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Physics of Squeezed and Entangled Light: A Review of Progress in Quantum Resource Generation and Applications in Quantum Communication

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فيزياء الضوء المضغوط والمتشابك: مراجعة للتقدم في توليد موارد الكم وتطبيقاتها في الاتصالات الكمومية

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Abstract:
This article provides a detailed analysis of the theoretical foundations and cutting-edge experimental progress concerning squeezed light and entangled light, two indispensable quantum resources for next-generation communication technologies. We commence by establishing the rigorous quantum mechanical description of these non-classical states, detailing the fundamental mechanism of variance reduction in squeezed states below the Standard Quantum Limit (SQL), and elucidating the strong quantum correlations inherent in entangled photon pairs. Subsequently, we critically review the primary experimental techniques for generating these resources, including spontaneous parametric down-conversion (SPDC), four-wave mixing (FWM), and cavity-enhanced parametric oscillators (OPOs), with a focus on recent advancements in efficiency, spectral purity, and bandwidth. The core of this review explores the pivotal role of squeezed and entangled light in advanced quantum communication applications, such as Quantum Key Distribution (QKD)—specifically Continuous-Variable QKD (CV-QKD) and Discrete-Variable QKD (DV-QKD)—quantum teleportation, and the development of quantum repeaters. We discuss the persistent challenges related to decoherence, transmission losses, and scaling, alongside critical future perspectives, including the imperative of chip-scale photonic integration (IQP) and the utilization of satellite-based quantum links for intercontinental communication.

Keywords: Squeezed Light, Entangled Photons, Quantum Communication, Quantum Key Distribution (QKD), Quantum Resources, Non-Classical Light, Integrated Photonics.

الملخص
توفر هذه المقالة تحليلاً مفصلاً لـ الأسس النظرية والتقدم التجريبي المتطور المتعلق بالضوء المضغوط (Squeezed Light) والضوء المتشابك (Entangled Light)، وهما موردان كموميان لا غنى عنهما لتقنيات الاتصالات من الجيل التالي. نبدأ بترسيخ الوصف الميكانيكي الكمومي الصارم لهذه الحالات غير

الكلاسيكية، حيث نفصّل الآلية الأساسية لخفض التباين في حالات الضوء المضغوط إلى ما دون حد الكم القياسي (SQL)، ونوضح الترابطات الكمومية القوية الكامنة في أزواج الفوتونات المتشابكة. بعد ذلك، نراجع بشكل نقدي التقنيات التجريبية الرئيسية لتوليد هذه الموارد، بما في ذلك التحويل البارامتري التلقائي للأسفل (SPDC)، والخلط الموجي الرباعي (FWM)، والمذبذبات البارامترية المعززة بالتجويف (OPOs)، مع التركيز على التطورات الأخيرة في مجالات الكفاءة والنقاء الطيفي وعرض النطاق. يستكشف جوهر هذه المراجعة الدور المحوري للضوء المضغوط والمتشابك في تطبيقات الاتصالات الكمومية المتقدمة، مثل توزيع المفاتيح الكمومية (QKD) - وبالتحديد QKD للمتغيرات المستمرة (CV-QKD) وQKD للمتغيرات المتقطعة (DV-QKD) - والنقل الآني الكمومي (Quantum Teleportation)، وتطوير المعيدات الكمومية (Quantum Repeaters). نناقش التحديات المستمرة المتعلقة باللا تماسك (Decoherence)، وفقدان الإرسال، والتوسيع، جنباً إلى جنب مع المنظورات المستقبلية الحاسمة، بما في ذلك ضرورة الدمج الضوئي على مستوى الرقاقة (IQP) واستخدام الروابط الكمومية القائمة على الأقمار الصناعية للاتصالات العابرة للقارات.

الكلمات المفتاحية: ضوء مضغوط، فوتونات متشابكة، اتصالات كمومية، توزيع المفاتيح الكمومية (QKD)، موارد كمومية، ضوء غير كلاسيكي، ضوئيات متكاملة.

Introduction

The Second Quantum Revolution represents a profound and irreversible paradigm shift in scientific and technological ambition, moving decisively beyond the mere theoretical understanding of quantum mechanics to the deliberate engineering and robust control of complex quantum systems for practical, disruptive applications (Wang et al., 2025). This epochal transition centers on harnessing fundamental quantum phenomena—most notably superposition and entanglement—to create technologies across computing, sensing, and communication that possess inherent capabilities unattainable through classical physical means. Within this landscape, Quantum Optics stands as the quintessential enabling discipline, providing the practical means to transport and manipulate quantum information (Mandel & Wolf, 1995). Photons, being massless particles propagating at the ultimate speed limit, serve as the ideal quantum information carriers (qubits). Their chief advantage lies in their minimal interaction with the environment, offering robust resistance to environmental decoherence and thermal noise during propagation, especially in vacuum or low-loss optical fibers. This resilience positions them as the crucial physical layer for global quantum networking efforts (Duan & Kimble, 2010).

