Entanglement Distribution in Installed Fiber with Coexisting Classical Light for Quantum Network Applications

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Abstract: We show polarization entangled photons coexisting with milliwatt power classical light over 45.6 km of installed optical fiber. The entanglement source has a built-in alignment signal for quantum transmitter-receiver polarization basis alignment.

Future quantum networks will leverage the traditional fiber optical infrastructure as much as possible to gain cost efficiency in deploying such networks. This means that quantum signals will likely coexist with classical communications that carry either information related (e.g., synchronization and quantum network control signals or quantum-protocol related data) or unrelated (e.g., independent high-rate data communication) to the quantum channel. The choice of wavelength to implement classical communications for quantum network control is flexible when dark fibers are available, allowing the lowest-loss C-band to be used for quantum signals so that classical communications can be placed in other bands to minimize noise crosstalk. However, when considering integration of quantum networks with the entire fiber infrastructure, the network design must presume that high-power classical signals will occupy the C-band, making quantum signal allocation to the C-band nearly impossible due to the presence of Raman scattering, four-wave mixing, and amplified spontaneous emission from optical amplifiers. One approach to suppressing such noise is to place the quantum signals in the 1310-nm telecom O-band [1], thus ensuring that the sub-photon-level quantum signals will be far detuned (~35 THz) on the anti-Stokes side of the much stronger C-band classical light. Such wavelength allocation of the quantum signals to the O-band significantly reduces their contamination from the background noise photons, but it happens at the expense of slightly higher loss (~0.1 dB/km more than the C-band) which then lowers the reach of the quantum signals. The full implications of this noise-reach trade-off on the design of heterogenous quantum networks still needs to be worked out, but in the near term when the geographical extent of the quantum networks is limited to metro scales owing to immaturity of the available quantum hardware, it is a reasonable choice to make progress on developing quantum network protocols and control algorithms. In that spirit, here we demonstrate that metropolitan scale distances can be accessed by quantum signals in the O-band and outperform C-band quantum transmission in these coexistence scenarios.

There have been many experimental studies of quantum-classical coexistence in standard telecom fibers that employ O-band quantum transmission using attenuated laser light as proxy for quantum signals. Most such studies have been in the context of quantum key distribution (QKD) because QKD is the most advanced application of quantum communications [2]. However, quantum network functions beyond QKD, such as teleportation, quantum repeaters, etc., will require the distribution of quantum entanglement in real-world scenarios. Although more difficult to distribute than attenuated laser light, entangled photons luckily have an inherent robustness to background noise due to their spectral and temporal correlations. Narrow spectrally and temporally filtered coincidence detection of entangled photon pairs can allow for signal photons to be distinguished from uncorrelated background photons. Using such techniques, we show that polarization-entangled quantum light can copropagate with milliwatt-level classical light over 45 km of installed underground fiber that presents about 20 dB of loss to the quantum signals. Such classical light levels are consistent with modern high-rate communication channels and exceed other entangled and classical light coexistence experiment that used C-band for both the quantum and classical channels [3, 4].

In our experiments, the use of O-band/C-band quantum/classical wavelength allocation allows us to achieve much higher copropagating classical powers (about 7 dBm) while still maintaining nonclassical visibility (> 71%) in polarization entanglement two-photon interference. Figure 1(a) shows a schematic of our experiment. We send one photon of the polarization-entangled photon pair over a 45.6-km loop of underground installed fiber, which is part of the Illinois Express Quantum Network (IEQNET) [5]. The underground fiber link connects the Quantum Communications Lab at Northwestern University in Evanston to the Starlight Communications Facility located on the Northwestern Campus in Chicago (link distance of 22.8 km) where we loop the copropagating light back to the Evanston Lab for characterization with polarization analyzers and low-dark-count superconducting nanowire single photon detectors (SNSPDs) which have ~30% detection efficiency in the O-band. The equivalent measured loss rate in the underground fiber link is 0.43 dB/km at 1310 nm, which is higher than expected in modern fibers typically used in laboratory experiments, making the equivalent loss closer to a 60 km distance if newer fibers were used.

