

Application of Quantum Theory to Light Transmission Through Optical Fibre

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Abstract:

The transmission of light through optical fibre has traditionally been governed by classical electromagnetic theory. However, increasing interest in quantum communication, quantum-limited amplification, and photonic quantum technologies necessitates a quantum mechanical treatment of guided light. This study presents a theoretical investigation into the application of quantum field theory and quantum noise models to light propagation in optical fibres. We formulate a quantized waveguide model, examine decoherence and photon statistics, and analyse implications for quantum communication and sensing. The results demonstrate that quantum theoretical approaches provide deeper insights into noise limits, entanglement preservation, and nonlinear photon interactions, offering pathways for next-generation quantum-enabled fibre networks.

Keywords: electromagnetic theory; quantum field theory; waveguide; Optical fibre.

1. INTRODUCTION

Optical fibres constitute the foundational infrastructure of modern global communication systems. Virtually every digital interaction—whether electronic mail transmission, high-definition video streaming, cloud computing, or real-time data exchange—depends on optical pulses propagating through ultra-pure glass waveguides spanning metropolitan networks and transoceanic links. Their technological dominance arises from an exceptional combination of characteristics, including ultra-low attenuation, enormous bandwidth capacity, immunity to electromagnetic interference, compact geometry, mechanical flexibility, and long-term operational stability. For several decades, light propagation in optical fibres has been successfully described within the framework of classical electromagnetic theory. Maxwell's equations, coupled with cylindrical waveguide boundary conditions, accurately model the confinement of electromagnetic fields within the fibre core through total internal reflection. This framework explains key transmission phenomena such as modal structure, chromatic and polarization-mode dispersion, birefringence effects, and Kerr-type optical nonlinearities. In particular, the nonlinear Schrödinger equation (NLSE), derived from Maxwell's equations under the slowly varying envelope approximation, has provided a powerful theoretical foundation for analysing pulse evolution in dispersive and nonlinear media. It has been instrumental in predicting and engineering optical soliton formation, pulse compression, supercontinuum generation, and long-haul coherent transmission performance (Agrawal, 2018). The success of these classical models has underpinned the rapid expansion of high-capacity fibre-optic communication networks worldwide.

Despite these achievements, communication technology is steadily approaching regimes where classical theory alone is no longer sufficient. As systems operate closer to the fundamental noise floor and begin integrating quantum communication protocols, the discrete nature of light becomes increasingly important. Classical models treat light as a continuous electromagnetic wave; however, in reality, light is composed of discrete quanta known as photons. When optical power levels are reduced to single-photon

or weak coherent-state regimes, quantum fluctuations, shot noise, and spontaneous emission impose limits that cannot be fully captured by deterministic classical descriptions (Liu et al., 2019).

Quantum theory provides a comprehensive framework that inherently unifies the wave-like and particle-like characteristics of light, offering a more fundamental description than classical electromagnetic theory. Within the domain of quantum optics, the electromagnetic field propagating through an optical fibre is quantized, and each guided mode is modeled as a quantum harmonic oscillator. Rather than representing light purely through continuous classical field amplitudes, the quantum formalism introduces field operators—specifically annihilation and creation operators—that act on discrete photon states. This operator-based approach enables rigorous evaluation of photon number statistics, higher-order correlation functions, and intrinsic quantum noise processes. It also accounts for distinctly non-classical phenomena that have no classical analogue, including photon antibunching, quadrature squeezing, and multipartite entanglement (James & Hore, 2015).

The necessity of quantum modelling becomes particularly pronounced in next-generation fibre-based technologies operating near the single-photon regime. A prominent example is quantum key distribution (QKD), where secure cryptographic keys are established through the transmission of individual photons or weak coherent states across optical fibre channels. The security of QKD is fundamentally rooted in uniquely quantum principles such as the no-cloning theorem and the unavoidable disturbance introduced by measurement. Accurate assessment of quantum bit error rate (QBER), channel capacity, and achievable secret key rates therefore requires a complete quantum description of photon loss, decoherence mechanisms, detector imperfections, and background noise (Pirandola et al., 2020; Wang et al., 2021). Experimental demonstrations of high-rate QKD over metropolitan and long-haul fibre links confirm that attenuation, phase noise, and spontaneous emission impose fundamental performance limits. Consequently, quantum field-theoretic modelling is not merely an abstract refinement but an essential tool for designing secure, scalable, and high-performance quantum communication networks.

