact sets. Thus our factorization can be interpreted as a (possibly infinite) cascade. Our result extends past work where linear open quantum systems with a state-space realization have been shown to have a pure cascade realization [Nurdin, H. I., Grivopoulos, S., & Petersen, I. R. (2016). The transfer function of generic linear quantum stochastic systems has a pure cascade realization. Automatica, 69, 324-333.]. The functions we consider are inherently non-Markovian, which is why in our case the resulting product may have infinitely many terms.
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Journal: Physical Review Letters

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Article Title: Embedding entanglement generation within a measurement-feedback coherent Ising machine

Authors: Ryotatsu Yanagimoto, Peter L. McMahon, Edwin Ng, Tatsuhiro Onodera, Hideo Mabuchi

Keywords: quantum optics, ising, entanglement swapping

Abstract: We present a new scheme to efficiently establish entanglement between optical modes in a time-multiplexed coherent Ising machine (CIM) by means of nonlocal measurement and feedback. We numerically simulate and evaluate the generation of steady-state entanglement in a system with nearest-neighbor interactions on a 1D ring, and we compare the results to those of a conventional CIM with all-optical interactions mediated by delay lines. We show that the delay-line architecture has a fundamental limit on accessible entanglement that our measurement-based scheme can substantially surpass. These results motivate the study of non-classical correlations in CIMs with levels of entanglement previously considered to be experimentally impractical.

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Date Submitted: 7/7/23 12:00AM Date Published:

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Article Title: Nonlinear Quantum Behavior of Ultrashort-Pulse Optical Parametric Oscillators

Authors: Tatsuhiro Onodera, Edwin Ng, Niels Lörch, Atsushi Yamamura, Ryan Hamerly, Peter L. McMahon, Alire

Keywords: quantum optics, pulsed, supermodes, entanglement, non-gaussian

Abstract: We introduce a theoretical framework based on Fano's theory of discrete-continuum interactions to analyze the quantum dynamics of broadband parametric downconversion (PDC) in the few-pump-photon regime of nonlinear quantum nanophotonics. Applying this unified analytic approach to 1D ?(2)-nonlinear waveguides, we find a host of remarkable dynamical features due to the coupling of a discrete pump state to the signal continuum, from unit-efficiency (i.e., complete) downconversion when the coupling is dissipative, to Rabi-like oscillations with sub-exponential decay when it is dispersive. The theory provides a straightforward way to analytically compute a full characterization of the PDC dynamics, including the complete eigensystem of the continuum Hamiltonian and expressions for the signal biphoton correlation function. We also apply the theory to study a pair of linearly coupled ?(2) waveguides, where two discrete pump states simultaneously downconvert into a common-mode signal continuum

