Halting single photon dissipation by Zeno effect

A. N. Vetlugin[1], M. Sidorova[1,2], R. Guo[1], C. Soci[1], and N. I. Zheludev[1,3]
1 Centre for Disruptive Photonic Technologies, SPMS, TPI, Nanyang Technological University, Singapore 637371
2 DLR, Institute of Optical Sensor Systems, 12489 Berlin, Germany
3 Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, Southampton SO17 1BJ, United Kingdom
a.vetlugin@ntu.edu.sg, c.soci@ntu.edu.sg

Abstract: We experimentally demonstrate that a single photon propagating through multiple absorbers in intricate optical networks can experience a significant reduction in dissipation rate as the number of absorbers increases.

The subtle nature of quantum correlations makes it impossible to compensate for optical losses by amplification. As a result, light in optical quantum networks decays exponentially as it propagates through multiple absorptive elements. This creates a massive challenge for the practical implementation of quantum technologies, where quantum computation and large-distance quantum communication suffer the most. Here, we show that the dissipation rate of quantum light propagating through highly absorptive optical networks can be significantly reduced and, in the limit, halted by employing the Zeno effect.

The prototypical example of the Zeno effect is shown in Fig. 1A. An atom illuminated by the resonant laser experiences coherent dynamics – a Rabi oscillation between the (initial) excited and ground states. After half a cycle, the atom is surely in the ground state. However, if periodic disruptions, such as measurements, are applied to the atom, the coherent dynamics breaks and the atom tends to stay excited. Effectively, each measurement re-initializes the excited atom's state, and the Rabi cycle starts from the beginning. In the limit of continuous measurements, the atom's dynamics halts completely.

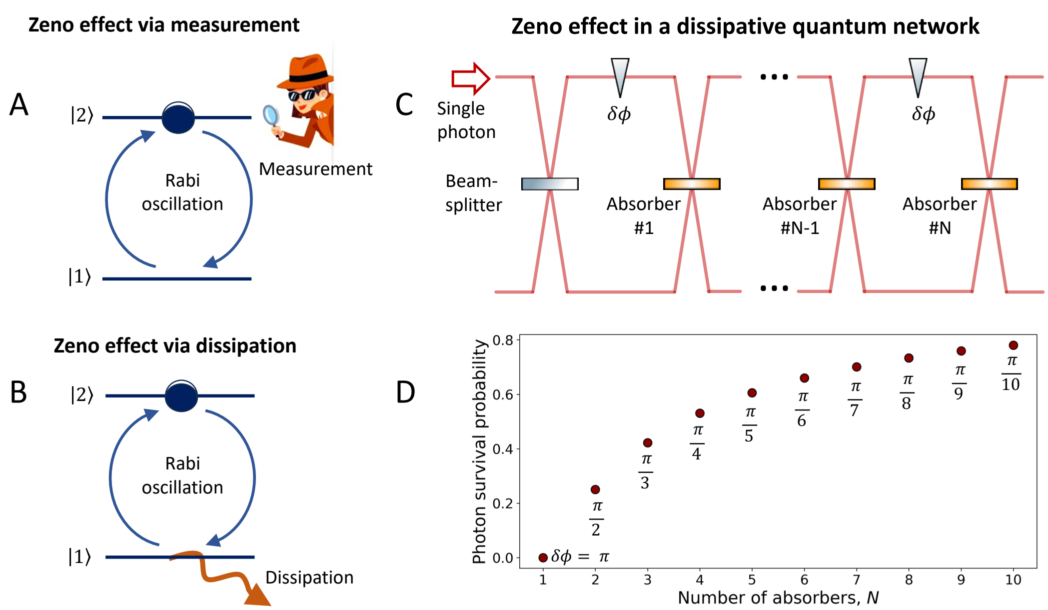

Fig. 1. **Zeno effect**. Zeno effect is observed when the coherent dynamics of the system (e.g., Rabi oscillation) is periodically interrupted by an external process (e.g., measurement as in **A** or state-selective dissipation as in **B**). For a photon propagating through a highly dissipative network (**C**) containing N absorbers and phase shifts $\delta\phi \sim 1/N$, the Zeno effect manifests in an increase in the survival probability (**D**) with increasing N.