To perform basis selective measurements on quantum information encoded in polarization, the polarization analyzers (PAs) at the receiving nodes (Bob and Charlie, see Fig. 1(a)) must be aligned such that their polarization reference frames map directly to that defined at the entanglement source (Alice). For this purpose, it is desirable to have a simple procedure to quickly align these basis reference frames. To solve this issue, we incorporate at Alice a broadband classical alignment signal that can be routed through the wavelength division multiplexed (WDM) fiber connections to Bob and Charlie to align their polarization analyzers. We generate the polarization entangled quantum light via cascaded second harmonic generation-spontaneous parametric down conversion (c-SHG-SPDC) in a single periodically poled lithium-niobate waveguide (PPLN) [6]. The cascaded second order interaction acts as a quasi-four wave mixing process used in fiber-based sources of entanglement, where the pump, signal, and idler wavelengths all occupy the O-band. This analogue allows us to incorporate at the source a broadband wavelength multiplexed built-in classical basis alignment signal based on approaches used in fiber-based entanglement sources [7]. We utilize the broadband amplified spontaneous emission (ASE) from a Praseodymium-doped fiber amplifier (PDFA) used in the setup to multiplex in a polarized signal in the wavelength bands defined by the filters used at Bob and Charlie. The alignment procedure consists of sending two alignment signals, one with a vertical (V) polarization and the other with a diagonal (D) polarization state, which the receiving nodes at Bob and Charlie use to orient their waveplates while counting single photons to align their polarization basis with that at Alice. The two non-orthogonal polarization basis signals allow the receiving nodes to align their PAs relative to the source's generated entangled state. This method can be useful for WDM based polarization entanglement quantum networks such as in [8].

The PPLN waveguide is phase matched for SHG of the 1320 nm pump pulse train at 417 MHz repetition rate with 80 ps pulse-width. We place the waveguide inside a polarization Sagnac loop to generate polarization entangled photon pairs. The pump light entering the loop is split by a polarizing beam splitter (PBS_A) into two counter-propagating directions. The c-SHG-SPDC generates broad-bandwidth quantum amplitudes for photon pairs centered around 1320 nm in both directions, and upon recombination at the PBS the two-photon quantum state becomes polarization-entangled in the state $\frac{1}{\sqrt{2}}(|HH> + e^{i\phi}\,|VV>)$. We separate the signal/idler photons into bands using a standard coarse wavelength division multiplexer (CWDM). The CWDM outputs 20 nm wide bands with center wavelengths of 1310 and 1330 nm. The broadband spectrum of the c-SHG-SPDC allows the source to support distribution over the full O-band to easily scale the network to more users by carving the spectrum into more WDM output channels. We send the 1310 nm channel over the 45.6 km underground fiber link while keeping the 1330 nm channel locally. A 100 GHz DWDM filter centered at 1320 nm passes the pump wavelength (1320 nm) and rejects the broad ASE spectrum into another fiber that can either be used to transmit the V or D alignment signals. For H/V basis alignment the ASE signal is injected into one arm of the Sagnac loop in Alice's source to be reflected at PBS_A