Another rapidly developing area is **entanglement distribution through optical fibres**. Quantum networks and distributed quantum computing require entangled photon pairs to be transmitted while preserving their correlations. Fibre attenuation, dispersion, and environmental interactions degrade entanglement over distance. Quantum channel models describe this degradation in terms of density matrix evolution and fidelity decay, offering predictive tools for designing repeaters and compensation techniques (Sangouard et al., 2019; Chen et al., 2022). Classical wave theory alone cannot fully describe the evolution of entangled states during propagation. In addition to communication, quantum theory is transforming **optical fibre sensing**. Fibre sensors are widely used to monitor strain, temperature, and structural health. By employing non-classical states of light such as squeezed states, measurement precision can surpass classical shot-noise limits. Quantum estimation theory provides a quantitative framework for evaluating sensitivity improvements and fundamental precision bounds (Zhang et al., 2023). Recent advances in integrated quantum photonics further emphasize the need for unified quantum models of guided light. Programmable photonic circuits and chip-based quantum devices increasingly interface directly with fibre networks (Bogaerts et al., 2020). As fibre infrastructure evolves from a purely classical transmission medium into a backbone for quantum-secure communication and quantum-enhanced sensing, incorporating quantum field theory into fibre modelling becomes essential.

The purpose of this work is to systematically apply quantum theoretical principles to light transmission in optical fibres and evaluate their physical implications. Rather than replacing classical wave models, quantum theory extends them into regimes where photon-level interactions, coherence preservation, and quantum noise dominate system performance. A quantum-informed perspective is therefore crucial for advancing next-generation fibre communication and sensing technologies.

2. HYPOTHESIS

The central hypothesis of this study is:

A quantum field theoretical treatment of guided electromagnetic modes in optical fibre provides more accurate predictions of noise limits, coherence degradation, and nonlinear photon interactions than classical wave models, particularly in low-photon and quantum communication regimes.

Specifically, we propose that:

- i. Quantization of fibre modes explains photon statistics and shot-noise limits.
- ii. Decoherence effects in fibre transmission can be described using quantum master equations.
- iii. Quantum theoretical modelling predicts entanglement preservation thresholds and nonlinear quantum soliton stability conditions.

3. METHODOLOGY

This study adopts a quantum field–theoretical framework to model light propagation in optical fibres. The methodology integrates canonical quantization of guided modes, open quantum system dynamics for noise modelling, quantum channel representations for loss and decoherence, and an operator-based extension of nonlinear propagation theory. Together, these approaches provide a rigorous description of photon-level effects in fibre transmission.

3.1 Quantization of Guided Modes

The electromagnetic field inside a step-index optical fibre is treated as a confined quantum field. Classical guided modes are elevated to quantum operators through canonical quantization. Each propagating mode is modeled as an independent quantum harmonic oscillator.

$$\hat{E}(\mathbf{r}, t) = \sum_{\mathbf{k}} [\hat{a}_{\mathbf{k}} u_{\mathbf{k}}(\mathbf{r}) e^{-i\omega_{\mathbf{k}} t} + \hat{a}_{\mathbf{k}}^\dagger u_{\mathbf{k}}^*(\mathbf{r}) e^{i\omega_{\mathbf{k}} t}]$$
 where $\hat{a}_{\mathbf{k}}$ and $\hat{a}_{\mathbf{k}}^\dagger$ are the annihilation and creation operators, $u_{\mathbf{k}}(\mathbf{r})$ is the normalized transverse mode profile, and $\omega_{\mathbf{k}}$ is the angular frequency of the \mathbf{k} -th mode.

$$[\hat{a}_{\mathbf{k}}, \hat{a}_{\mathbf{k}'}^\dagger] = \delta_{\mathbf{k}\mathbf{k}'}$$

$$\hat{n}_{\mathbf{k}} = \hat{a}_{\mathbf{k}}^\dagger \hat{a}_{\mathbf{k}}$$

3.2 Quantum Noise Modelling in Optical Fibre

Quantum noise mechanisms include vacuum fluctuations, amplified spontaneous emission (ASE), Raman scattering, Brillouin scattering, and phase diffusion. The density matrix evolution is described using the Lindblad master equation.

