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Review Paper on Quantum Technology for Use with Optical Fiber

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Abstract

As in our day to day life communication has become very vital. Its importance has increased so much, that it has become vital for our survival. Moreover, information is dependent on physical system upon which it is processed and by which is carried. If we talk about optical communication, it can be thought as form of colored smoke signals. Today's we are covering our planet in a network of optical fibers. In this paper, our research is based on quantum technology where each particle is described by a quantum wave function characterizing the state of the system. The ability to generate, manipulate, transmit and detect a single or very few photon(s) may open new routes that can trigger a completely new generation of communication systems. Scientists at Dutch University have conducted an experiment that proves one of the most radical claims of quantum theory called "entanglement", which Einstein famously rejected. This is a property in which objects separated by great distance can interact and instantaneously affect each other's behavior. The experiment also proves subatomic particles do not take form until they are observed. It shows that quantum technologies can address two of the more challenging problems communication engineers face nowadays: capacity and security. Indeed, by radically decreasing the number of photons used to encode each bit of information, we can more efficiently explore the full capacity to carry information of optical fibers.

Keywords: *Optical fibers, quantum, physical system, communication, information*

INTRODUCTION

Quantum theory was developed in the first decades of the 20th century in an endeavor to understand the fundamental properties of matter and its interaction with electromagnetic radiation. Despite quantum theory's ability to predict the results of some of the more intriguing experiments of the time, some of the peculiarities of the theory (e.g., Heisenberg's uncertainty principle or the existence of entangled states) caused serious skepticism in the scientific community. Therefore, it came as no surprise that the first efforts and developments were carried out envisioning validation of the theoretical pre-dictions rather than looking for practical applications. These efforts gave the theory very solid foundations, and quantum theory is now widely accepted as a complete and accurate physical theory. Quantum key distribution (QKD) systems are the first commercial communication systems to explore the laws of quantum mechanics to provide new functionalities [1]. The underlying principle of QKD is that nature prohibits the gain of information on the state of a quantum system without disturbing it, which can be used to provide unconditionally secure distribution of secret keys. This paper discusses and clarifies how actual quantum technologies can be used to improve fiber optic communication systems. First, we review the classical limits on carrying information of fiber optic communications systems, and discuss how encoding information in single or a few photons can increase this capacity [2]. Then we describe new functionalities that can be added to communication systems by exploring the quantum nature of the photons. An application of the channel capacity concept to an additive white Gaussian noise (AWGN) channel with *B* Hz bandwidth and signal-to-noise ratio *S/N* is the Shannon–Hartley theorem:

$$C = B\log_2\left(1+\frac{S}{N}\right)$$

In this expression C is channel capacity, B is bandwidth, S and N are signal and noise power respectively.

Quantum Entanglement

Quantum ensnarement is a physical wonder that happens when matches or gatherings of particles are produced or cooperate in ways such that the quantum condition of every molecule cannot be portrayed autonomously-rather, a quantum state may be given for the framework. In a simple example consider a molecule with quantum turn 0 that decays into two new particles, Particle A and Particle B. Molecule A and Particle B head off in opposite direction. Notwithstanding, the first molecule had a quantum twist of 0. Each of the new particles has a quantum twist of 1/2, but since they need to indicate 0, one is +1/2 and one is - 1/2.

This relationship implies that the two particles are entangled. When you measure the twist of Particle A, that estimation affects the conceivable results you could get when measuring the twist of Particle B. What's more, this is not only a fascinating hypothetical expectation, however, has been confirmed tentatively through tests of Bell's Theorem.

Quantum Sources

True single photons sources (typically known as on-demand sources or photon guns) are still quite complex to realize since most of them demand cryogenic temperatures or only operate in a vacuum. Typically, these single photon sources use an external control system, such as a laser, to put a quantum system in an excited state, which is going to emit a single photon during the relaxation process. Examples of quantum systems used in single photon sources are single atoms or molecules, single ions, color centers, quantum dots and quantum wells [3–5]. Although, this kind of source allows us to obtain true single photons, they also demand the manipulation of very complex systems, usually involving complex free-space optical alignment systems. Thus, these sources are difficult to implement and not easily integrated with other components of the communication system.

A different approach to obtain single photons is based on the generation of time correlated photon pairs in a nonlinear material. In this case, one photon of the pair signals (heralds) the presence of the other photon. These sources are known as heralded single photon sources, and are based on a pump laser and a nonlinear medium. Due to a nonlinear process, typically spontaneous fourwave mixing in optical fibers, two photons from the pump laser are annihilated and two photons are created in symmetrical frequencies around the pump laser such that the net energy and momentum are conserved. The nonlinear medium can be an optical fiber and in this case the photon pair is already generated inside the fiber, which greatly facilitates the integration of the source with the rest of the communication system. Note that these photons are easily distinguishable due to their distinct frequencies [6]. Due to the probabilistic nature of the nonlinear process, these sources are not usually classified as on-demand sources. However, they are much simpler to implement than true single photon sources.

