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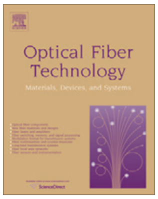

Invited Paper

Wavelength-multiplexed entanglement distribution

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ABSTRACT

The realization of an entanglement distribution optical fiber network connecting multiple parties would permit implementation of many information security applications such as entanglement-based quantum key distribution and quantum secret sharing. However, due to material absorption and scattering in optical fiber, photons that are the carriers of quantum entanglement experience loss during propagation and the overall photon arrival rate can be very low in such a network. One way to increase photon arrival rate is to make full use of the available transmission bandwidth of optical fiber and this is achievable via wavelength-multiplexing. We review our recent work on wavelength-multiplexed entanglement distribution and discuss system design considerations from a telecommunication engineering perspective.

1. Introduction

An entanglement distribution quantum network connecting multiple parties would permit a wide variety of information security applications that require users to share and consume quantum entanglement as a resource [1]. Examples of such applications are entanglement-based quantum key distribution [2–4], quantum secret sharing [5–7], and distributed quantum computing [8]. In [9], we studied the concept of a local-area entanglement distribution optical fiber network, in which a centrally located service provider produces entangled photon-pairs via spontaneous parametric down-conversion (SPDC) and distributes these photon-pairs over fiber-optic transmission lines to application users whenever there is a demand. This network architecture is advantageous because the service provider can cater to the needs of a large number of application users within the network using just a small number of entangled photon-pair sources. To realize this kind of entanglement distribution network, a stable source of high quality entangled photon-pairs is desired. Several research groups have already demonstrated good-quality, telecom-band entangled photon-pair sources based on either SPDC in a second-order nonlinear optical material [10–12] or spontaneous four-wave mixing in an optical fiber [13–16]. Entanglement distribution over 100 km or longer optical fiber has also been demonstrated in a number of recent experiments [9,17–21]. Furthermore, Treiber et al. demonstrated fully automated entanglement-based quantum key distribution system over 50 km of telecom fiber, showing the practicality of the concept [22].

As photons propagating in optical fiber experience material absorption and scattering, many are lost during transmission, and one would expect a very low photon arrival rate in a quantum network. For typical fiber loss of 0.2 dB/km, only 1% of the transmitted photons would survive after 100 km. One way to improve the entanglement distribution rate is to make full use of the available optical fiber bandwidth for photon transmission. This can be achieved by wavelength-division multiplexing (WDM), as in conventional fiber-optic transmission systems [23,24]. In a conventional WDM system, multiple optical carriers, which are lasers each having a slightly different wavelength and carrying data from different users, are multiplexed and transmitted over a single strand of optical fiber. Simultaneous amplification of all wavelength channels is made possible by using erbium-doped fiber amplifiers (EDFAs), which have a gain bandwidth covering about 35 nm in the 1.55 μm band. Wavelength-multiplexing, demultiplexing and channel add-drop functions are performed using high quality arrayed waveguide gratings (AWGs) and optical add-drop multiplexers (OADMs) that have become readily available commercially.

In this work, we show how the concept of WDM can be compatible with entanglement distribution, despite that a multi-wavelength entanglement distribution system differs from a conventional WDM system in several important aspects. Firstly, EDFAs cannot be used due to spontaneous emission noise that would corrupt the quantum channel. Secondly, unlike conventional WDM,

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entanglement distribution does not involve direct encoding of information from many different users, and this allows the use of a single broadband source of entangled photon-pairs for wavelength-multiplexed entanglement distribution between a pair of users [25,26]. This work is organized as follows. In Section 2, we explain the concept of wavelength-multiplexed entanglement distribution. In Section 3, we describe the principle and experimental demonstration of a broadband source of polarization-entangled photon-pairs based on a pulse-pumped short nonlinear optical waveguide. Section 4 describes an experiment that demonstrates the feasibility of wavelength-multiplexed entanglement distribution, while in Section 5 we briefly discuss system design issues, providing some directions for future progress. Section 6 is the conclusion to this paper.

