Generation of a pulsed polarization entangled photon pair using a Sagnac interferometer

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In this paper, we report on a scheme to generate a pulsed polarization entangled photon pair through the use of a Sagnac interferometer. To demonstrate its workability, we experimentally obtained two-photon quantum interference for the polarization variable. The main advantage of this scheme is its exceptional stability, compared to other schemes based on the interferometric technique. It does not need any active or passive techniques to stabilize the interferometer, even the instrument is exposed to a relatively turbulent environment.

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Sources for creating entangled photon pairs are essential tools in a variety of fundamental quantum-mechanical and quantum-information experiments, such as in testing Bell-inequalities [1–3], quantum cryptography [4], teleportation [5], dense coding [6], quantum computation [7], and other areas. At present, the most accessible and controllable source of entanglement is the process of spontaneous parametric down-conversion (SPDC) in a nonlinear crystal [8,9]. SPDC can be used to generate entangled photon states using type-I or type-II phase matching. Two-paired down-converted photons have the same polarizations in type-I phase matching and they emit along the concentric cones around the direction of the pump beam. In type-II phase matching, the down-converted photons have orthogonal polarizations. These differently polarized photons are emitted along two different cones with the cone axes at opposite sides of the pump beam. Correlated photons are produced in the $|HV\rangle + |VH\rangle$ state [9] in two particular emission directions. Type-II SPDC has been used extensively since the 1990s as a source of two-photon entangled states for space-time, polarization, and space-time–polarization double entanglement [9]. Another way of generating polarization entangled photon pairs using two cascaded thin nonlinear crystals was presented by Kwiat *et al.* some time ago [10]. For applications in the quantum-information field, cw-pumped SPDC is not very useful, because entangled photon pairs occur randomly within the coherence length of the pump laser. This huge uncertainty in time makes it difficult to use in many applications, such as quantum teleportation, quantum swapping, etc. Using a femtosecond pulse laser as a pump can resolve this difficulty. Consequently, we can see how the generation of a pulsed two-photon entangled pair is a very important topic. We could use type-II SPDC to produce it directly, but ultrashort pulse-pumped type-II SPDC has very poor quantum correlation compared to the case with cw laser, due to the very different behavior of two-photon wave packets [11]. Recently, there have been many proposals and experimental demonstrations on how to generate pulsed entangled two-photon pairs [12–19]. It is our opinion that these proposals and demonstrations can be divided into three varieties: The first is where type-II phase matching is used directly, but with a narrow-band filter or a very thin crystal [12]. The second is where a special two-crystal geometry is used, such as by Kim *et al.* [14], Nambu *et al.* [15], Bitton *et al.* [16], and Shi and Tomita [18]. The third is based on the interferometric technique, such as by Kim *et al.* [13], Kim and Grice [17], and Shi and Tomita [19]. With the third variety, an interferometric technique is used to generate an entangled photon pair. This technique is insensitive to the thickness of the crystal and is also insensitive to the bandwidth of the filter. Its main problem is that the interferometer cannot be stabilized for very long and it is not robust against environmental disturbances. Therefore, we usually have to use an active or passive technique to stabilize. The question is could we avoid the use of passive or active techniques altogether, but still gain stable interference? The answer to this is a resounding ‘‘yes.’’ In this paper, we present a very simple way of doing this based on a Sagnac interferometer, which is widely used as an optical sensor, especially with fiber optics. One advantage in using this instrument is its stability in the phase difference between two interfering beams due to its special loop structure. Very recently, a space Sagnac interferometer was used for photonic memory [20], and a fiber Sagnac interferometer was used for quantum Fourier transformation [21] and quantum key distribution [22]. In our work, we also used a Sagnac interferometer instead of other common interferometers, such as the Mach-Zehnder [13] or Michelson interferometers [19], to generate a pulsed polarization entangled photon pair. To demonstrate its workability, we experimentally obtained two-photon quantum interference for the polarization variable. The main advantage of this scheme is its exceptional stability. During the experiment, the entire setup was placed on an optical table and exposed to fluctuations of air and temperature introduced by an air conditioner. Despite this, we were still able to obtain very stable interference and this demonstrated that the Sagnac interferometer is a useful tool in quantum optical experiment. In what follows, we will describe the scheme in detail.