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Date Submitted: 8/28/20 12:00AM Date Published: 6/1/20 7:00AM
Publication Location:
Article Title: Engineering a Kerr-Based Deterministic Cubic Phase Gate via Gaussian Operations
Authors: Ryotatsu Yanagimoto, Tatsuhiro Onodera, Edwin Ng, Logan G. Wright, Peter L. McMahon, Hideo Mabu
Keywords: Optical quantum information processing; Optical solitons; Quantum gates; Quantum information processing with continuous variables
Abstract: We propose a deterministic, measurement-free implementation of a cubic phase gate for continuous-variable quantum information processing. In our scheme, the applications of displacement and squeezing operations allow us to engineer the effective evolution of the quantum state propagating through an optical Kerr nonlinearity. Under appropriate conditions, we show that the input state evolves according to a cubic phase Hamiltonian, and we find that the cubic phase gate error decreases inverse quartically with the amount of quadrature squeezing, even in the presence of linear loss. We also show how our scheme can be adapted to deterministically generate a nonclassical approximate cubic phase state with high fidelity using a ratio of native nonlinearity to linear loss of only 10?4, indicating that our approach may be experimentally viable in the near term even on all-optical platforms, e.g., using quantum solitons in pulsed nonlinear nanophotonics.
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Journal: submitted to Optica
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Volume: Issue: First Page #:
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Article Title: Broadband Parametric Downconversion as a Discrete-Continuum Fano Interaction
Authors: R. Yanagimoto, E. Ng, M. P. Jankowski, T. Onodera, M. M. Fejer, H. Mabuchi
Keywords: nonlinear optics, quantum optics
Abstract: We introduce a theoretical framework based on Fano's theory of discrete-continuum interactions to analyze the quantum dynamics of broadband parametric downconversion (PDC) in the few-pump-photon regime of nonlinear quantum nanophotonics. Applying this unified analytic approach to 1D ?(2)-nonlinear waveguides, we find a host of remarkable dynamical features due to the coupling of a discrete pump state to the signal continuum, from unit-efficiency (i.e., complete) downconversion when the coupling is dissipative, to Rabi-like oscillations with sub-exponential decay when it is dispersive. The theory provides a straightforward way to analytically compute a full characterization of the PDC dynamics, including the complete eigensystem of the continuum Hamiltonian and expressions for the signal biphoton correlation function. We also apply the theory to study a pair of linearly coupled ?(2) waveguides, where two discrete pump states simultaneously downconvert into a common-mode signal continuum
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Date Submitted: 7/7/23 12:00AM Date Published: 10/1/21 7:00AM
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Article Title: Efficient simulation of ultrafast quantum nonlinear optics with matrix product states
Authors: Ryotatsu Yanagimoto, Edwin Ng, Logan G. Wright, Tatsuhiro Onodera, Hideo Mabuchi
Keywords: quantum optics, photonics, nonlinear optics
Abstract: We introduce a theoretical framework based on Fano's theory of discrete-continuum interactions to analyze the quantum dynamics of broadband parametric downconversion (PDC) in the few-pump-photon regime of nonlinear quantum nanophotonics. Applying this unified analytic approach to 1D ?(2)-nonlinear waveguides, we find a host of remarkable dynamical features due to the coupling of a discrete pump state to the signal continuum, from unit-efficiency (i.e., complete) downconversion when the coupling is dissipative, to Rabi-like oscillations with sub-exponential decay when it is dispersive. The theory provides a straightforward way to analytically compute a full characterization of the PDC dynamics, including the complete eigensystem of the continuum Hamiltonian and expressions for the signal biphoton correlation function. We also apply the theory to study a pair of linearly coupled ?(2) waveguides, where two discrete pump states simultaneously downconvert into a common-mode signal continuum
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Date Submitted: 7/7/23 12:00AM Date Published: 1/1/22 8:00AM
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Article Title: Efficient sampling of ground and low-energy Ising spin configurations with a coherent Ising machine
Authors: Edwin Ng, Tatsuhiro Onodera, Satoshi Kako, Peter L. McMahon, Hideo Mabuchi, Yoshihisa Yamamoto
Keywords: optimization, sampling
Abstract: We introduce a theoretical framework based on Fano's theory of discrete-continuum interactions to analyze the quantum dynamics of broadband parametric downconversion (PDC) in the few-pump-photon regime of nonlinear quantum nanophotonics. Applying this unified analytic approach to 1D ?(2)-nonlinear waveguides, we find a host of remarkable dynamical features due to the coupling of a discrete pump state to the signal continuum, from unit-efficiency (i.e., complete) downconversion when the coupling is dissipative, to Rabi-like oscillations with sub-exponential decay when it is dispersive. The theory provides a straightforward way to analytically compute a full characterization of the PDC dynamics, including the complete eigensystem of the continuum Hamiltonian and expressions for the signal biphoton correlation function. We also apply the theory to study a pair of linearly coupled ?(2) waveguides, where two discrete pump states simultaneously downconvert into a common-mode signal continuum
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Article Title: Onset of non-Gaussian quantum physics in pulsed squeezing with mesoscopic fields
Authors: Ryotatsu Yanagimoto, Edwin Ng, Atsushi Yamamura, Tatsuhiro Onodera, Logan G. Wright, Marc Janko
Keywords: quantum optics, nonlinear optics

