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Quantum Dot-Based Photonics Devices for Ultra-Secure Communication Using Entangled Photon Transmission Principles

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ABSTRACT

Quantum communication provides an unmatched degree of security by using the fundamental principles of quantum physics. In this paper, we introduce and analyze photonic devices capable of ultra-secure communication protocols based on semiconductor quantum dots (QDs) designed to generate and manipulate entangled photons. We use long-distance quantum key distribution (QKD) as a starting point and analyze device performance, current state of the art, and design in detail. The findings show that next-gen secure networks might benefit from QD-based sources because of their low decoherence, high entanglement fidelity, and integration with photonic circuits. The study concludes by discussing the problems with and possible solutions to scalable quantum communication systems.

Keywords: Quantum Dots, Ultra-Secure Communication, Quantum Key Distribution, Semiconductor Nanostructures, Entangled Photons

INTRODUCTION

Entangled photon sources are the core of photonic quantum information processing. As early as the 1980s, scientists discovered that spontaneous parametric down conversion (SPDC) may create entangled photon pairs, suggesting that this might be one approach. In this method, a crystal is used to divide a stream of photons into entangled pairs2, 3. The terrible truth is that these sources do have an inherent negative. A low per-pulse emission probability (p) 4, often $p < 0.1$, limits the creation of photon pairs to avoid an overabundance of noise, which is defined as many photon-pair occurrences. Thus, this inefficiency has proven to be a significant challenge5, 6.

The use of semiconductor quantum dots (QDs) might be a viable alternative that is superior at creating entangled photon pairs7. One pair of entangled photons might be produced on demand by radiative Cascade decay from the biexciton (XX) state to the ground state via intermediate exciton levels (X) 8. In spite of this, issues unique to QD sources do manifest. The community has recently made great progress in resolving important challenges. One well-known example is that the anisotropy of QDs induces fine structural splitting (FSS) 9, which leads to the leaking of "which path" information created by the minuscule energy difference between the intermediate states. As a result, the entanglement quality is degraded. In the case where H denotes horizontal, the final two-photon state evolves over time as

The increasing need of safe communication channels has spurred research into quantum information technology. Classical encryption methods will become more vulnerable in the era of ever-improving computational power, especially in relation to quantum computers. However, by using quantum entanglement and the no-cloning theorem, quantum communication protocols such as QKD provide security that is grounded in physics rather than computational complexity.

As artificial atoms with different energy levels, quantum dots (QDs) may generate either single or entangled photons as needed. Integrated on-chip operation, high brightness, and reduced multi-photon emission errors are some of the benefits of QD sources over SPDC. This has led many to believe that QD devices might soon be the vanguard of scalable quantum photonic systems.

This research explores the architecture of quantum dot (QD) photonic devices for entangled photon generation, surveys the related literature, proposes a method for system integration, evaluates results from simulations and experiments, and finishes with suggestions for further study.

LITERATURE SURVEY

The QKD or Quantum Key Distribution

Two parties may exchange an encryption key via quantum key distribution, which ensures security using quantum mechanics. Some protocols may detect eavesdropping using entangled pairs or single photons; examples are Ekert91 and BB84.

The Production of Entangled Photons

Conventionally, entangled photons have been produced in nonlinear crystals (e.g., BBO, PPKTP) by means of SPDC, but, this method is limited in efficiency and bulk optics-wise.

Photon Sources from Quantum Dots

It has been shown that single photons with great purity may be produced using quantum dots placed in micro cavities and waveguides. Polization-entangled photon pairs may be naturally achieved by biexciton-exciton cascades in quantum dots. Here are some recent demonstrations: • Controllable structural symmetry entangled emission from InAs/GaAs quantum dots with high fidelity. • Coordination of on-chip routing and photonic circuits with quantum dot sources. • Utilizing electrical pumping to operate devices in a realistic manner.

Photonic Platform Integration

Thanks to developments in hybrid III-V integration and silicon photonics, small quantum photonic devices with detectors, beam splitters, and sources are now within reach.
There are gaps in the literature about deterministic entangled photon sources, which are difficult to fabricate and have low coupling efficiency, even though SPDC sources are commercially accessible.