Figure 1 is an outline of a simplified Sagnac interferometer, which consists of a round loop and a 50-50 beam splitter (BS). When a light beam arrives at the BS, it is divided into two equal parts, with one part traveling clockwise through the round loop and the other part counterclockwise. These two parts finally arrive at the BS again. If the Sagnac interferometer is not very large or the change in interactions over time between it and the environment an not very fast, then the influences introduced by the environment on the two parts are the same. This means the clockwise and counter-

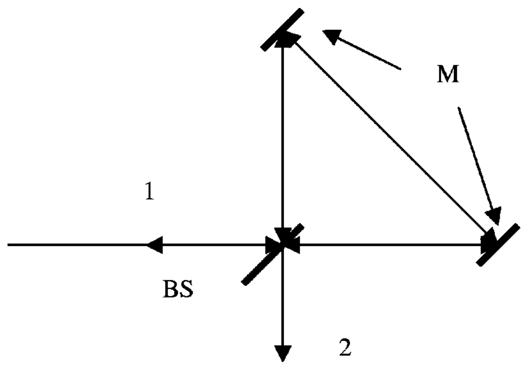

FIG. 1. Overview of setup for Sagnac interferometer. BS, beam splitter; M, Mirror.

clockwise paths are automatically compensated so that they are of equal length, and the phase difference between the clockwise and counterclockwise loops can be stably maintained, resulting in stable interference. In a Mach-Zehnder or a Michelson interferometer, there are two different paths. Usually, as the influence the environment has on these two paths is different, and there is no stable phase difference between them, it is difficult to stabilize interference. One possible way of solving this is using an active or passive technique for stabilization. However, it is unnecessary to use either of these techniques for the Sagnac interferometer because of its special loop structure. Instead, to generate a polarization entangled photon pair, we simply add a piece of nonlinear crystal, which is cut with type-I phase matching for the SPDC in the loop, and also place a half-wave plate (HWP) $\lambda/2$ for light ω in the interferometer, where, $\omega(\lambda)$ is the frequency (wavelength) of light. The HWP is at an angle of 45°. The HWP for light ω equals the wave plate λ for light 2ω . When 2ω pump light arrives at the BS, half is transmitted through it, which pumps the nonlinear crystal, for example, generating a horizontal photon pair $|2H\rangle$. After the HWP, the polarization of this pair is rotated vertically $|2V\rangle$. The reflected part of the 2ω pump produces another horizontal photon pair $|2H\rangle$. These two processes mix at the BS. If we could erase all the information about these two processes and make them indistinguishable, and just consider cases where there was only one photon in each BS output, then we could obtain a polarization entangled photon pair $|HH\rangle_{12}+|VV\rangle_{12}$, where, subscripts 1 and 2 refer to the outputs of the BS. If a cw laser is used as the pump laser, and the BS is very thin, the procedure is quite simple. All we need is the state of the output from the two BS output ports. However, for an ultrashort pump laser, such as a femtosecond laser, the process is more complicated. Here we have to consider the thickness of the BS and HWP, because they introduce different dispersions between the pump laser and SPDC light, and make the two SPDC processes distinguishable. Therefore, we have to use various compensation components. Based on this, we designed the following experiment.

