Two-Pumps-Based Entanglement Generation Source Enabling Entanglement-Assisted Communication over Beyond Strong Atmospheric Turbulence Channels

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Abstract: Two S-/L-band pumps, satisfying PPLN-waveguide quasi-phase-matching-condition, are used to generate bright entangled-photons providing needed flexibility in wavelength-selection over entire C-band. By performing phase-conjugation on idler photons, we demonstrate entanglement-assisted communication at 1Gb/s over 1.5km FSO link operated in beyond strong turbulence regime.

Entanglement represents a unique quantum information feature enabling the communications above the Shannon limit, quantum sensors with sensitivity approaching the Heisenberg limit, and secure communications with security guaranteed by the quantum information theorems [1]. The quantum communication over free-space optical (FSO) channels is severely affected by absorption, diffraction, scattering, and atmospheric turbulence effects [2]. To improve the reliability of the FSO links in strong turbulence regime and beyond we recently proposed to use the entanglement-assisted (EA) communication in which the phase-conjugation, required before homodyne detection takes place, is performed on idler photons [3] rather than signal photons by employing so called phase-conjugated receiver (PCR) [4],[5]. In PCR the phase-conjugation is performed on signal photons at receive side. Given that in atmospheric turbulence channels signal photons are severely affected by diffraction, absorption, scattering, and turbulence effects only few weak photons eventually reach the destination, and it is extremely difficult to perform any phase-conjugation on just few weak signal photons. By performing the wavelength conversion by the PPLN waveguide on bright idler photons, so that the idler photons have the same wavelength as the signal photons, we can use just a classical homodyne balanced detector as an entanglement-assisted detector, thus significantly simplifying the system design and operation [3]. In this paper, in order to improve the flexibility on wavelengths' selection in signal-idler photon pairs, we propose to employ two pumps instead of single pump [3], which satisfy the quasi-phase matching condition in PPLN waveguide over the entire C-band. By properly selecting the pump wavelengths we can ensure that wavelengths corresponding to signal and idler photons are both located in the C-band thus improving the nonlinear conversion efficiency significantly. By performing the wavelength conversion on bright idler photons we demonstrate that the entanglement-assisted communication at 1 Gb/s over 1.5 km FSO link, established at the University of Arizona campus, is possible even when the transmission is affected by beyond strong atmospheric turbulence channel conditions.

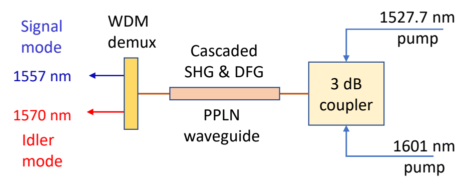

Fig. 1. The proposed S-/L-band pumps-based entanglement generation source suitable for implementation in PICs by cascaded SHG and DFG processes. The 1557 nm and 1570 nm bands are entangled. SHG: second-harmonic generation, DFG: difference frequency generation.

Traditional approaches to generate entangled states suitable for quantum communication over fiber-optics links employ the expensive high-power 780 nm pump lasers [1],[4],[5]. For high-speed EA communications, the linewidth of such pump laser should be in the order of tens of kHz. Such high-power tunable lasers could be orders of magnitude more expensive compared to the corresponding S-/C-/L-band pump lasers. In our proposed solution to generate entangled states, illustrated in Fig. 1, we propose to use mature, low-cost telecom devices operating in the C- and L-band, including tunable lasers, PPLN waveguides, and wavelength division multiplexing (WDM) demultiplexers. The type-0 PPLN waveguide is pumped by two continuous-wave 1527.7 nm and 1601 nm laser signals and entangled photons are generated by the cascaded second-harmonic generation (SHG) and difference frequency generation (DFG) concept we introduced in [6]. The SHG dominates in the first half of the PPLN waveguide, while the DFG dominates in the second half of PPLN waveguide. The pump signals' wavelengths are carefully chosen so that the signal and idler photons bands can be easily separated by a simple WDM demultiplexer. The HC Photonics has fabricated proposed PPLN waveguides. The corresponding experimental setup used to demonstrate the entanglement-assisted communication over 1.5 km FSO at 1 Gb/s in the presence of beyond strong turbulence is provided in Fig. 2. The entanglement generation source is implemented as described in Fig. 1. The signal and idler photons are separated by the WDM demultiplexer. The signal photons are modulated by the LDPC (3992, 2497)-coded BPSK sequence with the help of phase modulator. The expanded beam is transmitted towards the roof of Meinel building where the retro reflector is placed. The received beam is collected by the two periscope mirrors and compressing telescope. The portion of compressed beam is used to operate the adaptive optics and fast steering mirror (FSM). To improve the coupling efficiency, the 92% of the beam is coupled to the multi-mode fiber (MMF). The idler photons at 1570 nm undergo the wavelength-conversion and phase-conjugated photons are stored in the optical delay line (ODL). The received signal photons and phase-conjugated photons are mixed in optical hybrid before homodyne balanced detection takes place.