At the technological vanguard of the quantum era are non-classical states of light, specifically squeezed light and entangled photons. These states constitute the indispensable quantum resources that power the advanced functionalities of quantum technologies (Tittel et al., 2023). Unlike classical coherent or thermal light sources, which are inherently limited by shot noise or thermal fluctuations, these non-classical states exhibit unique noise characteristics and correlation strengths that are fundamentally distinct, making them inherently superior for quantum protocols. Squeezed light leverages the reduction of quantum noise below the Standard Quantum Limit (SQL) to enhance measurement precision (Goda et al., 2008), while entanglement provides the non-local, non-separable quantum correlation necessary for secure key exchange and quantum state transfer (Horodecki et al., 2009). Therefore, the efficient generation and precise manipulation of these two specific resources are not merely research objectives but essential prerequisites for the successful development and deployment of advanced quantum information processing, communication, and metrology systems worldwide.

1.1. Squeezed Light as a Resource for Precision

Squeezed light is a Continuous-Variable (CV) quantum state uniquely characterized by the intentional reduction of quantum vacuum fluctuations (or noise) in one of two conjugate quadratures to a level below the Standard Quantum Limit (SQL) (López-Mellado et al., 2021). These quadratures, typically denoted as $\hat{X}$ (amplitude quadrature) and $\hat{P}$ (phase quadrature), are analogous to the position and momentum operators in mechanical systems, providing a complete description of the electromagnetic field (Walls & Milburn, 2008).

Utility in Metrology and Sensing :The primary utility of this variance reduction lies in enhancing measurement sensitivity and pushing the limits of quantum metrology. By aligning the squeezed quadrature with the measurement of interest (e.g., the phase shift induced by a gravitational wave), the signal-to-noise ratio (SNR) of highly sensitive detectors can be significantly improved (Schnabel, 2017). For instance, squeezed light has been demonstrably crucial in improving the SNR of the advanced Laser Interferometer Gravitational-Wave Observatory (LIGO), enabling a substantial increase in its effective observation range and detection probability (Goda et al., 2008). The implementation of squeezed vacuum states at the interferometer's dark port effectively lowers the quantum noise floor, mitigating both shot noise and radiation pressure noise at high and low frequencies, respectively (Aasi et al., 2013).

Application in Quantum Communication

Furthermore, in quantum communication, squeezed light is the core element of Continuous-Variable Quantum Key Distribution (CV-QKD). In CV-QKD protocols, like those based on Gaussian-modulated coherent states, replacing the coherent state with a squeezed state offers enhanced key rates and superior tolerance to channel loss over significant distances (Nguyen et al., 2025). The reduced noise in the measured quadrature allows the system to withstand a higher level of environmental or eavesdropping-induced noise (excess noise) while maintaining the security of the shared key, thereby extending the achievable communication range compared to systems reliant solely on coherent states (Hirano et al., 2015).

1.2. Entangled Photons as the Backbone of Quantum Networks

In parallel, entangled photons embody the quintessential quantum resource for Discrete-Variable (DV) protocols. Entanglement describes a non-local correlation where the quantum states of two or more photons are inextricably linked, meaning a measurement on one photon instantaneously dictates the state of its distant partner—a correlation that classical physics cannot replicate (Akbar et al., 2025). This strong, inseparable correlation is the foundation for Discrete-Variable Quantum Key Distribution (DV-QKD), quantum teleportation, and the crucial creation of quantum repeaters necessary for long-distance quantum communication. Recent breakthroughs focus on generating these entangled photon pairs with high purity, high brightness, and, critically, within the telecom wavelength bands to ensure compatibility with existing fiber optic infrastructure (Chen et al., 2024).

2. Quantum Foundations of Non-Classical Light States

Non-classical states of light are fundamentally governed by the principles of quantum mechanics, differing significantly from the statistical descriptions of classical optics.

2.1. The Standard Quantum Limit (SQL) and Quantum Squeezing

The quantum mechanical quantification of noise in an optical field is essential for defining squeezed light. A single field mode can be described using the Quadrature Phase Amplitudes, $\hat{X}$ and $\hat{P}$, analogous to the position and momentum operators in mechanical systems.