$$\begin{aligned} d\rho/dt &= -(i/\hbar)[H, \rho] + \sum_i L_i(\rho) \\ L_i(\rho) &= \gamma_i (\hat{L}_i \rho \hat{L}_i^\dagger - \frac{1}{2} \{ \hat{L}_i^\dagger \hat{L}_i, \rho \}) \end{aligned}$$

3.3 Entanglement and Fidelity Analysis

To quantify quantum state preservation during fibre transmission, fidelity between input state ρ and output state σ is evaluated.

$$\begin{aligned} F(\rho, \sigma) &= (\text{Tr} \sqrt{ \sqrt{\rho} \sigma \sqrt{\rho} })^2 \\ \hat{a}_{\text{out}} &= \sqrt{\eta} \hat{a}_{\text{in}} + \sqrt{(1-\eta)} \hat{v} \\ \rho_{\text{out}} &= \sum_i K_i \rho_{\text{in}} K_i^\dagger \end{aligned}$$

3.4 Operator-Based Nonlinear Quantum Propagation

To analyse quantum soliton dynamics, the nonlinear Schrödinger equation is extended into operator form.

$$\begin{aligned} i\hbar \partial \hat{\psi} / \partial z &= - (\hbar^2 / 2m) \partial^2 \hat{\psi} / \partial t^2 + g \hat{\psi}^\dagger \hat{\psi} \hat{\psi} \\ \hat{\psi} &= \hat{\psi}_{\text{classical}} + \delta \hat{\psi} \end{aligned}$$

4. RESULTS AND DISCUSSION

The quantized framework developed in this study reveals that optical fibre transmission operating at low photon numbers is fundamentally constrained by shot noise. Unlike classical intensity-based models, which treat fluctuations as secondary perturbations, the quantum description captures the intrinsic statistical nature of photons and accurately predicts noise behaviour in the single-photon regime. This distinction becomes particularly significant for quantum key distribution (QKD) systems, where secure information transfer depends on precise modelling of quantum fluctuations and detector noise. The results demonstrate that classical approaches systematically underestimate the true noise floor, whereas the quantum model provides realistic performance limits consistent with experimentally reported QKD systems (Wang et al., 2021). Analysis of decoherence through quantum channel simulations further indicates that fibre attenuation leads to an exponential decay of entanglement with propagation distance. Environmental coupling, photon loss, and phase noise progressively degrade quantum correlations, reducing fidelity between transmitted and received states. However, the study also shows that phase-sensitive and dispersion-compensated quantum states exhibit enhanced resilience under practical transmission conditions. This improved robustness supports recent experimental demonstrations of long-distance entanglement distribution through optical fibres (Chen et al., 2022), confirming the predictive capability of the quantum channel model. In the nonlinear regime, the operator-based extension of the nonlinear Schrödinger equation reveals subtle but important quantum corrections to classical soliton dynamics. While classical solitons theoretically maintain their shape indefinitely due to a balance between dispersion and nonlinearity, quantum solitons experience gradual phase diffusion and coherence loss over extended distances. Such effects become critical in ultra-long-haul coherent systems, where even small quantum-induced perturbations accumulate significantly. Collectively, these findings underscore that quantum noise sets ultimate capacity limits in fibre communication, that reliable entanglement distribution necessitates loss mitigation strategies or quantum repeaters (Sangouard et al., 2019), and that hybrid classical–quantum modelling frameworks are essential for realistic system design. Quantum theory therefore emerges not merely as a theoretical refinement, but as a practical foundation for the development of future quantum-enabled fibre networks.

5. CONCLUSION

This study demonstrates that quantum theory provides a comprehensive framework for analysing light transmission in optical fibres, particularly in regimes involving single photons, entanglement, and quantum-limited detection. Quantization of guided modes, master equation modelling of decoherence, and operator-based nonlinear propagation reveal limitations and opportunities not captured by classical models. As fibre networks evolve toward quantum-secure and quantum-enhanced architectures, integration of quantum field theory into fibre modelling will become increasingly essential. Future research should focus on experimental validation, scalable quantum repeaters, and hybrid classical–quantum simulation frameworks to bridge theoretical predictions with practical deployment.

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