Technique of active phase stabilization for the interferometer with 128 actively selectable paths

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1.Introduction

RRDPS-QKD has advantage over the traditional Bennett-Brassard-1984 (BB84) protocol in term of eliminating the fundamental threshold of bit error rate of 11[1] . The RRDPS protocol has a better tolerance of bit errors, which makes it easier to accomplish QKD in high noise background[2], such as the application of long distance free-space communication.

However, the implementation of the RRDPS scheme relies on the realization of a variable-delay Mach-Zehnder interferometer, which is extremely sensitive to the mechanical and acoustic vibrations, temperature drift and other disturbances[3]. These disturbances lead to phase imbalances between two arms of the interferometer. Although a frame of high-damping materials have been employed to envelop the interferometer as a passive protection, we still need a solution to eliminate the residual phase instability caused by the drift of the central wavelength of the laser or other low frequency disturbances. Besides, a suitable phase should be modulated on PM immediately when a new light path is selected. Therefore, a system of active phase control with closed feedback loop is designed and put into use.

2. Experiment Design

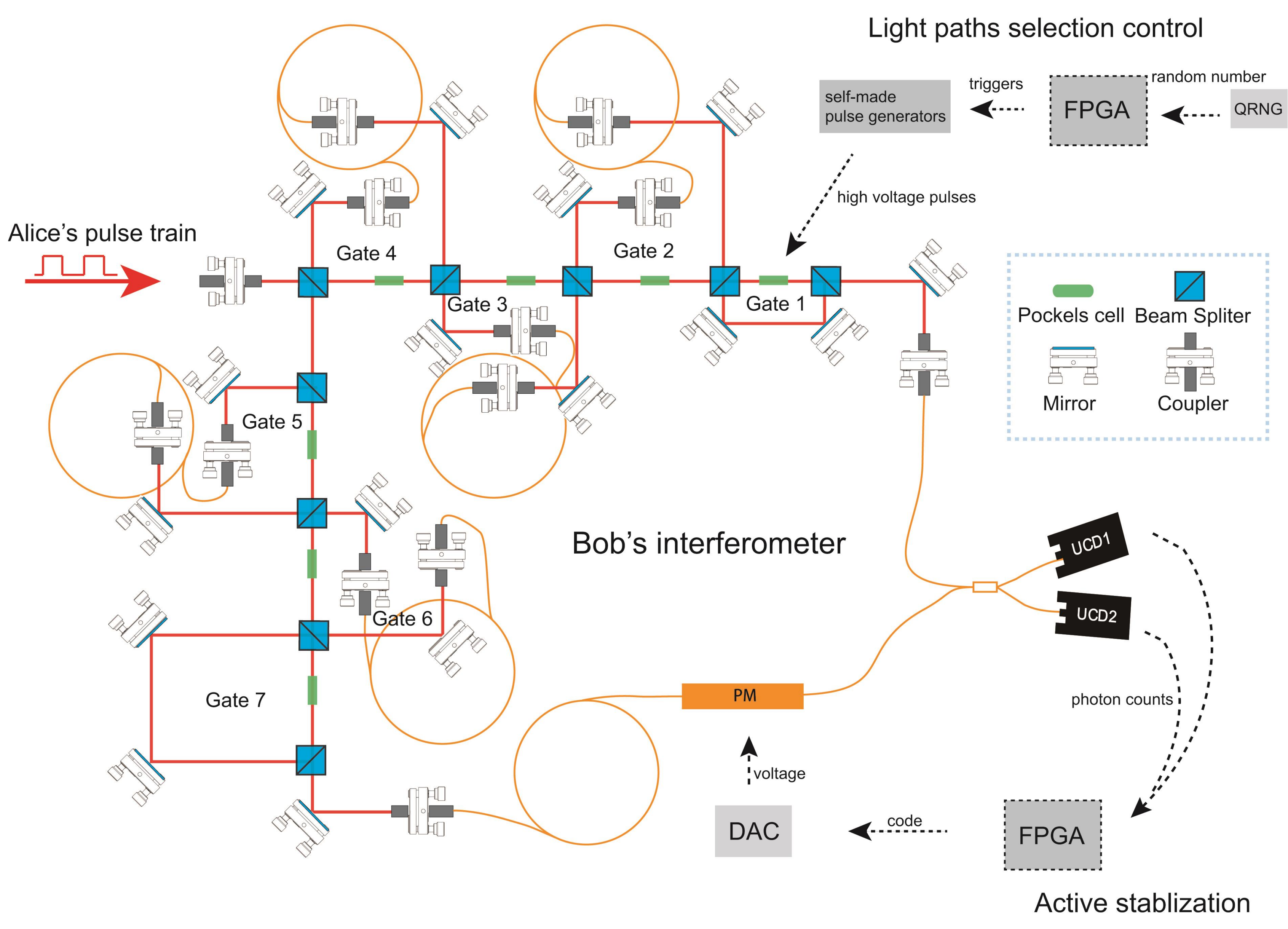

Fig.1 128 delays selectable Mach-Zehnder interferometer with Bob's control system