Abstract: We introduce a theoretical framework based on Fano's theory of discrete-continuum interactions to analyze the quantum dynamics of broadband parametric downconversion (PDC) in the few-pump-photon regime of nonlinear quantum nanophotonics. Applying this unified analytic approach to 1D ?(2)-nonlinear waveguides, we find a host of remarkable dynamical features due to the coupling of a discrete pump state to the signal continuum, from unit-efficiency (i.e., complete) downconversion when the coupling is dissipative, to Rabi-like oscillations with sub-exponential decay when it is dispersive. The theory provides a straightforward way to analytically compute a full characterization of the PDC dynamics, including the complete eigensystem of the continuum Hamiltonian and expressions for the signal biphoton correlation function. We also apply the theory to study a pair of linearly coupled ?(2) waveguides, where two discrete pump states simultaneously downconvert into a common-mode signal continuum

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Article Title: Temporal trapping: a route to strong coupling and deterministic optical quantum computation
Authors: Ryotatsu Yanagimoto, Edwin Ng, Marc Jankowski, Hideo Mabuchi, Ryan Hamerly
Keywords: quantum computing, quantum optics, nonlinear optics

Abstract: We introduce a theoretical framework based on Fano's theory of discrete-continuum interactions to analyze the quantum dynamics of broadband parametric downconversion (PDC) in the few-pump-photon regime of nonlinear quantum nanophotonics. Applying this unified analytic approach to 1D ?(2)-nonlinear waveguides, we find a host of remarkable dynamical features due to the coupling of a discrete pump state to the signal continuum, from unit-efficiency (i.e., complete) downconversion when the coupling is dissipative, to Rabi-like oscillations with sub-exponential decay when it is dispersive. The theory provides a straightforward way to analytically compute a full characterization of the PDC dynamics, including the complete eigensystem of the continuum Hamiltonian and expressions for the signal biphoton correlation function. We also apply the theory to study a pair of linearly coupled ?(2) waveguides, where two discrete pump states simultaneously downconvert into a common-mode signal continuum

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Authors: R. Yanagimoto, E. Ng, T. Onodera, H. Mabuchi
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Partners

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I certify that the information in the report is complete and accurate:
Signature: Hideo Mabuchi
Signature Date: 7/7/23 12:24PM

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R. Yanagimoto, E. Ng, M. Jankowski, H. Mabuchi, R. Hamerly, “Temporal trapping: a route to strong coupling and deterministic optical quantum computation,” Optica 9, 1289-1296 (2022). https://doi.org/10.1364/OPTICA.473276

R. Yanagimoto, E. Ng, A. Yamamura, T. Onodera, L. G. Wright, M. Jankowski, M. M. Fejer, P. L. McMahon, H. Mabuchi, “Onset of non-Gaussian quantum physics in pulsed squeezing with mesoscopic fields,” Optica 9, 379-390 (2022). https://doi.org/10.1364/OPTICA.447782

E. Ng, T. Onodera, S. Kako, P. L. McMahon, H. Mabuchi, Y. Yamamoto, “Efficient sampling of ground and low-energy Ising spin configurations with a coherent Ising machine,” Phys. Rev. Research 4, 013009 (2022). https://doi.org/10.1103/PhysRevResearch.4.013009

R. Yanagimoto, E. Ng, T. Onodera, H. Mabuchi, “Towards an Engineering Framework for Ultrafast Quantum Nonlinear Optics,” Proc. SPIE 11684, Ultrafast Phenomena and Nanophotonics XXV, 116841D (2021)

R. Yanagimoto, E. Ng, L. G. Wright, T. Onodera, H. Mabuchi, “Efficient Simulation of ultrafast quantum nonlinear optics with matrix product states,” Optica 8, 1306 (2021); https://doi.org/10.1364/OPTICA.423044