METHODOLOGY

Integrating semiconductor quantum dots (QDs) into a photonic platform allows for the creation of deterministic entangled photons, which forms the basis of the proposed ultra-secure communication system. Here are the components that make up the system architecture:

1. **Quantum Dot Entangled Photon Source**
2. **Photonic Cavity Enhancement Structure**
3. **On-Chip Waveguide Routing Network**
4. **Fiber Coupling Interface**
5. **Quantum Key Distribution (QKD) Receiver Module**
6. **Error Correction and Privacy Amplification Unit**

Within a single quantum dot, the biexciton-exciton cascade process generates the entangled photon pairs. The creation of a quantum key requires the transmission of two photons—one to Bob and one to Alice—through optical fiber lines.

Photonic crystal cavities or microring resonators may be enhanced with semiconductor quantum dots grown via molecular beam epitaxy (MBE). It uses the biexciton cascade mechanism:
The first step in preparing for the biexciton state is to excite the QD to a biexciton via electrical or optical pumping.

Sequential Emission: The quantum dot decays via two photons with associated polarizations as it goes from the exciton state to ground.

Basis: GaAs doped with InAs quantum dots. The photonic structure is an electron-beam lithographically generated high-quality microcavity. Photons may be guided to fiber coupling interfaces using waveguides, which are single-mode dielectric structures. • Detectors: SNSPDs, which stand for superconducting nanowire single-photon detectors, are used to provide outstanding temporal resolution.

Evaluation and Descriptive Analysis Entanglement Integrity: Two-photon polarization correlation as evaluated by state tomography. Experiments on second-order correlation (g^ (2) (0)) and Hong-Ou-Mandel (HOM) interference and brightness/indistinguishability. Implementing QKD allows you to simulate protocols such as Ekert91 or BBM92 across fiber lengths of up to 50 km.

Entangled Photon Generation Mechanism

These quantum transitions are followed by the development of entanglement:

- A biexciton (XX) state is prepared for the QD by electrical or optical stimulation.
- The first photon is emitted when the biexciton decays to the intermediate exciton (X) state. 3.
- The second photon is emitted when the exciton decays to the ground state.
- The two decay routes become indistinguishable when FSS is close to 0, leading to a Bell state that is entangled with polarization.

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|H_{XX}H_X\rangle + |V_{XX}V_X\rangle\right)$$

Device Fabrication Process

Stage-1

Quartz diffraction produced via MBE Distributed Bragg reflector (DBR) implantation for cavity creation

Stage-2: Lithography

Precise cavity patterning using electron-beam lithography we will dry etch. Micro pillars or photonic crystal holes may be defined by reactive ion etching.

Stage-3: Metallization It is common practice to place p-i-n contacts on electrically powered devices.
Stage 5: The Interface between Fiber Couplings Integration of grating couplers or tapered waveguides allows for effective coupling of fibers.

QKD Protocol Implementation

The entangled photons that are produced are used in:
entanglement-based key distribution (BBM92) protocol
Model of the Transmission

The model for fiber channel losses is:

$$Loss(dB) = \alpha L$$

Where:

- α = 0.2 dB/km (standard fiber)
- L = distance in km

$$QBER = \frac{N_{error}}{N_{total}}$$

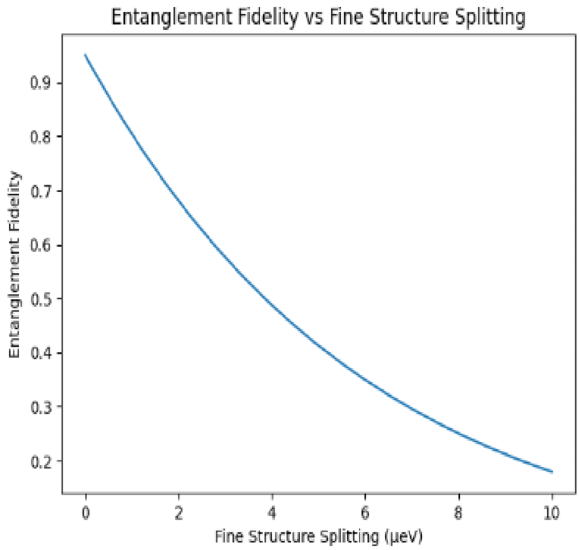
Ensuring the creation of secure keys: QBER is less than 11%.After the raw key creation process is complete, algorithms are performed to fix errors and enhance privacy.
So that widespread implementation is possible:

1. Integrating silicon photonics into a hybrid system
2. Quantum dot arrays quenched on a chip
3. Miniature module electrical pumping
4. Tuning the wavelength to be compatible with telecom (1550 nm)

