Interferometric Activation of Quantum Dephasing Channels

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Abstract: We report an optical phenomenon that allows perfect quantum communication through a pair of dephasing channels each with zero quantum capacity. Our results are useful for enriching the structure of the quantum communication theory.

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1. Introduction

The laws of quantum mechanics allow communication to be unconditionally secure, provided that one can send information-carrying states through channels that can reliably maintain quantum coherence. In reality, however, most of the communication channels are noisy and have low capacity for carrying quantum information due to the well-known effect of decoherence. The decoherence problem can be reduced to the dephasing problem only with the use of polarization-maintaining (PM) fibers for polarization-encoded photonic qubits. We have proposed and reported an experimental realization of a promising method for creating robust bidirectional quantum communication links through paired PM fibers [1]. Our setup represents an interferometric activation method that resembles (but not identical to) the setting of superactivation of zero-quantum-capacity channels [2] where quantum communication is made possible by combining a pair of *different* but complimentary zero-quantum-capacity channels that are individually useless for quantum communication. Here, we would focus on the unidirectional transmission of the interferometric setup.

2. Experimental setup and results

The interferometric activation setup is shown in Fig. 1a and b. Fig. 1b shows a diagram illustrating the evolution of a quantum state in the special case where the noise from the two fibers are perfectly correlated. In our experiment, we use the polarization beam splitters (PBS) to encode and decode two PM fibers with the basis set at $\{|H\rangle, |V\rangle\}$. A reference light is coupled to a feedback control system by using the piezo motion to lock the relative phase between the two arms of the interferometer, which is separated from the signal photon by optical gratings at each output port (not shown in the output 2).

Quantitatively, the amount of quantum information transmitted through a noisy channel can be quantified by *coherent information*, $\mathscr{I}_c = S[\mathscr{E}(\rho_A)] - S[(\mathscr{E} \otimes I)(|\Psi\rangle_{AB}\langle\Psi|)]$, where $\mathscr{E}$ represents the quantum operation of a noisy channel and ρ_A is the initial input state, $|\Psi\rangle_{AB}$ is the purified state of ρ_A, i.e., $\rho_A = \mathrm{Tr}_B(|\Psi\rangle_{AB}\langle\Psi|)$. I is the identity operator, and $S[\rho] = -\mathrm{Tr}(\rho \log \rho)$ is the von Neumann entropy of a density matrix ρ. Here the term channel is equally applicable to either a single fiber, or the combined fibers in the experimental setup. The quantum capacity $\mathscr{Q}_1 \equiv \max_\rho \mathscr{I}_c$ of a single-use quantum channel is defined by the maximum coherent information that can be achieved over all possible input

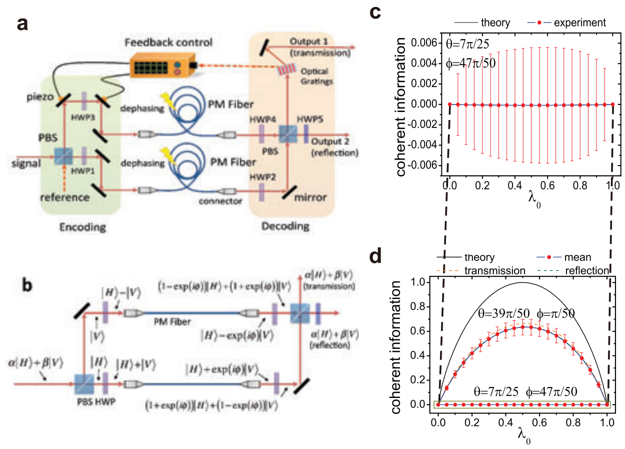

Fig. 1. **a**, The setup for the interferometric activation over a pair of 120-meter-long polarization-maintaining (PM) fibers. **b**, The quantum state evolution of a photon in the case where the noise from the two fibers are perfectly correlated. **c**, Coherent information of the single fiber. **d**, Coherent information of the paired fibers. The case for the single fiber is further shown in the dark yellow pane for comparison.

states ρ. More generally, quantum capacity is defined through the average coherent information transmitted through multiple uses [3–5]; but for dephasing channels [6], both definitions are equivalent.

For any state ρ in the two-dimension space, it can always be expressed in some orthogonal basis $\{|\psi\rangle, |\psi_\perp\rangle\}$ as $\rho = \lambda_0|\psi\rangle\langle\psi| + \lambda_1|\psi_\perp\rangle\langle\psi_\perp|$, where $|\psi\rangle = \cos\theta|0\rangle + \sin\theta e^{i\phi}|1\rangle$ and $|\psi_\perp\rangle = \sin\theta|0\rangle - \cos\theta e^{i\phi}|1\rangle$, and $\lambda_0 + \lambda_1 = 1$. The corresponding purified state can be written as $|\Psi\rangle = \sqrt{\lambda_0}|\psi\rangle|0\rangle + \sqrt{\lambda_1}|\psi_\perp\rangle|1\rangle$. Therefore, the coherent information $\mathscr{I}_c$ for any quantum channel transmitting qubits depends only on three independent parameters, namely λ_0, θ and ϕ, which are employed for describing the experimental data.

We found that the maximal value of coherent information of the single fiber is near to zero ($8.55 \times 10^{-16} \pm 3.50 \times 10^{-16}$), which is shown in Fig. 1c. The maximum coherent information for the interferometric setup is about 0.636 ± 0.005, which is shown in Fig. 1d. Given the high value of the quantum capacity achieved (from 10^{-16} to 0.636), we conclude that the protocol of the proposed method does allow optical fibers with zero-quantum-capacity to transmit quantum information.

3. Conclusion

In summary, our method allows us to *activate* a pair of PM fibers, each of which has zero quantum capacity, for transferring quantum information. Our approach is robust, scalable and easier to implement (no need to entangle photons). These results not only suggest a practical means for protecting quantum information sent through optical quantum networks, but also provide potentially a new physical platform for enriching the structure of the quantum communication theory.

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