Figure 2 outlines the experimental setup. A femtosecond laser from a mode-locked Ti:sapphire laser (coherent:Vitesse) is used to pump a 1-mm β-barium-borate (BBO) crystal, cut collinearly with type-I phase matching to produce a frequency-doubled radiation 400-nm laser. The 400-nm laser will be used as the pump laser for SPDC later. The wavelength of the femtosecond laser from the Vitesse is 800 nm and the pulse width is less than 100 fs. The power of laser is about 870 mW. The repetition rate is 80 MHz. We used a dichroic mirror (transmits 800-nm and reflects 400-nm light.) DBS1 and three blue filters to cut the remaining fundamental light. By DBS2, the 400-nm laser is guided into a Sagnac interferometer, which mainly consists of a 50-50 beam splitter BS1 and two mirrors. We place another 1-mm BBO crystal, collinearly cut at type-I phase matching for SPDC in the loop. The phase-matching angle of the crystal is $\Theta_m = 29.18°$. We also place a half-wave plate for 800-nm light HWP1 and a 0.56-mm silica quartz plate (QP) for time compensation in the interferometer. After BS1, the 400-nm pump laser is divided into almost two equal parts. The SPDC light produced by transmitted part is rotated to its orthogonal polarization by HWP1 at an angle of 45°. The reflected pump part first transmits through about a 1.2-mm pinhole and HWP1 and then pumps the BBO crystal. We used this small pinhole for two reasons: the first was to fix the direction of alignment and the second was to balance the number of photon pairs between the two processes. We measured the re-

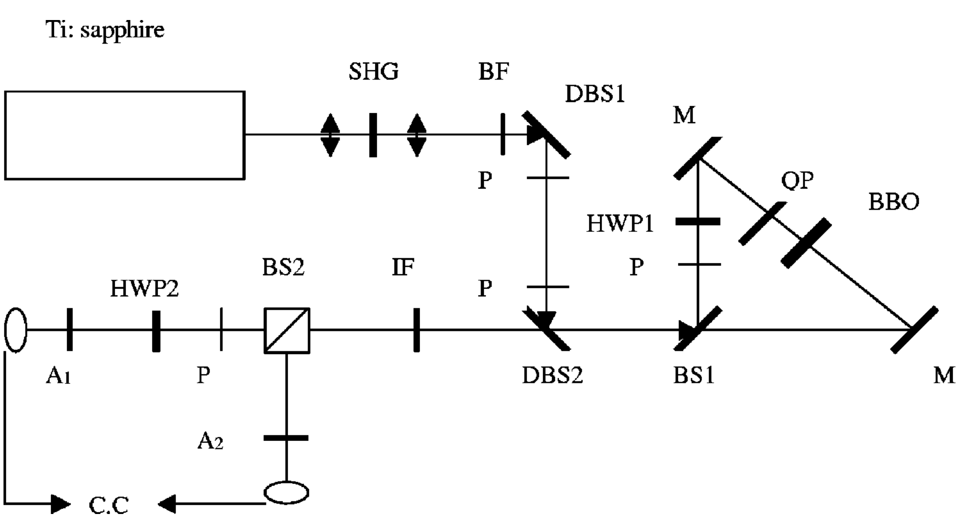

FIG. 2. Experimental setup. SHG, second-harmonic generation; BF, blue filter; DBS1 (2), dichroic mirror transmits 800-nm and reflects 400-nm light; BS1 (2), beam splitter; HWP1 (2), half-waveplate; P, pinhole; IF, interference filter; $A_{1(2)}$, polarizer; M, mirror; QP, quartz plate; CC, coincidence circuit.