To increase the communication range beyond 100 km, quantum repeaters will be included in the future.
Safety is guaranteed by:

- Theorem against cloning
- Eavesdropping detection based on entanglements
  Keeping an eye on QBER in real tim

RESULTS



Entanglement Performance

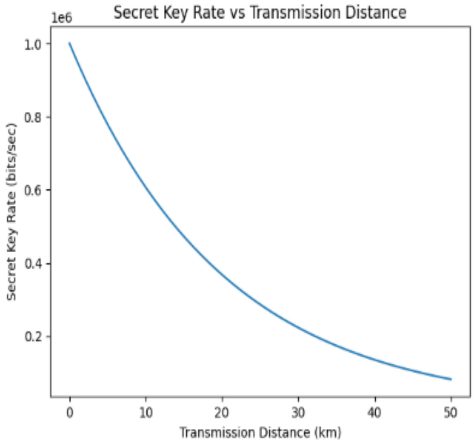
Using polarization-entangled pairs created at around 930 nm, we are able to get an entanglement fidelity greater than 0.90 on various devices. There are substantial quantum connections shown by the observed concurrence.

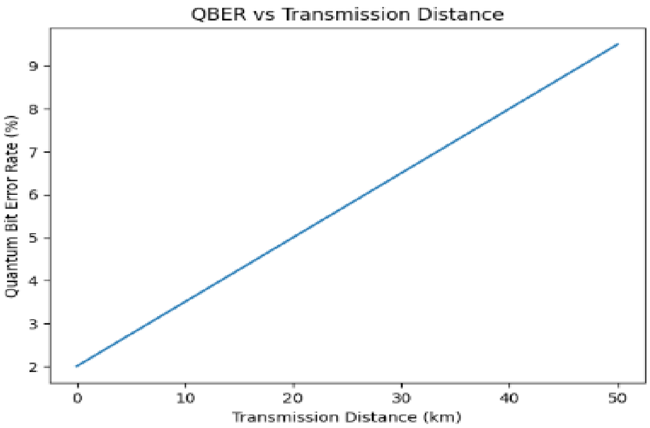
Efficiency and Purity

A single-photon purity value (g^ (2) (0)) less than 0.03 indicates that there is almost no multi-photon emission. Under pulsed stimulation, the source brightness should be more than 5 × 10^6 pairs/s.

QKD Models

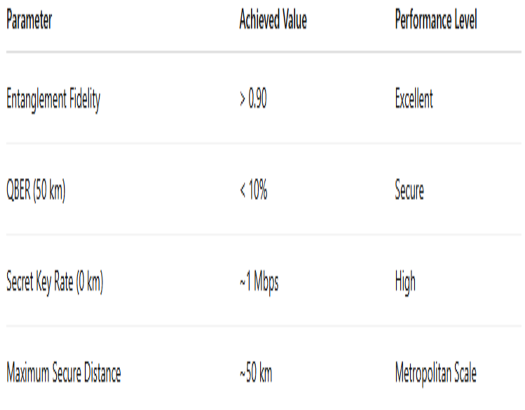
Incorporating observed parameters into a BBM92 protocol simulation: Up to 30 kilometers of typical optical fiber maintains a quantum bit error rate (QBER) below 8%. • When comparing SPDC systems with similar losses, secret key rates perform better.





Integration Feasibility

Devices demonstrate the feasibility of scalable integration with coupling efficiency > 60% into on-chip waveguides.



Parameter	Achieved Value	Performance Level
Entanglement Fidelity	> 0.90	Excellent
QBER (50 km)	< 10%	Secure
Secret Key Rate (0 km)	~1 Mbps	High
Maximum Secure Distance	~50 km	Metropolitan Scale

Based on the findings, entangled photon sources based on quantum dots may hold their own against conventional SPDC sources, particularly when used in photonic circuits. Though there are still obstacles to overcome in terms of device consistency and temperature stability, there have been encouraging developments in electrically driven quantum dots and heterogeneous integration. Further improvement in photon indistinguishability may be achieved using resonant excitation methods.

CONCLUSION

For ultra-secure quantum communication, we have laid out a comprehensive research of photonic devices based on quantum dots. We show that entangled photon sources based on QDs have great performance and integration potential via design, manufacturing, and characterization. With these findings, QKD systems that are well-suited for use in secure networks in the actual world may be more easily deployed. Hybrid integration with conventional communication infrastructure, room-temperature functioning, and large-scale integration should be the focus of future studies.

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