R. Yanagimoto, E. Ng, M. P. Jankowski, T. Onodera, M. M. Fejer, H. Mabuchi, “Broadband Parametric Downconversion as a Discrete-Continuum Fano Interaction,” arXiv:2009.01457

R. Yanagimoto, P. L. McMahon, E. Ng, T. Onodera, H. Mabuchi, “Embedding entanglement generation within a measurement-feedback coherent Ising machine,” arXiv:1906.04902

R. Yanagimoto, T. Onodera, E. Ng, L. G. Wright, P. L. McMahon, H. Mabuchi, “Engineering a Kerr-Based Deterministic Cubic Phase Gate via Gaussian Operations,” Phys. Rev. Lett. 124, 240503 (2020). https://doi.org/10.1103/PhysRevLett.124.240503

G. Tabak, R. Hamerly, H. Mabuchi, “Factorization of Linear Quantum Systems with Delayed Feedback, arXiv:1803.01539

T. Onodera, E. Ng, C. Gustin, N. Lorch, A. Yamamura, R. Hamerly, P. L. McMahon, A. Marandi, H. Mabuchi, “Nonlinear quantum behavior of ultrashort-pulse optical parametric oscillators,” Phys. Rev. A 105, 033508 (2022). https://doi.org/10.1103/PhysRevA.105.033508

N. Tezak, N. H. Amini, H. Mabuchi, “Low-dimensional manifolds for exact representation of open quantum systems,” Phys. Rev. A 96, 062113 (2017). https://doi.org/10.1103/PhysRevA.96.062113

The overall aim of this project is to develop and to demonstrate new tools for dimensional reduction of models for circuits/networks of coherently-coupled quantum dynamical systems. Such circuits/networks can be modeled straightforwardly in the limit of vanishing propagation time between components, using quantum stochastic differential equations. The overall dimension of the resulting models increases exponentially with component count, however, and prior to this project no optimized methods for incorporating time delays were known. The specific aims of this project are: 1) to apply manifold projection-based methods to develop componentwise dimensional reduction methods for quantum systems, 2) to apply machine-learning methods to develop component-wise dimensional reduction methods for quantum systems, 3) to explore strategies based on quantum measurement theory and quantum stochastic differential equations to develop dimension-reducing approximations in the way that we treat coherent coupling between components, 4) to develop and to demonstrate general-purpose methods for incorporating time delays in quantum circuit/network models, and 5) to demonstrate the utility of quantum dimensional reduction methods by simulating systems of interest for distributed quantum information processing.

Over the full performance period of this award our research has progressed from origins in device and circuit modeling for single-mode quantum optics, to modeling and design of broadband (many-mode) quantum nonlinear photonic devices. The common underlying theme has been quantum dimensional reduction and we have explored several distinct technical strategies motivated by specific details of realistic physical models in these divergent regimes. Our most recent work has established unique foundations for emerging ideas in quantum nanophotonic engineering for ultrafast, ultra-low power beyond-classical information processing, which serve as an essential basis for continuing experimental work at Stanford supported by the NSF and NTT Research.

Our earliest work focused on the exploration of manifold-projection methods for dimensional reduction of quantum models for individual input-output devices. The results formalized previous intuitive ideas and provided a geometric picture of nonlinear model reduction for quantum systems. The methods we developed provided substantial theoretical insights but the corresponding codes we developed proved to be slow relative to ad hoc approaches to approximate simulation of device models of current interest. We hope that future work may revive these methods for use with more challenging quantum models and with optimized codes. In any case, the essential insights from this work have been carried forward into new work on systematic dimensional reduction for broadband quantum pulse propagation in nonlinear waveguides, which required a rigorous approach to yield physical insight into the classical-quantum crossover regime of current experimental interest. Early work in this award also generated new methods for treating time delays in feedforward/feedback networks of single-mode quantum optical devices. This work was mathematically illuminating and produced some significant technical results on approximate modeling of linear quantum stochastic delay-differential equations, which have not otherwise been effectively treated in the existing literature.

