3. Experiment

Next we describe our measurement of optical delay in a double-prism system with 25-fs optical pulses. The pulses are generated by a mode-locked Ti:Sapphire laser (Chinook, KM Laboratory) operating at a 80 MHz repetition rate. We use a pair of 1-inch prisms (L = 3.59 cm) and a displacement parameter of d = 4.49 mm (N = 8). The refractive index n of each prism is 1.510 at λ = 800 nm, making the expected optical path length contribution of the prism pair nNL = 43.4 cm. We use the interferometer shown in Fig. 3 to measure the path length introduced by the prism pair. The interferometer is initially set up without the prism pair. Reference (R) and probe (S) beams are focused onto the BBO crystal and arms "A" and "B" are adjusted until second harmonic generation is detected (see the blue spot between S and R on the screen in Fig. 3).

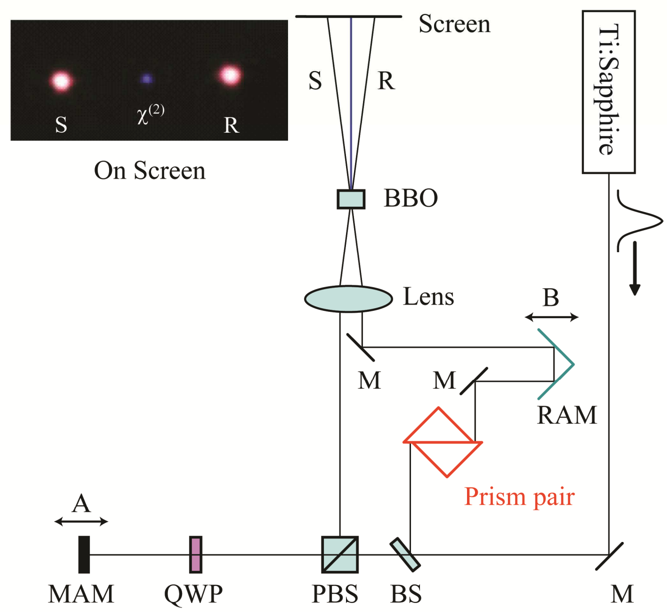

Fig. 3. Observation of prism-pair optical delay using 25 fs light pulses. Inset: Optical spectrum of the input and output pulses across the prism pair. M: Mirror, BS: beam splitter, MAM: micromotor activated mirror, RAM: right angled mirror, PBS: polarization beam splitter, QWP: quarter-wave plate with axis at 45°.

The prism pair is inserted in the probe arm, and arms "A" and "B" are adjusted until the second harmonic generation is once again observed. The measured length difference is 43.4 cm, which corresponds to 1.45 ns of delay. The full-width at half-maximum duration of the pulses is 25 fs. The delay-bandwidth defined as the ratio of these two time intervals is equal to $(1.45\text{x}10^{-9})/(25\text{x}10^{-15}) = 5.8\text{x}10^{4}$. An alternative definition of the delay bandwidth product entails multiplying the time delay by the actual bandwidth of the light pulses. This definition describes how much bandwidth is available for the delay in a system. The measured bandwidth of our pulses is 50 THz, and the delay-bandwidth product is $(1.45\text{x}10^{-9})$ x $(50\text{x}10^{12}) = 7.3\text{x}10^{4}$. Note that for either definition, the value is limited by the available pulse bandwidth, not by the prisms themselves.

To confirm that this double-prism method is suitable for use in quantum information systems, we measured the delay using the Hong-Ou-Mandel (HOM) interferometer shown in Fig. 4. We pumped a BBO crystal with a continuous-wave Argon-ion laser operating at 364 nm to generate our entangled photons. A pair of 20 mm prisms (L = 28.3 mm) was placed in one arm of a Hong-Ou-Mandel (HOM) interferometer, and the path length of the other arm was controlled by one manual translation stage with 500 μm resolution and one computerized

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translation stage with 100-nm resolution. Detection was performed with two fiber-coupled PerkinElmer (SPCM-AQRH-14-FC) avalanche photodiodes and a coincidence circuit with a 12-ns window. Coincidence measurements were made for different positions of the computerized translation stage to observe the Mandel dip, which was then fitted in MATLAB to extract position information. We repeated the process for various values of N by changing d and adjusting the position of the manual translation stage. The two prisms were moved symmetrically with micrometer-driven translation stages to prevent transverse beam displacement of the output beam and ensure that any observed time delay was due to the increase in N. While the HOM interferometer gives position measurements that are reproducible within a few microns or better, the total resolution of this system is limited to approximately ± 500 μm by uncertainty in the position measurement of the manual translation stage.