Why choose 128 delays?

Because…in the RRDPS-QKD protocol, key rate is given by the formula:

$$R = Q[1 - h(e_{bit}) - h(\frac{v_{th}}{L-1})]$$

Where *R* is the final key bit per *L*-pulse train, larger *L* ensures higher tolerance of bit errors. For example, for *L* = 128, *R* is positive up to e_{bit} = 0.35 [4].

128 light paths of different lengths should be prepared so as to achieve discrete delay values *r*= {0 ns, 2 ns, 4 ns, 6 ns,…, 254 ns} precisely. Seven delay gates access to seven optical fibers of different lengths are embedded in Bob's interferometer. Each gate switches under the control of a Pockels cell. A Pockels cell behaves like a half-wave plate at the half-wave voltage. In order to achieve fast switching between 0 V and half-wave voltage, which is around 2100 V in experiment, seven custom-built RF-MOSFET based high voltage generators are employed to supply the square-shaped 2 kV pulses with repetition rate of 10 kHz. These generators are triggered by an FPGA Virtex-6 embedded in the Bob's control system. The triggers' sequence are encoded by a 7-bit random number generated by a RNG chip WNG8 on board during QKD process. As shown in Fig.1, thanks to the Bob's control system as well as the high voltage generators, the whole interferometer can transform into any one of the 128 light paths as soon as the random number changes, whose switching rate reaches 10 kHz.