2. Concept

In many earlier experimental demonstrations of entanglement distribution over optical fiber [9,17–21,27], entangled photon-pairs were filtered with narrowband filters before transmission. This was done to reject out-of-band noise photons and also to avoid undesirable effects caused by chromatic and polarization-mode dispersion of the transmission fiber. Consequently, only a small fraction of the total available transmission bandwidth was used for entanglement distribution. From a telecommunication engineering point of view, this is not bandwidth-efficient and it would be desirable if the transmission bandwidth can be fully utilized. One might consider wavelength-multiplexing classical WDM data channels and quantum channels so that the same optical fiber connecting two users is used for both classical WDM data transmission as well as for entanglement distribution. However, there are several difficulties that must be overcome. Firstly, noise photons originating from spontaneous Raman scattering (SRS) [28] and spontaneous parametric scattering of the classical signals could seriously pollute the quantum channel. For example, Nweke et al. have shown experimentally that the necessary wavelength separation for impairment-free multiplexing of quantum channel and WDM channel on a shared fiber is at least 170 nm [29]. This is to avoid SRS from the classical channel. Amplified spontaneous emission (ASE) noise from EDFAs must also be filtered to well below the single-photon-level in order to eliminate in-band noise photons at the quantum channel. In addition, we can also expect interchannel four-wave mixing (FWM) [24] among the classical WDM channels to create substantial crosstalks. This is especially detrimental if the quantum channel is located nearby the classical WDM channels. Furthermore, multiple classical WDM channels might impose a pattern-dependent cross-phase modulation (XPM) [24] on the quantum channels. This would modulate the relative phase of entangled photon-pairs and degrade entanglement fidelity. Special care must therefore be taken to minimize these effects.

One alternative is to wavelength-multiplex many quantum channels so that the available fiber transmission bandwidth is fully utilized for entanglement distribution. As entanglement distribution rate for a single channel is expected to be low because of accumulated fiber loss, wavelength-multiplexing is a natural and attractive way to increase the overall entanglement distribution rate. One potential obstacle to implementing the wavelength-multiplexed approach is the narrowband operation of existing entangled photon-pair sources. The operating bandwidths of fiber-based sources are usually limited by SRS [28] while sources based on quasi-phase-matched (QPM) crystals or waveguides are typically narrowband because of long device lengths and operations far from degeneracy [27,30]. From the loss spectrum of optical fiber [23], we have estimated that the usable transmission window of optical fiber spans about 200 nm from around 1.45 to 1.65 μm, assuming a fiber loss requirement of <0.3 dB/km. To fully utilize this transmission bandwidth, a service provider would need to wavelength-multiplex a large number of narrowband entangled photon-pair sources as depicted in Fig. 1a, but this is not cost-effective.

Unlike conventional WDM systems, entanglement distribution does not involve encoding of information from users, and so it is in fact possible to use just one single entangled photon-pair source with broadband output for wavelength-multiplexed entanglement distribution. Replacing the dashed box in Fig. 1a by a broadband source would simplify the system and reduce implementation cost considerably. The requirement for this broadband source is that it must produce highly-entangled photon-pairs for all wavelength channels simultaneously. We show how this can be done in Section 3.

Fig. 1b shows the concept of wavelength-multiplexed entanglement distribution. A service provider uses a single broadband source of entangled photon-pairs to distribute entanglement to application users. For wavelength-demultiplexing of transmitted photons into independent wavelength channels, AWGs can be used, as in conventional WDM systems. The wavelength-demultiplexing AWGs also act as narrowband filters which suppress undesirable effects due to chromatic and polarization-mode dispersion prior to detection. In the next section, we describe the principle and experimental demonstration of a broadband source of polarization-entangled photon-pairs.

3. Broadband source of entangled photon-pairs

We have chosen to demonstrate wavelength-multiplexed entanglement distribution in our experiments using polarization-entangled photon-pairs because of the ease of polarization manipulation over a broad bandwidth using inexpensive polarization beam-splitters and wave-plates. The disadvantage of polarization encoding is that photon polarization states are affected by random birefringence drifts in the transmission fiber. Nevertheless, it has been shown that such impairments can be mitigated by active polarization stabilization [31,32].

We first show by calculation that the spontaneous parametric down-conversion (SPDC) bandwidth of a short, type-0 quasi-phase-matched (QPM), MgO-doped periodically-poled lithium niobate (PPLN) waveguide can potentially span hundreds of nm covering the entire telecom-band. The SPDC bandwidth depends critically on the phase-matching condition, which in turn depends on the device length. The choice of a very short device length is thus crucial for broadband photon-pair production. Next, we describe our method of creating polarization entanglement by superimposing two coherently-pumped SPDC processes. Then we discuss our experimental demonstration of a broadband source of polarization-entangled photon-pairs well-suited for wavelength-multiplexed entanglement distribution over optical fiber.

3.1. Principle

In general, the refractive index of any optical material is wavelength-dependent. The refractive index of lithium niobate can be approximated by the three-oscillator Sellmeier equation. Using the Sellmeier coefficients given in [33], we can obtain both the ordinary and extraordinary indices for a 5 mol.% MgO-doped congruently grown lithium niobate as a function of wavelength. In SPDC, a pump photon at frequency ω_p is split into a pair of daughter photons, called signal and idler. The signal photon has frequency ω_s and the idler photon has frequency ω_i. Energy conservation requires the condition

$$\omega_p = \omega_s + \omega_i, \qquad (1)$$

to be satisfied. The efficiency of energy transfer from the pump mode to the signal and idler modes depends on the phase relation