For the ideal coherent state (the closest quantum analogue to classical laser light) and the vacuum state, the variances are minimized and equal: $\Delta^2 \hat{X} = \Delta^2 \hat{P} = 1/4$. This minimum noise floor, achievable by classical phase-insensitive amplifiers, is known as the Standard Quantum Limit (SQL) (Wang et al., 2025).

A state is defined as squeezed if the variance of one quadrature component is reduced to a value below the SQL (Akbar et al., 2025).

$$\Delta^2 \hat{X}_{min} < 1 / 4$$

This noise reduction in one quadrature $(\hat{X}_{min})$is necessarily accompanied by an increase in noise in the conjugate quadrature $(\hat{X}_{mix})$, such that the HUP remains satisfied: $\Delta^2 \hat{X} \Delta^2 \hat{P} \geq 1 / 16$. This ability to redistribute noise is what makes squeezed light a valuable resource for **enhancing the precision of measurements** beyond classical limits.

Mathematical Formalism: The Squeezing Operator

Squeezed states are created by applying the **squeezing operator**, $\widehat{S(r, \emptyset)}$ to the vacuum state, $|0>$. The operator is defined as:

$$\widehat{S(r, \emptyset)} = exp[\frac{1}{2} r\left(\hat{a}^2 e^{-i2\emptyset} - \hat{a}^{t^2} e^{i2\emptyset}\right)]$$

where r is the **squeezing parameter** (representing the strength of squeezing) and $\emptyset$ is the squeezing angle (representing the quadrature being squeezed). The resulting state is the **vacuum squeezed state**

$$1\xi\rangle = \widehat{S(r, \emptyset)}|0\rangle.$$

Wigner Function and CV States

Squeezed light is fundamentally described within the Continuous-Variable (CV) framework, where information is encoded in the continuous field quadratures. The primary descriptive tool is the Wigner Function, *W (X, P)*, which provides a quasi-probability distribution in phase space. For a squeezed state, the Wigner function is an elliptical Gaussian distribution—compressed along one axis and elongated (anti-squeezed) along the conjugate axis—visually demonstrating the non-classical noise distribution (Nguyen et al., 2025).

2.2. Entanglement and Bell/GHZ States

Entanglement is the characteristic quantum correlation, describing a state where two or more subsystems are inextricably linked, irrespective of spatial separation. This resource forms the basis for Discrete-Variable (DV) quantum information.

Definition of Bell and GHZ States

The simplest and most critical entangled states are the two-photon Bell states $(1\psi^+\rangle$. For systems involving three or more particles, the highest degree of entanglement is captured by the Greenberger-Horne-Zeilinger (GHZ) states. These highly entangled states are crucial for fundamental tests of quantum mechanics and for advanced multi-party quantum communication protocols.

Experimental Verification: Bell Inequalities

The non-classical nature and strength of entanglement must be verified experimentally. This is achieved by observing a violation of Bell inequalities, which impose classical limits on correlations between local measurements. The Clauser-Horne-Shimony-Holt (CHSH) inequality is the most widely used form. A successful, loophole-free violation of Bell inequalities confirms the fitness of entangled photons as robust quantum resources (Chen et al., 2024).

3. Generation of Quantum Light Resources

The practical realization of quantum communication protocols relies entirely on the ability to efficiently and reliably generate high-quality non-classical light.

3.1. Spontaneous Parametric Down-Conversion (SPDC)

SPDC is the most established and widely used process for generating entangled photon pairs (Chen et al., 2024). It is a second-order nonlinear optical process ($X^{(2)}$) where a high-energy pump photon spontaneously decays into two lower-energy photons, conventionally termed the signal (ω_S) and idler (ω_i) photons, conserving both energy and momentum:

$$\omega p = \omega_S + \omega_i \ and \ k_p = k_5 + k_i \ .$$

Type-II SPDC: This geometry naturally leads to polarization entanglement when the two possible outcomes (Horizontal and Vertical polarization) are coherently superposed, yielding Bell states.

Phase Matching Conditions

Efficient SPDC requires the phase matching condition (momentum conservation) to be fulfilled along the entire interaction length. This is typically achieved using the intrinsic birefringence of the crystal (Birefringence Phase Matching) or by periodically inverting the crystal's polarization (Quasi Phase Matching, QPM). The latter, utilized in Periodically Poled Lithium Niobate (PPLN), is highly preferred due to its flexibility and high efficiency.