3. Hardware and logic Design

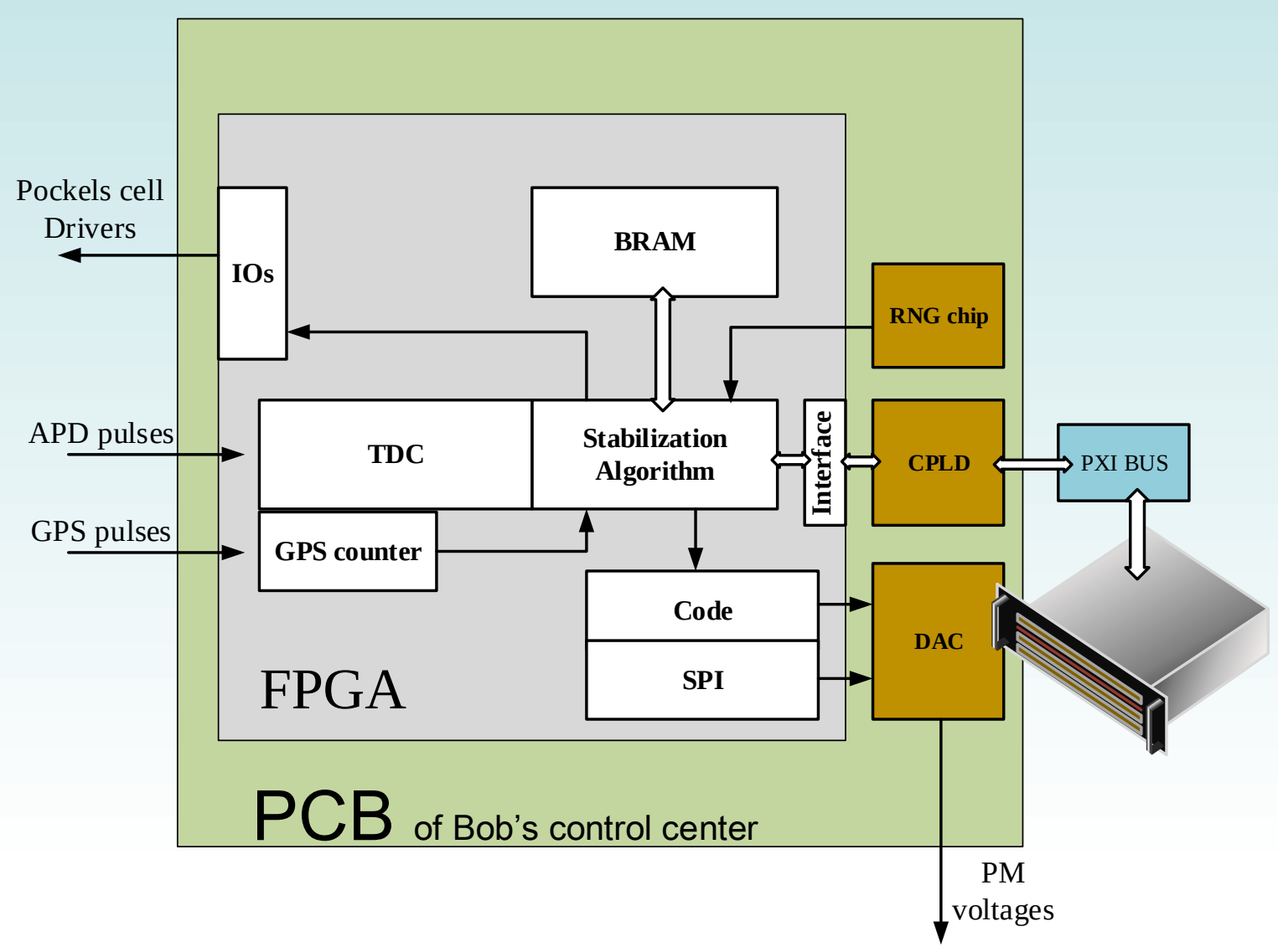

Fig.2 Hardware and logic design

As shown in Fig.2, a PCB board is designed to play a role as the Bob's control center, and embeded in one PXI box. The main components on PCB are Virtex-6 FPGA, one DAC, one CPLD and one RNG chip. It mainly receives two APDs' pulses as input and outputs voltages to PM and trigger pulses for Pockels cell drivers. The GPS pulses synchronizes the whole system

4. Stabilization Preparation

In order to realize real-time phase stabilization, Bob's control system is designed to refresh the optimal data for phase stabilization in first 340 ms of every second, which is named stabilization preparation stage. For each delay *r*, an optimal compensation voltage of PM, which is deployed to adjust the relative phase between two arms of the interferometers, should be measured and recorded.