Remarkably, a state-selective dissipation can play the same role as quantum measurements, disrupting coherent evolution, Fig. 1B. In this paper, we exploit this mechanism to increase the photon survival probability in the dissipative optical network. The photon propagates through a series of interferometers, as schematically shown in Fig. 1C. Here, the coherent dynamics is an oscillation between symmetric and anti-symmetric superposition states as the photon acquires the interferometric phase $\delta\phi$. Each interferometer is halted with a state-selective absorber, which is completely opaque for the symmetric state while transparent for the anti-symmetric state. Such an absorber can be implemented as a thin metallic layer (as in this work), plasmonic metamaterial, or a stack of graphene sheets. Counterintuitively, by increasing the number N of absorbers and simultaneously decreasing the phase shift $\delta\phi \sim 1/N$, one creates conditions favorable for the photon survival and the absorption rate becomes negligible for large enough N, Fig. 1D.

In the experiment, we use a heralded single-photon source where an idler photon from spontaneous parametric down-conversion (SPDC) heralds the presence of a signal photon, Fig. 2A. The signal photon enters an interferometer consisting of a 50:50 beamsplitter and two mirrors. We place the absorber fabricated by depositing thin chromium films on both sides of a λ/2 silicon nitride substrate on the nanopositioner at the center of the interferometer. A highly reflective beamsplitter (90:10) and a back-reflecting mirror are used to circulate the signal photon multiple times through the same interferometer, replicating photon propagation through multiple absorbers, as in Fig. 1C. The output ports are monitored with single-photon detectors.

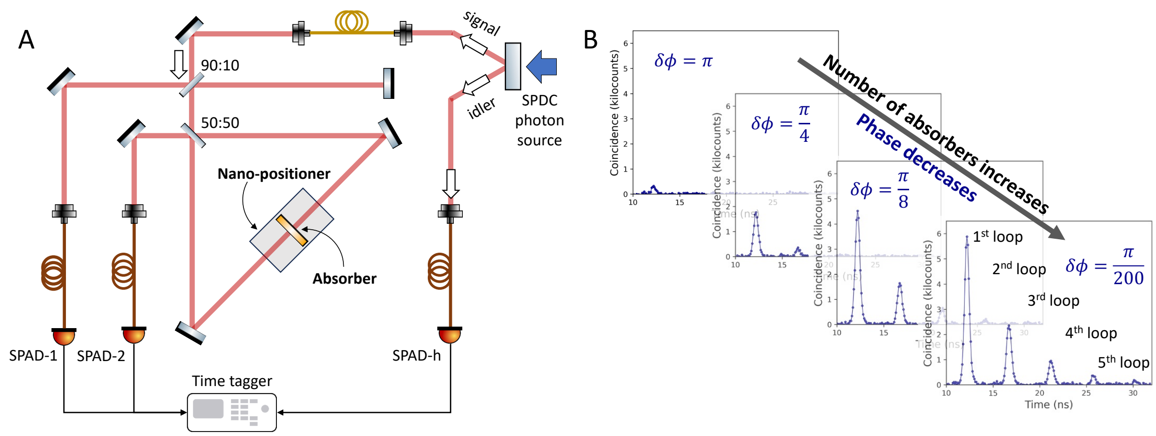

Fig. 2. **Halting light dissipation by the Zeno effect**. **A**: Time-correlated photon pairs are generated in the SPDC process (PPKTP Sagnac-based scheme). The idler photon is detected by a single-photon avalanche diode SPAD-h, starting the histogram acquisition by a time-tagger IDQ 900. The signal photon enters the multi-loop setup consisting of the interferometer and a feedback system consisting of a highly reflective beamsplitter 90:10 and a mirror. The absorber is placed on the nanopositioner, where the latter controls the phase of the interferometer δϕ. The signal photon is detected in output ports by SPAD-1 and SPAD-2, stopping the histogram. **B**: As the interferometer phase decreases, the photon survival probability increases, and it makes more loops through the setup despite interacting with more absorbers.

By changing the phase of the interferometer (shifting the nanopositioner) and measuring the coincidences between the idler and signal photons, we observe a transition from the highly absorptive to highly transparent regimes, Fig. 2B. For the phase shift of $\delta\phi = \pi$, the photon ends up in a state that is almost completely dissipated by the absorber after a single propagation through the interferometer. In contrast, when the phase shift is decreased, $\delta\phi = \pi/N$ (N=4, 8, and 200 in Fig. 2B), the photon makes a significantly longer trip, making it multiple times through the interferometer despite increasing number of interactions with the absorber.

These results show that a significant increase in the dissipation strength in quantum optical networks could drastically reduce the dissipation rate of light. Interestingly, frequent dissipative dynamics can 'freeze' the photon in the "transparent" state and, thus, prevent it from dissipation. This Zeno-effect-based mechanism can be exploited to increase the propagation length of quantum light in complex networks, enabling efficient quantum communication and quantum computation.