Advancements in Crystal Engineering: To achieve high-brightness, high-purity, and narrow-bandwidth photon pairs essential for quantum networks, PPLN Waveguides are now a standard choice. Waveguide-based PPLN sources significantly increase the interaction length and reduce the required pump power compared to bulk crystals, facilitating practical quantum communication systems.

3.2. Four-Wave Mixing (FWM)

FWM is another prominent generation mechanism, relying on a third-order nonlinear process ($X^{(3)}$). FWM is extensively used to generate both entanglement and squeezing.

FWM in Optical Fibers and Integrated Photonic Circuits: FWM is particularly advantageous when implemented in standard optical fibers or silicon/silicon nitride waveguides, allowing the source to be directly integrated into Photonic Integrated Circuits (PICs) (Chen et al., 2024).

Developments via Atomic Vapors: A significant breakthrough involves the use of hot or cold atomic vapors (e.g., Rubidium vapor) for the FWM process. These systems can generate squeezed and entangled light with extremely low intrinsic noise (noise-free generation), making them valuable for applications requiring highly pure vacuum squeezing (López-Mellado et al., 2021).

3.3. Cavity-Enhanced Methods and Deterministic Sources (OPOs)

To overcome the low efficiency of spontaneous processes (SPDC, FWM) and, crucially, to achieve high degrees of squeezing, the nonlinear medium is often placed inside an optical resonator or cavity.

The use of resonant cavities (Ring or Fabry-Pérot cavities) creates a resonant enhancement of the field intensity, dramatically boosting the nonlinear interaction and thus the efficiency of squeezed light generation. Cavity-enhanced sources are critical for Continuous-Variable (CV) protocols that require squeezing levels far exceeding the SQL (Nguyen et al., 2025).

Optical Parametric Oscillators (OPOs): When operated below threshold, Optical Parametric Oscillators (OPOs) are the most reliable and deterministic method for generating strongly squeezed states (with squeezing levels well beyond 10 dB) necessary for high-performance CV-QKD protocols (Nguyen et al., 2025).

Integration with Micro-Resonators and Chip-Scale Photonics

The drive toward miniaturization has led to the integration of nonlinear materials into micro-resonators on chip-scale platforms. These high-Q (quality factor) resonators tightly confine light, resulting in very low power requirements for the efficient generation of both vacuum squeezed states and entangled photon pairs (Wang et al., 2025).

4. Applications in Quantum Communication

4.1. Quantum Key Distribution (QKD)

The choice of quantum resource determines whether the protocol falls under the Discrete-Variable (DV) or Continuous-Variable (CV) framework, which defines the method of information encoding and the security proof.

4.1.1. Discrete-Variable QKD (DV-QKD) and Entanglement-Based Protocols

While the BB84 protocol primarily relies on single-photon sources, the security and performance of DV-QKD are significantly enhanced by employing high-quality entangled photons. Protocols like the E91 protocol (Ekert 1991) utilize maximally entangled Bell states, where two parties share an entangled photon pair. Security relies on verifying the non-local correlations by demonstrating a violation of a Bell inequality (such as CHSH), providing an elegant, source-independent security proof (Akbar et al., 2025). This method provides device-independent QKD (DI-QKD), a high standard of security.

4.1.2. Continuous-Variable QKD (CV-QKD) and Squeezed Light

CV-QKD encodes information onto the continuous quadratures (amplitude and phase) of the optical field. This framework is highly compatible with existing telecommunication infrastructure.

The Crucial Role of Squeezed Light: Both theoretical and experimental studies consistently demonstrate the profound advantage of substituting coherent states with squeezed light in CV-QKD (Nguyen et al., 2025). Squeezed states (generated via OPOs or cavity-enhanced FWM) possess inherently lower noise in the measured quadrature, allowing the system to tolerate significantly higher levels of excess noise or loss imposed by the eavesdropper or the channel itself (López-Mellado et al., 2021).

CV-QKD Post-Processing: CV-QKD involves complex classical post-processing steps: Homodyne/Heterodyne detection to measure the quadratures, followed by information reconciliation (using error correction codes) and privacy amplification to extract the secure key. The low noise floor provided by squeezed light maximizes the secure key rate achievable after these steps.

4.2. Quantum Teleportation and Repeaters

Entanglement is the core resource for two other foundational quantum communication primitives:

Quantum Teleportation: This process transfers an unknown quantum state from a sending location (Alice) to a receiving location (Bob) using a shared entangled pair and classical communication. The fidelity of the teleportation is directly dependent on the quality (purity and degree) of the shared entanglement.