5. Stabilization Algorithm

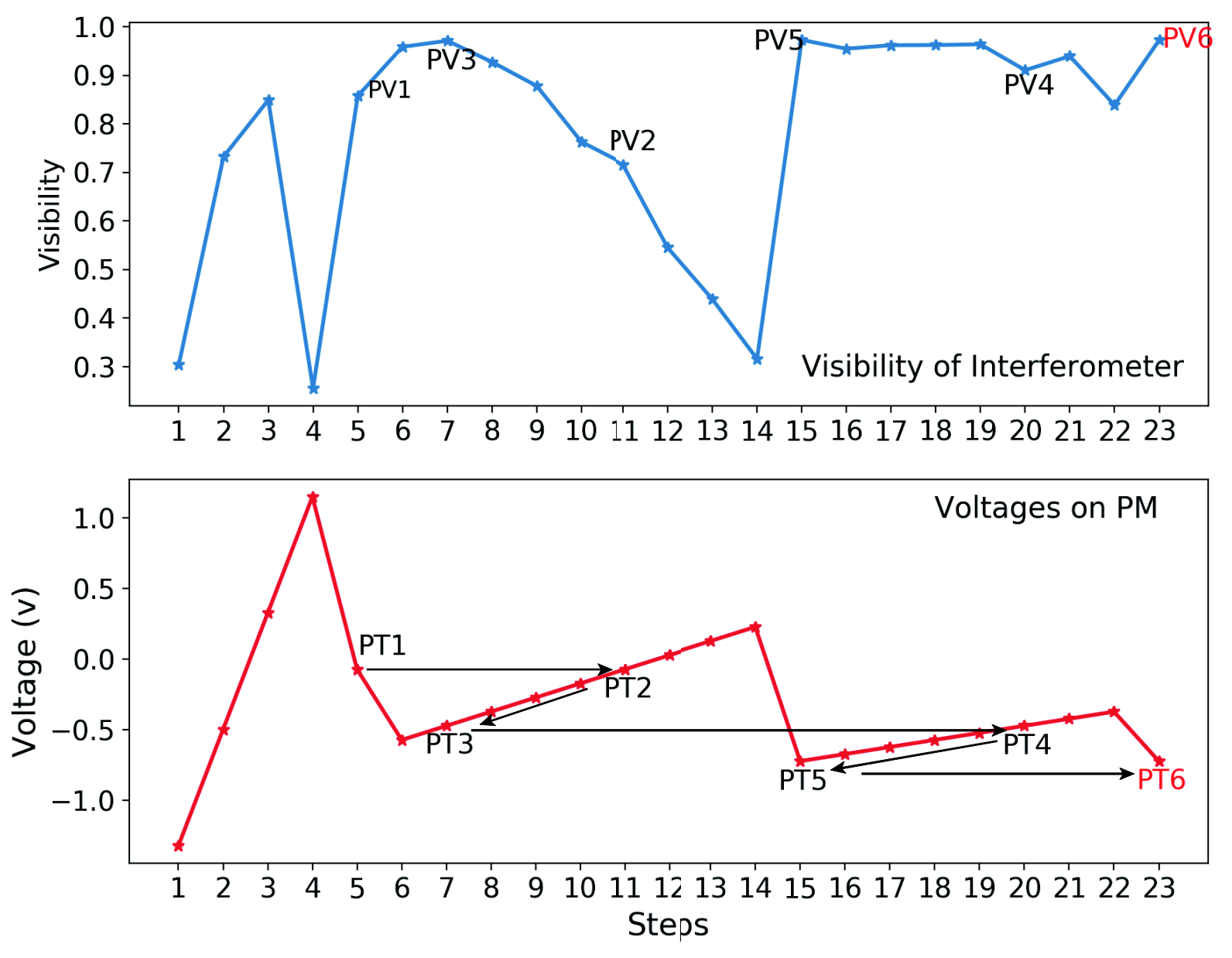

Fig.3 Algorimth working process. Top sub-figure demonstrates the visibility of interferometer when voltage implemented on PM in bottom sub-figure

During a period of 2.5 ms, one preliminary compensation voltage PT1 is firstly calculated in FPGA after four measurements of visibility by least-squares equation:

$$S(\alpha_r) = \sum_k (\frac{I_k}{I} - \frac{C_1^k}{C_1^k + C_2^k})$$

where C_1^k, C_2^k are photon counts captured by two APDs and recorded by FPGA. After PT1 is calculated, we implement another 9 voltages round voltage value of PT1 from Step 6 to Step 14, and get a higher visibility PV3 by the voltage value of PT3.

This process is called preliminary calibration stage. Then a secondary calibration stage is implemented from Step 15 to Step 22. During the secondary calibration stage, a working points with relatively highest visibility PT5 is figured out. Then, by the last step, PT6, with the same voltage of PT5, is implemented on Step 23. After these 23 steps changing voltages on PM, an optimal working voltage is determined corresponding to one particular paths interferometer among 128. At the end of the whole stabilization preparation, a reference table is constructed to store 128 new refreshed compensate voltage in this period of one second.

