Amplification of Optical Pulse Delays using Weak Measurements

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Abstract: A novel scheme for super-sensitive measurement of optical pulse delays is proposed based on the concept of weak-value amplification. We discuss an experimental implementation of this technique utilizing a Mach-Zehnder interferometer.

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In 1988 Aharonov *et al.* introduced weak measurement as a procedure to gain information about average properties of an ensemble of quantum states, without perturbing the wavefunction of each one considerably [1]. Unlike strong measurements, the result of a weak measurement, known as a weak value, can be beyond the range of eigenvalues of the observable's operator [2]. This property of weak values can be exploited in order to achieve very sensitive measurements of different observables. A number of previously performed experiments have resulted in measurement of a small transverse shift, angular deflection, and longitudinal phase shift of an optical beam [3–5] .

In all these experiments a small variation in the polarization state of photons is measured through a change in the state of a pointer. The pointer can be either a physically separate system or an extra degree of freedom of the particles involved in the measurement. It is in principle possible, to use the time information of a pulsed field as the pointer in a weak measurement. In this paper, we describe a procedure for performing such an experiment. We show that the weak-value amplification can lead to a drastic enhancement in the accuracy of pulse delay measurements.

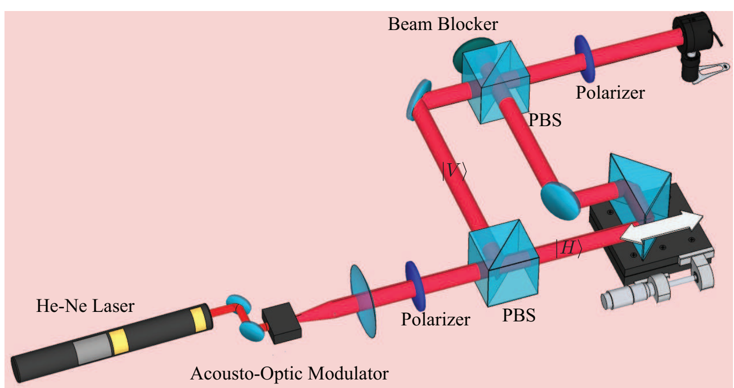

Fig. 1. Schematic diagram of the experimental setup.

Consider the Mach-Zehnder interferometer depicted in Fig. (1). The state of a single photon at the input port can be written as

$$|\Psi_{in}\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle) \otimes |f(t)\rangle e^{-i\omega_0 t}, \tag{1}$$

where we have assumed a quasi-monochromatic single optical mode with a pulse shape described by $|f(t)\rangle$. The horizontal and vertical polarization states are shown as $|H\rangle$ and $|V\rangle$ respectively. Lets consider a case when the interferometer considered in the experiment is imbalanced. In this situation, the photon state in the output is equal to

$$|\Psi_{out}\rangle = \frac{1}{\sqrt{2}}\left[|H\rangle|f(t-t_0)\rangle + |V\rangle|f(t)\rangle\right] e^{-i\omega_0 t}. \tag{2}$$

Here we have dropped the common delay time between the two polarization states in order to simplify the notation. Additionally, we have assumed the differential delay t_0 to be equal to a multiple of the period $\frac{2\pi}{\omega_0}$ and much smaller than the pulse width. This results in the convenient phase difference of zero in the output. For a more general sitatuation, any phase difference between the two arms can be compensated by a small change in one of the paths, keeping the group delay almost unchanged.

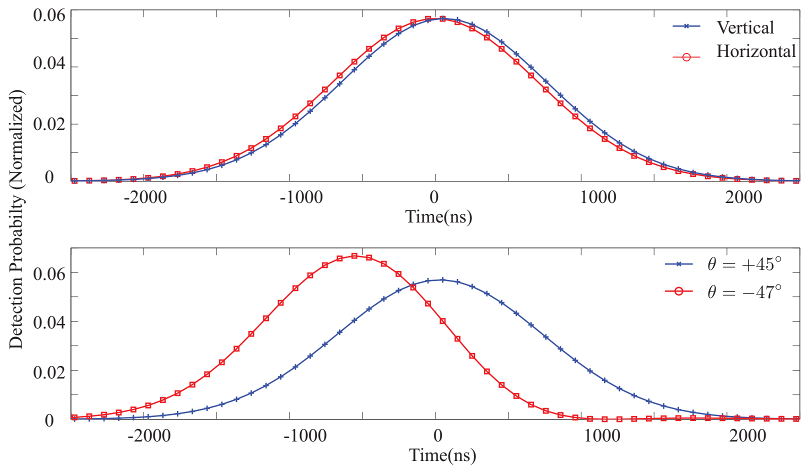

Fig. 2. (a) The situation where the H polarized pulse is delayed by 60 ns with respect to the V polarized. (b) The pulse shape after the post selection at $\theta = 45°$ and $\theta = -47°$. For the case of $\theta = -47°$ the delay is amplified to about 555 ns.

In order to amplify the time delay, we need the ability to project the output state on an arbitrary superposition of the two beams. This can be achieved by placing a polarizer at the output of the interferometer. Using the weak value formalism for the case of a Gaussian pulse shape, the post-selected state can be written as [1]

$$| \Psi_{PS}\rangle \propto [|H\rangle \cos(\theta) + |V\rangle \sin(\theta)] \otimes |f(t - \mathbf{A_w t_0})\rangle e^{-i\omega_0 t}. \tag{3}$$

Here A_w is the well-known weak value, and θ is the polarizer's angle. In this experiment the observable is the which-path information operator $\hat{A} = |H\rangle\langle H|$. The amplification factor A_w can calculated using

$$A_w = \frac{\langle \Phi_\theta \mid \hat{A} \mid \Psi_{in}\rangle}{\langle \Phi_\theta \mid \Psi_{in}\rangle}, \tag{4}$$

where $|\Phi_\theta\rangle$ is the post-selection polarization state. Fig. (2) shows simulation results for two different pos-selection angles. It can be seen that the delay gets drastically amplified as θ approaches $-45°$. We expect to have experimental results supporting these simulated results soon.

References

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