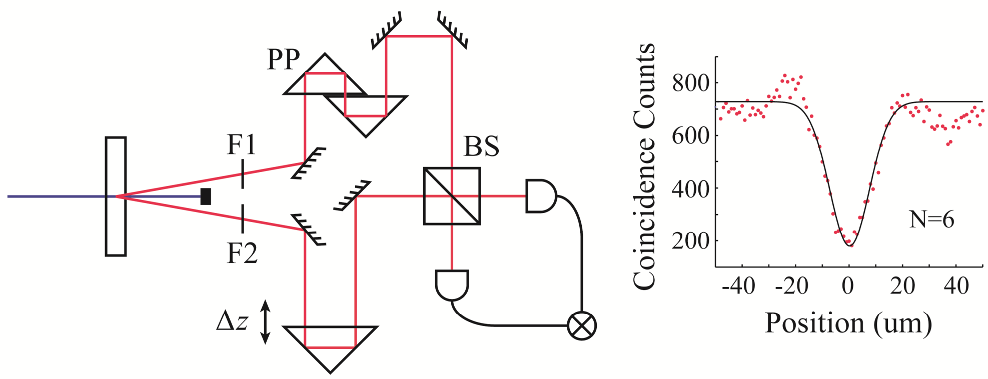

Fig. 4. Measurement of prism-pair optical delay using entangled photons. The Hong-Ou-Mandel interferometer setup is shown on the left. F1 and F2 are band-pass filters, PP is the prism pair system, BS is a non-polarizing beam splitter, and Δz represents the delay added by two independent translation stages. An example data trace for $N = 6$ is shown in the inset.

The measured delay is plotted in the upper panel of Fig. 5 for several different displacement parameters d corresponding to different values of N. The slope of the linear fit (black solid line) is 44.38 mm/transit, which is consistent with the observed experimental parameters (20 mm prisms with a 1.5 mm separation between them). For the case $N = 10$, the measured time delay is 1.18 ns, and the bandwidth of the system is 5.65 THz, limited by the 10-nm bandpass of the spectral filters.

The observed delay-bandwidth product is thus $(1.18\text{x}10^{-9})\text{x}(5.65\text{x}10^{12}) = 6.7\text{x}10^{3}$. The dynamic range of the data shown in the upper panel of Fig. 5 is so large that it is difficult to determine by eye how well the data agrees with theory. The lower panel of Fig. 5 shows the deviation from the fit with error bars corresponding to the 500 micrometer resolution of the manual translation stage. Within the experimental uncertainty, all of the data points agree well with the fit. The small deviations are believed to arise primarily from imperfections of the manual translation stage, but could also arise from a number of other sources, including a small amount of tilt between the two prisms and angular errors in the prisms themselves.

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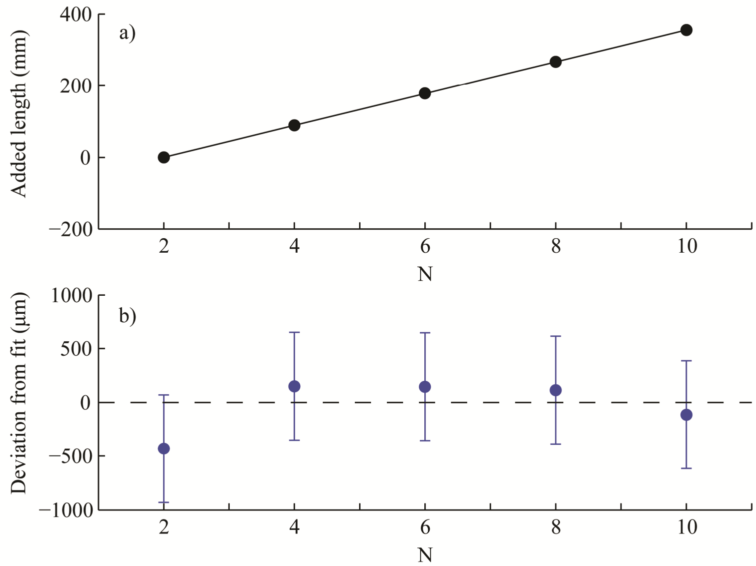

Fig. 5. Measured delay for various prism configurations using the setup of Fig. 4. In the upper plot, the observed values are well-represented by a linear fit (solid line). The slope of the fit is 44.38 mm/transit, in good agreement with the experimental parameters (*A* = 2 cm and a 1.5 mm gap between prism faces). The bottom plot shows the deviation of the individual data points from the fit, with error bars of ± 500 μm to represent the uncertainty in reading the position of the manual stage.

4. Conclusion

In conclusion, we report a simple method of low-loss, low-dispersion tunable optical delay using a prism pair. The observed delay-bandwidth product is 5.8×10^4 using a classical light source and 6.7×10^3 using quantum-state light. This system has potential for application in tunable optical-buffer memories for picosecond fiber-optic communication networks and for quantum communication systems. In addition, the system is capable of achieving even larger delay-bandwidth products for appropriate signal pulses.

The delay time of the prism pair system is controllable simply by adjusting the displacement parameter d or gap separation g shown in Fig. 1. Furthermore, this delay can be tuned over a large dynamic range without introducing angular or lateral beam deviation in the output beam, making it suitable for alignment-sensitive applications. This delay can be extended by adding another prism pair in series as in a microcavity ring resonator chain [10], allowing for even larger delay-bandwidth products. Since the double-prism device is linear system and is influenced only by material dispersion, the optical path length varies very little with signal wavelength. It can potentially allow for hundreds of nanometers of signal bandwidth, overcoming the primary limitation on delay-bandwidth product seen in most ultraslow light and microcavity delay schemes.

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