flected pump power after the pinhole and it was about 15 mW. The two SPDC processes finally mix at BS1. One output of BS1 is input to another 50-50 beam splitter, BS2. We inserted a 10-nm interference filter in front of BS2. At one of the outputs of BS2, we inserted about a 2-mm pinhole and another half-wave plate HWP2 for 800-nm light. At each output port of the BS2, we placed a detector package consisting of a Glan-Thompson analyzer A_1 or A_2 and a single-photon detector (PerkinElmer SPCM-AQR-14-FC). The outputs of detectors are sent to a coincidence circuit for coincidence counting. The coincidence circuit consists of a time-to-amplitude converter and single-channel analyzer (TAC+SCA, ORTEC 567) and a counter (SR400: Standford Research Systems). The time window for the coincidence counting is 2 ns. If the HWP1 and BS1 are infinitely thin, then the output state from BS2 should be the polarization entangled state $|HH\rangle_{12}+|VV\rangle_{12}$ by postselection. Unfortunately, our uv Fused Silica BS1 was about 1.5 mm thick, which introduced a large time difference between the transmitted and reflected paths. That is why we placed HWP1 and QP in the reflected beam. Through this, we could erase the time information between the two SPDC processes. Polarization entanglement can be manifested as a variation in the coincidence rate as a function of the relative angles between the polarization analyzers. This is typically observed in the following way: One of the polarization analyzers is fixed at a particular angle and the coincidence rate is measured as the other analyzer is rotated. For a maximally entangled state, the visibility is unity, independent of the setting of the first analyzer. This would be the case were all experimental conditions perfect. In practice, it is very difficult to achieve such an ideal situation, so, visibility is less than 100%. Usually, maximal visibility can be achieved by setting one polarizer to 0 or $\pi/2$; however, this is not a property of entanglement but of the experimental setup. There is the least visibility when the fixed polarizer is set at $\pi/4$, which represents the most exacting test for polarization entanglement. In our experiment, we fixed polarizer A_2 at $\pi/4$. We fixed polarizer A $_1$ and rotated the angle of HWP2 with each step 5°, which equalled the rotation of polarizer A_1 with each step 10°. The experimental data are shown in Fig. 3. The visibility was about 71%. We think the main reasons that visibility did not reach 100% were due to imperfections in the experiment, e.g., from the small difference in coincidence count rate between the two SPDC processes; from the small difference in dispersion between these two processes (although we compensated, this was not optimal).

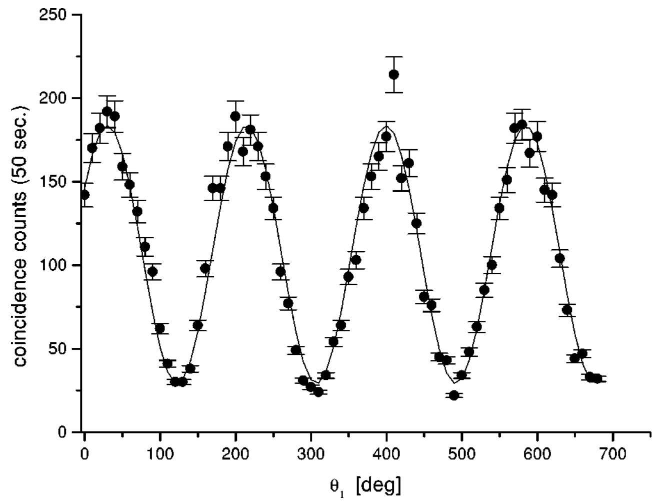

FIG. 3. Experimental results. Closed circles are experimental data and solid lines are least-squares fits to the data. Polarizer A_2 $\Theta_2=45°$. The angle Θ_1 of polarizer A_1 is rotated. Visibility is about 71%.

The other three Bell states can be prepared by inserting a combination of a half-wave plate and a phase shifter. Using our scheme, a nonmaximally entangled state, i.e., a state of the form $|HH\rangle+\epsilon|VV\rangle$, where, $\varepsilon\neq 1$, may be produced, simply by making the photon pair numbers from two processes different. This kind of state has proved useful in reducing the required detector efficiencies in loop-free tests of Bell inequalities [23]. Moreover, an arbitrary mixed state of type $\cos^2\Theta|HH\rangle\langle HH|+\sin^2\Theta|VV\rangle\langle VV|$ can be produced with our scheme by making the path difference between the two arms exceed the coherence length of the pump laser and making the photon pair numbers from the two processes different.

In summary, we demonstrated that a Sagnac interferometer can be used to generate a pulsed polarization entangled pair. The main advantage of this scheme is its exceptional stability, compared to other schemes based on the interferometric technique. It does not need any active or passive technique to stabilize interferometer, even the device is exposed to a relatively turbulent environment.

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