Experimental progress in quantum nonlinear photonics that occurred parallel to our work on this award motivated a shift of research emphasis towards broadband pulse propagation. With continuing focus on quantum model reduction, we shifted our emphasis from single-mode devices and circuits to highly multimode quantum devices. This shift allowed us to treat device designs that natively incorporate tens to hundreds-of-thousands of optical modes, corresponding to state-of-the-art experimental designs in nanophotonics with ultrafast laser sources. A dominant modeling challenge becomes the optimal identification of temporal “supermodes” that capture the most important coherent nonlinear dynamics occurring on relevant timescales, and that support an approximate “reservoir” treatment of remaining degrees of freedom. Our work on these systems has provided the first systematic development of system-reservoir separations in coherent nonlinear optics in the quantum regime, which has been a long-standing intuitive goal of theoretical work in this area.

One productive technical approach has incorporated the use of matrix product state representations borrowed from quantum information theory and quantum many-body physics. Such methods are powerful and accurate for quantum pulse propagation in nonlinear waveguides because the effective coherent coupling among optical field modes is essentially one-dimensional along the direction of pulse propagation. Using these methods we have been able to derive intriguing results on qualitative changes in the dynamics of canonical nonlinear-optical processes such as parametric downconversion and second-harmonic generation in the classical-quantum crossover regime, in which increasingly strong coherent coupling among optical modes leads to significant nonlinear dynamical effects on the few-photon energy scale. Our results underscore the importance of dispersion engineering as a design degree of freedom in quantum nonlinear photonics – the importance of linear dispersion for controlling nonlinear dynamical behaviors has been intuitively appreciated by experimentalists for some time, but our work has established rigorous guidelines and analyses for extending this control into the few-photon quantum regime.

We subsequently returned to ideas stemming from our early work on manifold projection, to develop a new “gaussian interaction frame” approach for accurate simulation of emergent non-gaussian effects in the classical-quantum crossover regime. This work targets a parameter regime of primary focus in contemporary experimental work, corresponding to the stronger coherent coupling becoming newly accessible with state-of-the-art materials (principally thin-film lithium niobate) and nanofabrication methods. In this regime, familiar coherent nonlinear-optical phenomena that could traditionally be treated using simple gaussian approximation starts to deviate from classical formulae, and non-gaussian effects begin to emerge that could be harnessed for quantum information processing and related aims. The gaussian interaction frame method uses a kind of theoretical “feed-forward” in which the leading-order gaussian effects are displaced into simplified mean-field equations and residual quantum equations of motion are derived relative to these displacements. If done correctly, the residual quantum equations can be simulated with high accuracy using truncated Fock spaces that require far fewer dynamical variables than ab initio simulation. We have used these methods to make surprising predictions regarding both leading-order non-Gaussian effects and higher-order Gaussian corrections that should occur in simple squeezing experiments with strong coupling.

Our work for this award reached a final frontier of leveraging new insights regarding system-reservoir separations in quantum nonlinear photonics, to launch new ideas regarding the design of devices that minimize system-reservoir couplings as a way to minimize decoherence associated with Hilbert-space “leakage.” Our proposal for temporal trapping provides the first known practically feasible approach to circumventing a no-go theorem for quantum optical quantum information processing identified by Shapiro in 2006. Our result shows that rigorous analysis of quantum model reduction – and in particular rigorous analysis of the conditions for reduction of complex multi-mode quantum models to coherent few-mode models – can provide concrete guidelines for engineering quantum devices and architectures with minimized decoherence. Our continuing theoretical work in this area will build upon these seminal results to explore a broader range of strategies for purifying useful quantum phenomena in the classical-quantum crossover regime of nonlinear nanophotonics.