Although, some applications in the field of quantum information demand single photon sources, there are other applications that require only weak coherent light fields. In that case, a highly attenuated laser can be used as a source of a few photons. That source follows Poisson statistics, which means that if the laser light is highly attenuated in order to obtain one or less photon per symbol, there is still a non-negligible probability of generating symbols with two or more photons. Nevertheless, that probabilistic source has the advantage of being fully integratable with today's communication technologies and can operate at very high speeds. A particular implementation of QKD, known as continuous-variable QKD (CVQKD), can be obtained with standard telecommunications components (i.e., a standard semiconductor laser diode and a PIN photodiode). This scheme is based on randomly encoding information in the phase and amplitude of a highly attenuated optical field and a homodyne detection scheme. The main idea behind CVQKD is to operate in such a low SNR regime that any malicious attempt to eaves-drop the information gets noticed due to the inevitable degradation of the SNR induced by a quantum measurement in two non-commuting variables.

Quantum Receivers

Extracting information from single or very few photons is still quite challenging. The difficulty arises from the fact that the photon energy is on the order of 10^{-19} J and the detector, after receiving a photon, typically has to convert that energy (or that click) in a macroscopic current. Single photon detectors are typically divided in two main categories, depending on whether or not they are capable of discriminating the number of photons that arrive at the detector in a certain time window.

Nowadays, there are commercially available non-resolving single photon detectors using different technologies, such as photomultiplier tubes, quantum dots with field effect transistors, super-conduction nanowires, up conversion processes and avalanche photodiodes. The most common single photon detector for QKD applications at telecom wavelengths is the avalanche photodiode working in the Geiger mode. The outcome of this detector is a macroscopic pulse of current if one or more photons reach the detector. This kind of detector works at temperatures of 210˚K to 250˚K, with a detection efficiency of around 75 percent in the visible spectral region and 10 percent in the infrared. One of the major advantages of the avalanche photodiode detector is that it can operate with a thermoelectric cooler. This makes it possible to integrate the detector in a compact, quiet, and user-friendly device. Although, non-resolving single photon detectors can be used in some applications;

others demand photon number resolving (PNR) detectors. The most common PNR detectors are based on super-conducting tunnel junctions, quantum dots with field effect transistors, parallel super-conducting nanowires, super-conducting transition edge sensors, visible light photon counters, space- or time-multiplexed avalanche photo-diodes, or avalanche photodiodes with self-differencing circuits. The self-differencing circuit allows precise measurement of the avalanche current and from that an estimation of the number of photons that have impinged on the detector can be obtained. Since photo-detection based on avalanche photodiodes is a very mature technology, this approach to PNR detectors seems to be quite promising for practical implementations.

INTRODUCTION TO NEW FUNCTIONALITIES

Using very few photons per symbol means that the photon's quantum nature gains more relevance in the design of the communication system. As quantum laws are substantially different from classical laws, they can be explored to give new functionalities to systems. In this section, we analyze this aspect, reviewing some advances in the field of quantum random number generation and key distribution, quantum repeaters and memories and quantum internet and computing.

Quantum Key Distribution

Quantum key circulation (QKD) utilizes singular photons for the trading of cryptographic key information between two users, where every photon represents to a solitary piece of information. The estimation of the bit, a 1 or a 0, is dictated by conditions of the photon, for example, polarization or twist. At the sender's end, a laser creates a progression of single photons, each in one of two polarizations: even or vertical. The polarization of the photon is measured at the recipient's end. In the event that a busybody blocks the photon to decide its polarization, the photon is destroyed all the while, and the meddler would need to create another, copy photon to pass on to the recipient.

In September 2015 the Institute for Nano Quantum Information Electronics (Director: Professor Yasuhiko Arakawa), the University of Tokyo, as a team with Fujitsu Laboratories Ltd. also, NEC Corporation, declared that they have accomplished quantum key dispersion (*1) at a world-record separation of 120 km utilizing a framework with a solitary photon emitter. These results were generated using an optical fiber quantum key distribution (QKD) system that was newly developed by the three parties. The new system is comprised of two key components. One is a high-purity quantum dot (*3) single-photon emitter operating in the 1.5 μm band, which reduces the occurrence of simultaneous multi-photon emissions, one of the major limiting factors for long-distance QKD, to one in a million. The other is an optical-fiber-based QKD system optimized for use with single-photon emitters by employing superconducting single-photon detectors (*4) with ultra-low-noise characteristics. This single-photon QKD system, which simplifies system operations and management, has now achieved a transmission distance of 120 km. It is expected that this system will bring significant momentum to achieving secure communications that are impossible to eavesdrop on and that cover major metropolitan areas [7].