6. Stabilization Result

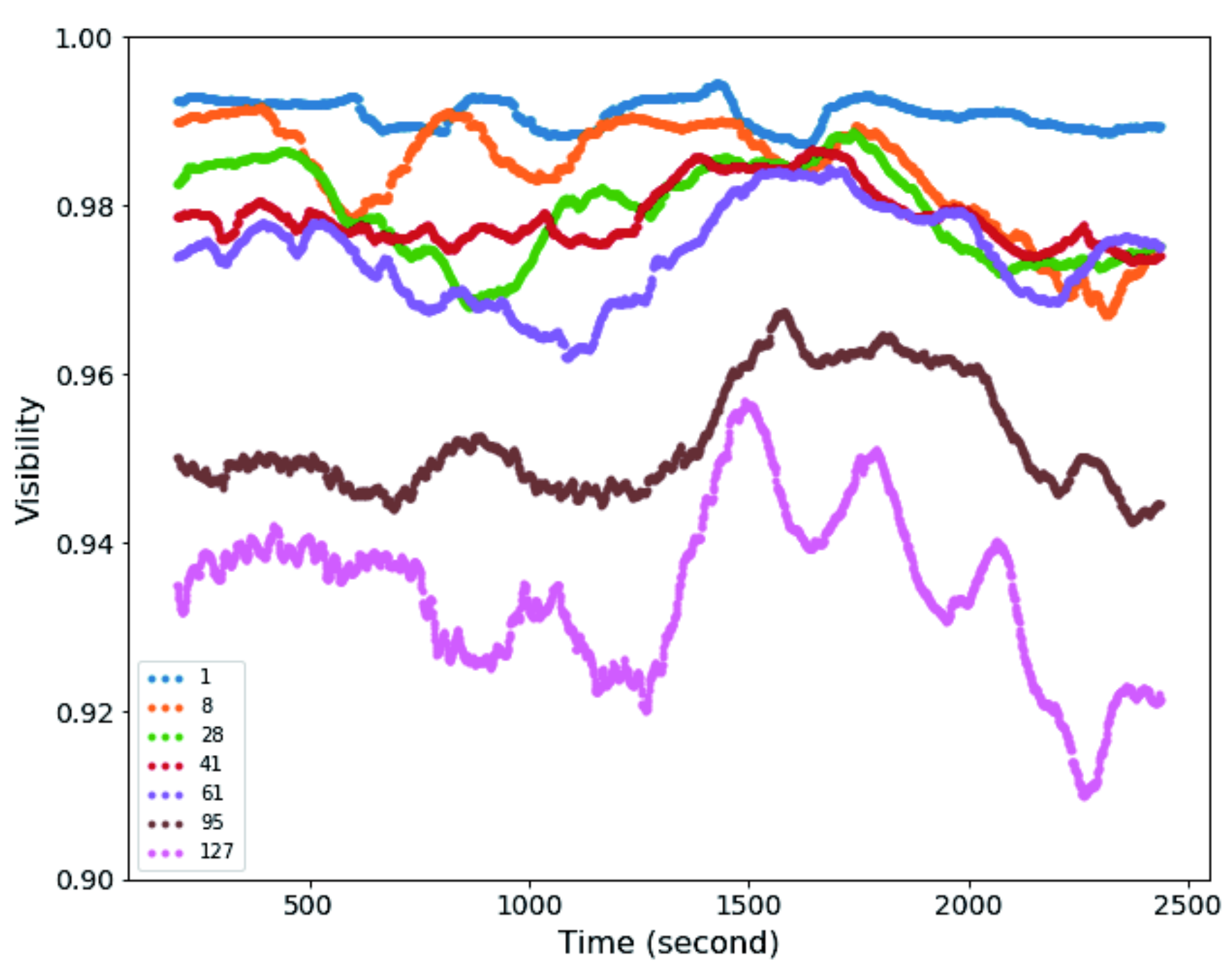

Fig.4 Phase stability with our active phase stabilization technique. Visibilities of interferometer with random delay values *r* during long time QKD experiment, taking *r*=1,8,28,41,61,95,127 for example.

As demonstrated in Fig3, with the help of our active phase stabilization technique, the unequal-arm interferometers with most of delay values of *r*, such as *r* = 1, 8, 28, 41,61,etc, can maintain a high visibility above 96 % during QKD for a long time. This active phase stabilization technique as well as the actively delays-selectable interferometers design strongly support the RRDPS-QKD experiment[5], which obtains a final key rate of 15.54 bps with total loss of 18dB and an error rate of 8.9%

References

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