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Published in:
Optica

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Bjerrum, A. J. E., Brask, J. B., & Andersen, U. L. (2021). Qubit Registers for Noiseless Amplification. *Optica*, *Th3A*, Article Th3A.5.

Quantum Information and Measurement (QIM) VI © Optica Publishing Group 2021

Qubit Registers for Noiseless Amplification

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Abstract: We perform a theoretical investigation into how the entanglement of a two-mode squeezed state can be stored and purified using noiseless amplification with a collection of solid-state qubits.

Summary

It is a well known fact that loss in optical fibers limits the range over which the distribution of optical quantum information is possible. Photon loss can, however, be overcome by using quantum repeaters [1]. Where entanglement between sender and receiver is established by first distributing entangled states over shorter segments, and then applying entanglement swapping and purification steps. For example by using probabilistic noiseless amplifiers.

In this work we present a method for the noiseless amplification of a two-mode squeezed vacuum (TMSV) state. The amplification is performed by splitting the state into sub-modes, each of which undergoes probabilistic noiseless amplification by interacting with a photoactive qubit. We explore two different applications, the generation of entangled many-qubit registers, and the construction of quantum repeaters for long-distance quantum key distribution. The proposed repeater is similar in structure to repeaters based on quantum scissors [2–5]. However, in this work the amplification step is realized by a state transfer from an optical mode to a set of solid-state qubits, which may then act as a quantum memory.

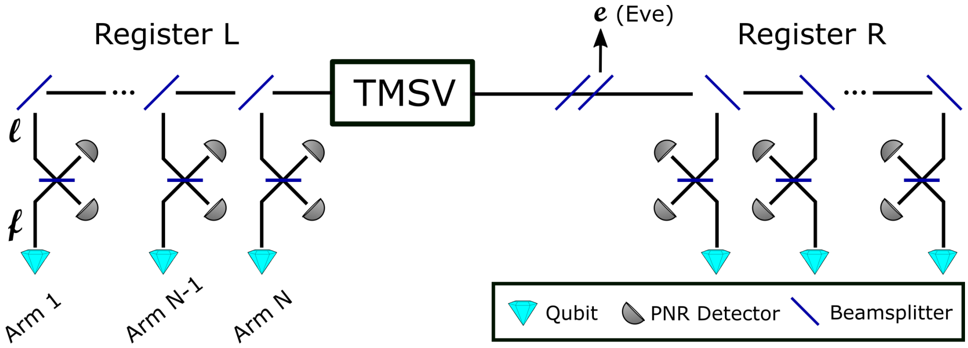

Fig. 1. *Layout of the entanglement-sharing scheme investigated in this work.*

A schematic of the entanglement-sharing setup is shown in Fig. 1. The registry qubits (diamonds) have a dark state ($|0\rangle$) and a bright state ($|1\rangle$). The bright state emits a single photon into the fiber mode f when excited by some external mechanism, such as a driving laser, whereas the dark state never emits a photon. We initialize the qubit q and fiber f in the state:

$$|q,f\rangle = \cos(\theta)\,|0\rangle_q\,|0\rangle_f + \sin(\theta)\,|1\rangle_q\,|0\rangle_f \tag{1}$$

A TMSV state shares quadrature correlations between the left and right registers. We assume that the photons of the TMSV state are indistinguishable from the photons emitted by the qubits.
At the left register the TMSV state is split evenly into the N arms of the register. Concurrently with this splitting of the TMSV, we excite the qubits, such that they will emit a photon if they are in the bright state. In each arm the two fiber modes f and l interact on a beamsplitter and two photon number resolving detectors (PNR detectors)

measure the output. Events where exactly one photon is detected are considered successful. Conditioned on all the measurements succeeding, we obtain correlations between the number of bright-state qubits in the left register, and the number of photons in the right part of the TMSV state. Repeating the procedure at the right register ultimately creates entanglement between the two registers.
In this work we consider asymmetric loss, with the loss occurring between the TMSV source and the right register.

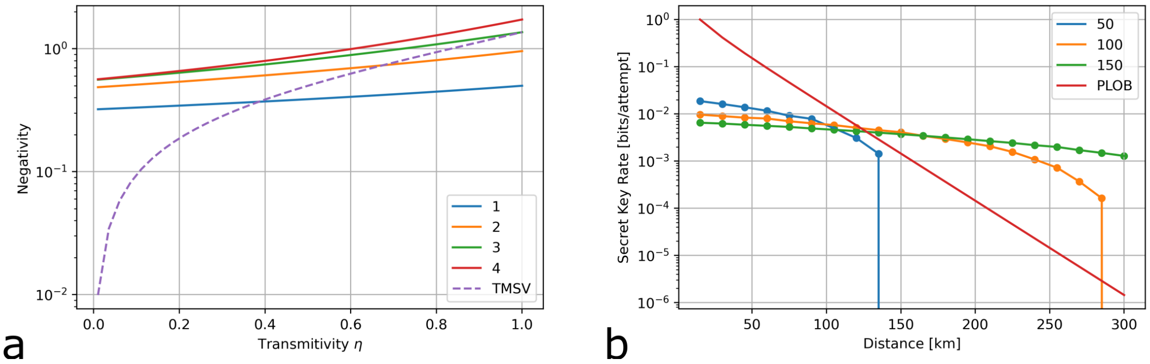

Fig. 2. ***a:*** *Negativity vs. channel transmitivity, for different numbers of qubits in the registers (legend). For reference we plot the negativity of the TMSV state.* ***b:*** *Secret key rate vs. total distance, for different allowed numbers of attempts (legend). For reference we plot the PLOB bound.*

Let θ_L and θ_R correspond to the superposition angle given in Eq. 1 for the left and right register qubits respectively. We find that setting θ_R to a low value and post selecting on successful experiments, results in a state that undergoes only minute loss in the fiber. θ_L may then in turn be tuned to maximize the entanglement between the two registers. In Fig. 2a we show how the negativity of the two registers vary with the transmitivity of the channel at the optimal values of θ_R. The negativity of the TMSV state used to generate the entangled registers is shown for reference as a dotted line. We see that the setup is capable of increasing the negativity for low fiber transmitivites η.

Two pairs of such entangled registers, (L_1,R_1) and (L_2,R_2), may then be used to build a repeater if we have access to a Bell measurement between the registers R_1 and L_2. Multiple repeaters may be joined in series to form a repeater array, potentially capable of sharing a secret key over large distances. In Fig. 2 **b** we plot how this repeater array may be used to beat the PLOB bound, defined as the maximum key rate for free fiber propagation [6]. The plot shows the secret key rate with 1 qubit per register. We employ direct reconciliation and assume that Eve may perform a collective attack [7]. Each experiment has a limited probability of success, which decreases in the gain angle θ_R. In the legend we indicate how many attempts the experimenter can tolerate before success. The more attempts the experimenter can tolerate, the smaller can θ_R be made. This in turn increases the range of the repeater since the shared state can then be made more entangled. All secret key rates are normalized by the number of attempts necessary before the experiment succeeds.

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