Quantum Repeaters and Memories

Quantum communications consists in the transfer of quantum states from one location to a distant one. In order to explore all the resources provided by quantum laws, such as superposition and entanglement, the transferred state must remain unknown during transmission. This forbids the creation of a copy of the state during transmission, which precludes its regeneration or amplification. Although optical fiber losses are quite low, around 0.2 dB/km at a wavelength of 1550 nm, they still represent an effective bottle-neck for long distance quantum communications. For instance, if one assumes an ideal single-pho-ton source generating 10^{10} photons/s, the photon rate after 500 km of fiber propagation will drop to around 1 photon/s due to fiber losses. This simple calculation shows that without quantum repeaters, it is not possible to extend quantum communications for distances longer than a few hundred kilometers. A quantum repeater is a device that is able to extend the reach of a quantum communication system, preserving the transmitted quantum state. This is possible through a technique known as entanglement swapping. Consider, for instance, that one has two pairs of entangled photons (A entangled with B, and C entangled with D) and that each photon is launched into four different optical fibers. Because A is entangled with B, both photons are perfectly correlated, that is, a measurement in one of the photons reveals the state of both. The same happens between C and D. Now, photons B and C are received at a quantum measurement device that asks these photons if they are identical. Note that the device does not measure (reveal) the state of B or the state of C; it just measures (reveals) their relative state. If the measurement succeeds (i.e., if the two photons carry the same quantum state), the quantum repeater establishes an entanglement between photons A and D without any previous interaction between these two pho-tons, and without revealing their states.

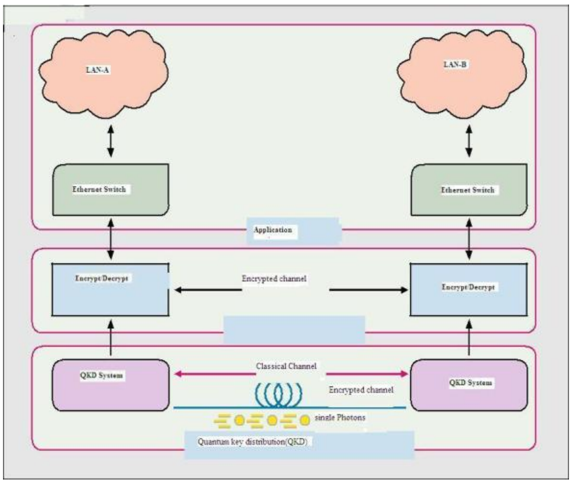

Fig. 1:

An example of a 2- layered encrypted channel link in which QKD is used to continuously generate new encryption keys. There are already QKD systems in the market that allow a change of encryption keys every minute.

This entanglement swapping allows the distance over which one can ensure the entanglement to be doubled. It allows the reach of the quantum communication system to be doubled. Note that after entanglement swapping, photons A and D carry the same quantum state. If the measurement fails (i.e., photons, B and C do not carry the same quantum state), another measurement must be performed. However, if that were to happen, new pairs of entangled photons must be readily available, which implies the availability of a device able to store quantum states (i.e., a quantum memory). Quantum memories are related to the capability to transfer quantum information in a reversible way between light and matter. Moreover, one must be able to store and recall (after a certain storage time) the quantum states on demand. To achieve long-distance quantum communications, several quantum repeaters can be interconnected. However, this requires quantum memories with large storage times to perform entanglement swapping between long chains of quantum regenerators.

Over the past few years there have been a large number of experiments demonstrating the feasibility of quantum repeaters; nevertheless, the technology is still quite far from being mature. Recently, some results have been reported in which it is demonstrated that it is possible to engineer room-temperature easy-to-operate quantum memories.

CONCLUSION

In this article, we have identified two major problems in today's fiber optic communication systems: capacity and security. A possible solution for both problems can be found in the use of a very low number of photons per symbol. In that regime, the communication system is governed by quantum laws. The peculiarities of quantum laws can be used to add new function-alities. There are already commercially available products that explore quantum laws to add new functionalities, such as QKD systems and quantum random number generators. Nevertheless, most of the more disruptive technologies still remain only in the laboratory domain, such as quantum repeaters, quantum memories, quantum routers, and quantum computers. If these systems can be materialized in some practical devices, a fully functional quantum Internet can start to emerge. It is clear that there are many exciting prospects for further development of quantum-based technologies and certainly, these developments are going to shape future communication networks.

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