Generation and study of time-multiplexed degenerate optical parametric oscillator pulses using a nonlinear fiber Sagnac loop

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A degenerate optical parametric oscillator (DOPO) is an optical oscillator that uses phase-sensitive amplification (PSA) [1, 2] as a gain medium. Since the phase of a DOPO only takes 0 or π, it can be used to represent an artificial spin for the Ising spin network. However, in a coherent Ising machine (CIM) [3, 4], DOPO generation with four-wave mixing (FWM) using a highly nonlinear optical fiber (HNLF) [5] cannot be used for the measurement feedback scheme, which needs a local oscillator (LO) whose phase is fixed with that of the DOPO for a balanced homodyne detector (BHD) measurement and as an injection pulse to take feedback information. By using a nonlinear fiber Sagnac loop [6], the DOPO states through the degenerate FWM and the pump input light can be spatially separated. The DOPOs based on a Sagnac loop configuration has already been realized in [7, 8], but coherence properties have not been studied. Here, we generated and studied coherence properties and randomness of time-multiplexed DOPO states [9].

The experimental setup is shown in Fig. 1 (a). The pulse train was prepared by modulating a continuous-wave (CW) light at 1525.5 nm using an optical intensity modulator (IM) with 1 GHz repetition rate (f). The pump pulse was amplified by using an erbium-doped fiber amplifier (EDFA) and then we placed an optical bandpass filter (BPF) to reduce the noise of EDFA. There are the parameters of HNLF zero-dispersion wavelength (1537 nm), length (1 km), dispersion slope (0.03 nm^{-2} km^{-1}), and nonlinear coefficient (21 W^{-1} km^{-1}). The input pump light was inserted to port 1 of the BS which was divided into two ports of 3 and 4, then the pump lights were launched into two endpoints of the HNLF in the Sagnac loop. At same time, vacuum states were launched into port 2 of the BS. Finally, squeezed vacuum states were generated via the degenerate FWM in both directions of the Sagnac loop. By adjusting the polarization controller (PC) inside the Sagnac loop [6], the pump pulse and squeezed vacuum state were spatially separated from ports 1 and 2, respectively, which obtained an ~30 dB pump suppression at port 2. After passing the optical cavity, the squeezed vacuum states would be launched into the Sagnac loop again to receive PSA.

For the measurement of the DOPO phase, we took a portion of the CW laser as an LO, which is then mixed with 10% of the DOPO light on a BS. We launched both output ports of the BS into the BHD. In the repetitive PSA in the Sagnac loop cavity, we obtained the phase of DOPO states only took 0 (positive) or π (negative) randomly as shown in Fig. 1 (b). In order to confirm the randomness of our DOPO pulses, we convert our phase of DOPO states to 0 and 1 for the NIST random number test [9]. Because the length (5,555) of our random bits was limited by the stability of the Sagnac loop, it was too short for some NIST tests. It passed eight tests–Frequency, BlockFrequency, CumulativeSums, Runs, LongestRun, FFT, Approximate entropy, and Serial.

Although the DOPO phase is completely random, once the system exceeds the oscillation threshold, a fixed pattern with each round trip should be observed in the cavity. We do the autocorrelation analysis to confirm the preservation of the phase pattern of the measurement in Fig. 1 (c), which is shown as a function of pulse delay in Fig. 1(b). The negative correlation indicates that the DOPO pulses go through a (2n + 1)π (n: integer) phase shift per circulation in the cavity. We observed an almost perfect negative correlation every 5,555th pulse delay seventeen times in each cycle. Thus, our DOPO states can be used as artificial spins for a CIM.

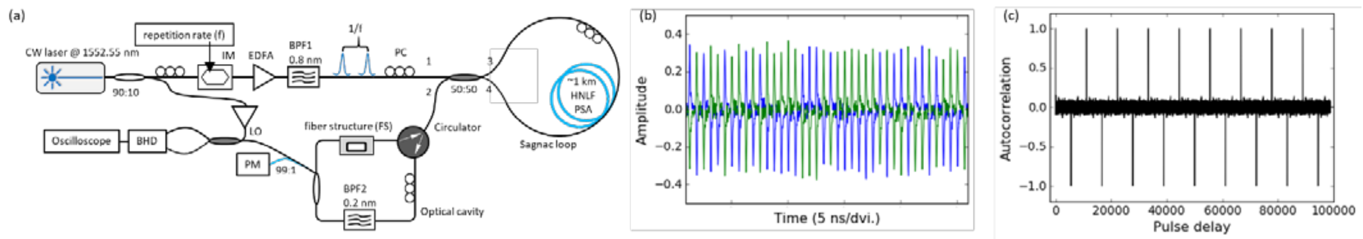

Figure 1: (a) Experimental setup of DOPO pulse generation and measurement based on a HNLF Sagnac loop. (b) The result of DOPO phase measurement by using the LO and BHD. (c) Autocorrelation analysis for the phase pattern in (b) as a function of pulse delay.

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