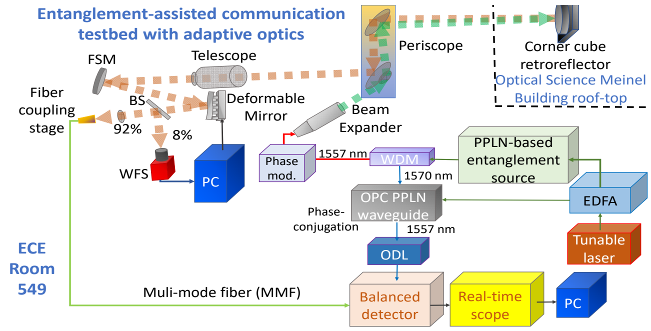

Fig. 2. The 1 Gb/s entanglement-assisted communication testbed operated in beyond strong turbulence regime.

The experimental results (collected on December 5, 2023) are summarized in Fig. 3 for transmit power of P_{Tx}=4.5 mW. In the same Figure, the histogram of received power is provided. Given that the distribution of received power is close-to-exponential, experiments have been conducted in beyond strong turbulence regime [2]. The proposed EA communication system, performing the phase-conjugation on idler photons, was fully operational in this turbulence regime. The LDPC decoder was able to correct all transmission errors. On the other hand, the conventional EA communication system performing the phase-conjugation on signal photons at receiver side, in other words the PCR, was not operational in this regime at all and the bit-error rate (BER) was 0.5. In Fig. 4 we provide the comparison against the corresponding classical counterpart, for P_{Tx}=5.4 mW, with results collected on December 8, 2023. The exponential distribution of received power indicates the saturation regime. Clearly, the proposed EA communication system significantly outperforms the classical one. In the same figure we provide the results when the adaptive optics (AO) is used. Even though the AO is designed for astronomic applications, operated in weak turbulence regime, it still provides some improvements in saturation turbulence regime.

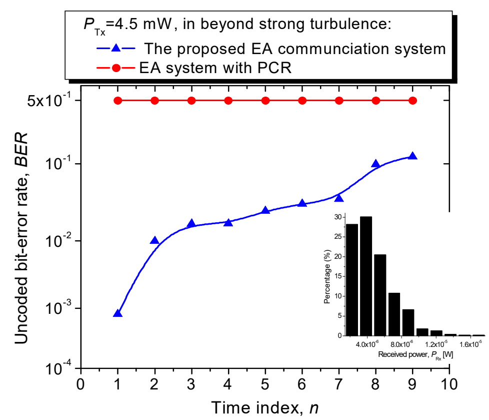

Fig. 3. The proposed EA communication system for different FSO channel realizations against the traditional EA with the PCR. (Dec. 5. 2023.)

To summarize, the proposed EA LDPC-coded BPSK communication system at 1 Gb/s, employing the entanglement generation source with two pumps and performing the phase-conjugation on idler photons, is operational in beyond strong turbulence regime. The traditional EA communication scheme with PCR [4],[5] is not operational in this turbulence regime. The proposed EA communication scheme significantly outperforms both traditional EA and classical communication schemes.

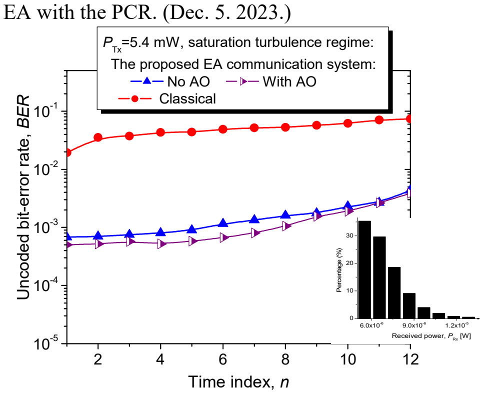

Fig. 4. The proposed EA communication system against the corresponding classical counterpart in saturation regime. (Dec. 8, 2023.)

References

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