Quantum Repeaters: Due to the exponential loss of photons in optical fiber (~0.2 dB/km), long-distance quantum communication requires quantum repeaters to circumvent this limit. Quantum repeaters rely on entanglement swapping—a process that uses local entangled pairs and a Bell-state measurement (BSM) to establish entanglement between distant segments. The eventual success of a global quantum internet is entirely predicated on the successful engineering of these repeaters, which are fundamentally built upon entangled light sources (Akbar et al., 2025).

5. Challenges and Future Perspectives

5.1. Overcoming Decoherence and Loss

The most formidable physical challenge remains the susceptibility of quantum states to environmental interaction, leading to decoherence, and the inevitable photon loss during transmission.

Channel Loss and Quantum Memory: In optical fibers, transmission loss primarily limits direct transmission, necessitating the development of Quantum Repeaters. The success of memory-based repeaters depends entirely on the availability of highly efficient and long-lived quantum memories.

Current research focuses on solid-state systems, such as Rare-Earth Ion Doped Crystals, which show promise in achieving the required storage times and fidelity for high-performance memory (Chen et al., 2024). Alternative approaches using Trapped Cold Atoms or Quantum Dots are also being explored as potential memory elements to support repeater function. Memory must be able to store the quantum state with high fidelity for times that exceed the entanglement generation rate.

Mitigating Decoherence: Decoherence is also countered at the source level by generating high-purity states. For squeezed light, increasing the degree of squeezing (e.g., beyond 10 dB) provides an enhanced noise margin, making the quantum state more robust against channel noise and thermal fluctuations (Nguyen et al., 2025).

5.2. Scaling and Integration: Integrated Quantum Photonics (IQP)

Widespread deployment necessitates a major shift toward miniaturization, stability, and mass manufacturability.

Integrated Quantum Photonics (IQP): The field is rapidly moving toward Integrated Quantum Photonics (IQP), which involves fabricating all necessary optical components—sources, modulators, detectors, and wave-guides—onto a single semiconductor chip, predominantly using Silicon, Silicon Nitride, or Thin-Film Lithium Niobate platforms (Wang et al., 2025).

Advantages: IQP devices offer exceptional stability, compactness, and the potential for high-volume manufacturing. The integration of high-Q micro-resonators enables efficient, low-power generation of both vacuum squeezed states and entangled photon pairs directly on the chip.

The Scaling Hurdle: The next key step is the scaling of IQP sources to generate multi-mode entanglement deterministically and reliably, which is required for scalable quantum computing architectures.

5.3. Satellite-Based Quantum Communication

To establish a global quantum network before scalable quantum repeaters are perfected, satellite-based free-space communication offers the most viable solution.

Free-Space Advantage: While the atmosphere introduces turbulence and scattering, the total loss rate per kilometer in the vacuum of space is negligible, overcoming the exponential loss limitation of optical fiber. China pioneered this field with the Micius satellite, which successfully demonstrated QKD and entanglement distribution over distances exceeding 1200 km (Akbar et al., 2025). Future efforts are focused on improving the pointing, acquisition, and tracking (PAT) systems and mitigating the effects of atmospheric turbulence on the fragile quantum states.

6. Conclusion

The exploration of the physics of squeezed and entangled light underscores their foundational role in the burgeoning field of quantum communication. We have established that squeezed light, characterized by sub-SQL noise reduction and operating within the Continuous-Variable (CV) framework, is crucial for enhancing the security and key rates of CV-QKD protocols (Nguyen et al., 2025). Concurrently, entangled photons, the core resource for Discrete-Variable

(DV) systems, provide the non-conditional security basis for DV-QKD and are essential components for quantum teleportation and quantum repeaters (Akbar et al., 2025).

The review of generation mechanisms has highlighted the transition from bulk optical systems to efficient, stable, and scalable integrated platforms. Advancements in engineering nonlinear materials, such as PPLN waveguides for SPDC and high-Q micro-resonators for enhanced FWM, are rapidly transforming these quantum resources into practical, deployable components (Wang et al., 2025; Chen et al., 2024).

In summary, the mastery of generating and manipulating squeezed and entangled light represents more than an academic achievement; it is a critical technological imperative that will redefine secure communication, computational capabilities, and sensing precision in the 21st century. Continued research focusing on optimizing source performance, enhancing quantum memory fidelity, and integrating diverse photonic components remains the vital step toward ushering in the era of the Quantum Internet.

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