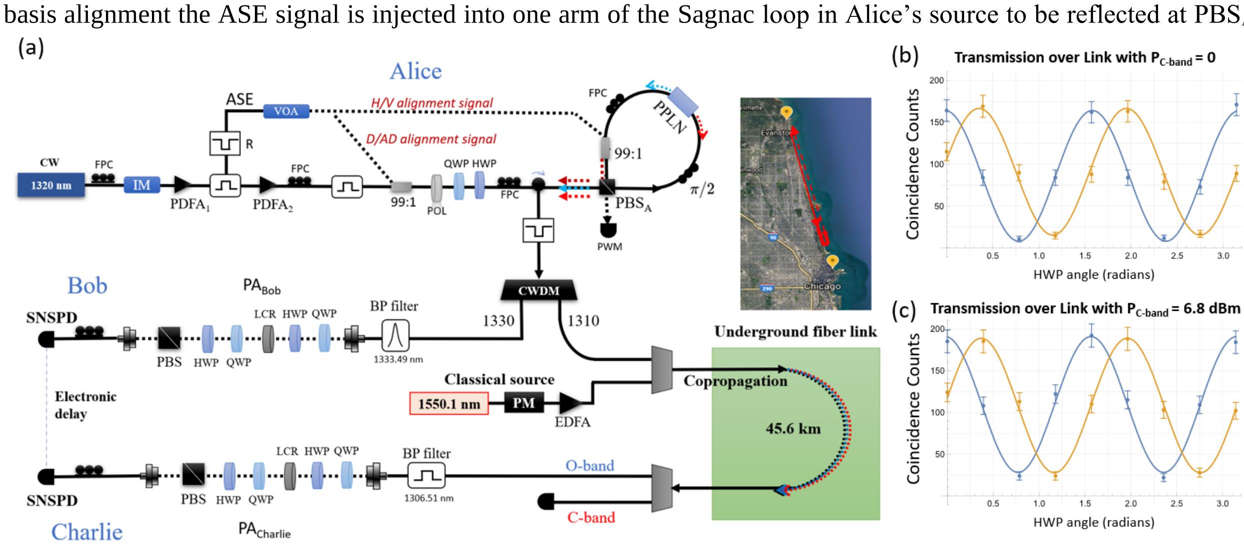

Fig. 1: (a) Experimental diagram for polarization entanglement source with built-in basis alignment signal and entanglement distribution over underground fiber link in the presence of C-band classical light. (b) and (c) TPI measurements: (b) Entangled photon sent over distribution fiber without classical light. (c) Entangled photon sent over distribution fiber with 6.8 dBm of copropagating classical light.

such that it emerges vertically polarized (defined by Alice's PBS) and propagates through both fiber channels to the PAs. At PA_{Bob} and $PA_{Charlie}$, we initially set the projective measurement waveplates to 0 degrees, with a liquid crystal retarder aligned at 0 degrees. The horizontal basis is then aligned via rotating the first QWP/HWP pair to minimize the single count rates in both Bob and Charlies single photon detectors. To align the last polarization degree of freedom we use a diagonal alignment signal which is generated by injecting ASE via a 99:1 splitter into the source pump path such that the output signal carries the same relative weighting and phase ϕ of H and V polarizations as the entangled photons. At both PAs, the projection HWPs are set at 22.5 degrees to project onto the D basis while an automated search scans the voltages applied to the LCR, which adjusts the relative phase between H and V components until the singles count rates are minimized. After the optimal voltages are found for both PAs, the relative phase has been set to ϕ = 0 degrees resulting in the arrival of the symmetric Bell state $|+> = \frac{1}{\sqrt{2}}(|HH> +|VV>)$ at Bob and Charlie.

To demonstrate coexistence, we amplify C-band laser light at 1550.1 nm with an Erbium-doped fiber amplifier (EDFA) and multiplex it into the underground fiber to copropagate with the O-band quantum signal. We phase modulate the C-band light to broaden its spectrum which emulates a data channel and inhibits stimulated Brillouin scattering. At the receiver, we demultiplex out the C-band light while further filtering the remaining signal and idler photons with 100 GHz bandpass (BP) filters centered at 1306.5 and 1333.5 nm, respectively. We detect the photons with SNSPDs, which are followed by a time-tagging correlation detection system. We apply an electronic delay between the two channels to account for the fiber delay and perform coincidence measurements using a coincidence correlation time window of ~0.5 ns, which is set such that the arriving photon pair pulse would not drift outside the window due to timing jitter from transmission over the fiber.

Polarization measurement apparatuses described above at Bob and Charlie first use the classical basis alignment signals from Alice to set their measurement basis to the same reference frame defined by Alice's source. After basis alignment is done, two-photon interference (TPI) measurements are made to analyze the performance of entanglement distribution without (Fig. 1(b)) and with (Fig. 1(c)) copropagating classical light. Figure 1(c) shows TPI fringes after the transmitted photon has propagated alongside 6.8 dBm of C-band launch power, where a visibility of 77% is observed in the HV basis and 74% in the DA basis. Both values are > 71% and thus fall in the nonclassical regime of two-photon interference. Given the ~0.5 ns temporal correlation window used in our coincidence detection, narrowing our frequency filtering even further to less than 5 GHz could presumably reduce Raman noise by another factor of ~20, which would allow for even higher copropagating powers (> 10 dBm) to be used. Further improvement to the quantum source to increase generation rates while maintaining high back-to-back visibilities should also allow us to further increase coexisting powers.

In summary, we have demonstrated that O-band/C-band quantum/classical wavelength allocation along with temporal and spectral filtering in coincidence detection are useful noise mitigation methods for coexistence scenarios in fiber-optic quantum networking. High visibility two photon interference fringes are demonstrated over 45.6 km of installed underground fiber with a copropagating ~7 dBm classical launch power. An O-band classical alignment signal is built into the entanglement source to align each node in a polarization entanglement network to the same polarization reference frame. The combination of these two methods allows for robust WDM based polarization entanglement networks to be integrated into real world installed fiber networks.

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