Generation of Stable and High Extinction Ratio Light Pulses for Continuous Variable Quantum Key Distribution

Xuyang Wang, Jianqiang Liu, Xuefeng Li, and Yongmin Li

***Abstract*— We propose and demonstrate an approach to generate stable and high extinction ratio light pulses with an extinction ratio >80 dB. To this end, a high stable bias locking technique is proposed, and a small size, easily integrated, cost-effective pulse generator based on delay line chips is designed and constructed. The pulse generator can generate voltage >12.5 V at a load impedance of 50 Ω, which is enough to drive the lithium niobate-based Mach–Zehnder (LNMZ) intensity modulator with a half wave voltage ∼6–8 V. The pulse width and delay time can be programmed directly via digital I/O ports. The bias locking technique utilizes a successive scanning and fitting method which overcomes the sensitivity limit of the photodetector and can achieve the bias voltage accurately and quickly. By this method, the bias points of two or more cascaded LNMZ intensity modulators can be locked stably. The presented system can be easily integrated into the continuous variable quantum key distribution system.**

***Index Terms*— Quantum key distribution, high extinction ratio light pulse, bias voltage control, pulse generator.**

I. INTRODUCTION

QUANTUM key distribution (QKD) is progressing steadily in the past decade and is now very close to practical applications. For coherent state continuous variable (CV) QKD, standard telecommunication components can be utilized and the need for specific devices, such as single-photon resources and detectors are eliminated. The sender Alice sends modulated coherent states to the receiver Bob through a quantum channel. Then Bob measures the quadratures of the received states with homodyne or heterodyne detection. The two legitimate parties Alice and Bob can infer the upper bound of the information leakage according to the channel parameters, i.e., the amount of excess noise and channel transmission loss [1]. To reach a long distribution distance and high secret key rate, it is necessary to reduce the excess noises produced by the system itself, which is supposed to be introduced by the eavesdropper Eve [2]. Among the sources of excess noises, the leakage from the local oscillator (LO) pulse to signal pulse plays an important role [3], [4].

In CV QKD, the sender Alice usually sends high extinction ratio (HER) light pulses larger than 80 dB or more in order to reduce the photon leakage from the LO pulse to signal pulse [3]. In order to generate HER light pulses from continuous wave (cw) light, Lithium Niobate-based Mach Zehnder (LNMZ) intensity modulator is usually used, which has the advantages of low driving voltage, high bandwidth, adjustable chirp, and has been widely used in analog and digital communication systems [5].

One of the largest concerns during the development of lithium niobate technology was the issue of bias drift [6], which is critical for the performance of LNMZ intensity modulators. Due to environmental perturbations and aging effects, the initial bias point is known to drift over time, which makes the offset bias voltage adjustment difficult for achieving HER. In order to optimize the modulation signal and the system performance, it is necessary to lock the bias point of the modulator to ensure that the modulator can work at a suitable working point in the transfer function curve [7]–[9]. The bias stability has received considerable attentions during the last decade. Several solutions for bias control have been proposed so far [10]–[15]. However, these methods are not suitable to use in CV QKD, in which two or more cascaded LNMZ intensity modulators are required to achieve an extinction ratio more than 80 dB. The error signal with enough signal to noise ratio is difficult to achieve due to the strong attenuation of the extinction part of the light pulse.

For the generation of HER light pulses, the LNMZ modulator should be driven by a high performance pulse generator. The commercial pulse generators usually suffer from a big size and high cost, and the pulse parameters are generally controlled via the interface of GPIB or USB. These control methods often cost a longer time than directly digital I/O controlling. Above issues of the commercial pulse generators hinder their applications in the CVQKD system.

In this paper, we propose a dither free, high stable bias locking technique and design a small size, easily integrated, cost effective pulse generator based on delay line chips. By combining them with the LNMZ modulators, we demonstrate experimentally that HER light pulses can be generated stably from cw light, which are suitable for CV QKD system.

Manuscript received January 30, 2015; revised April 1, 2015 and April 22, 2015; accepted April 23, 2015. Date of publication April 28, 2015; date of current version May 8, 2015. This work was supported in part by the National Natural Science Foundation of China under Grant 61378010, in part by the Natural Science Foundation of Shanxi Province under Grant 2014011007-1, and in part by the Program for the Outstanding Innovative Teams of Higher Learning Institutions of Shanxi. *(Corresponding author: Yongmin Li.)*

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Digital Object Identifier 10.1109/JQE.2015.2427031

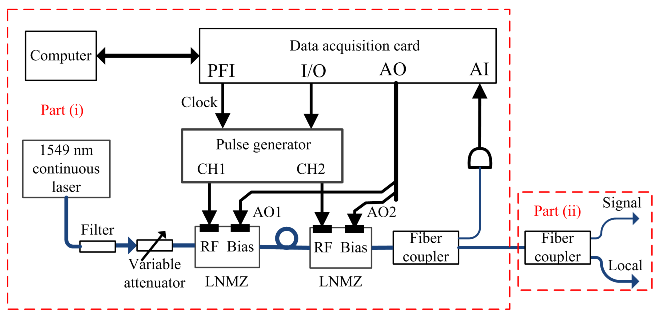

Fig. 1. Schematic diagram of the setup to generate HER light pulses.

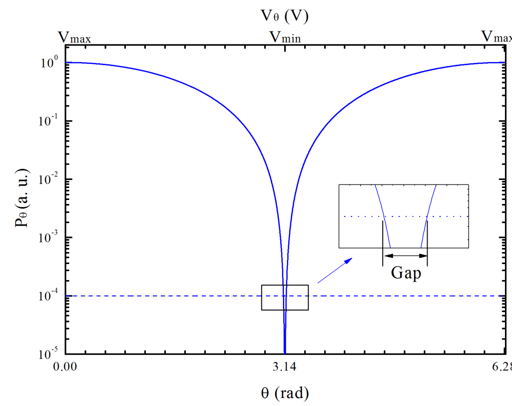

Fig. 2. Transmitted optical power of a Mach-Zehnder modulator in terms of the relative phase or bias voltage.

II. The Technique of Bias Voltage Locking

In this part, we firstly introduce the setup of generating HER light pulses. Then the detailed bias point locking technique is presented. At last, we give the locking result of one intensity modulator.

A. The Setup of HER Light Pulses Generation

The setup of generating HER light pulses is shown in Fig. 1. The cw light field from a 1549 nm laser is modulated by two cascaded LNMZ intensity modulators (M1, M2). A filter is used to suppress the fluorescence and a variable attenuator is used to tune the power of laser. The modulators have a nominal extinction ratio of 40 dB (MXER-LN-10, Photline). So an extinction ratio of about 80 dB is expected if two cascaded modulators are employed. The modulators have two input ports. One is low frequency input port with high input impedance of 1 MΩ, the other is the radio frequency (RF) input port with low input impedance about 50 Ω. The high impedance input port can be used for bias control with a low frequency bias voltage and we call it bias port hereafter. A 90/10 polarization maintaining fiber coupler is used to split ten percent of the laser beam to monitor the light intensity with a PIN photo-detector. The electric signal generated by the detector is acquired by data acquisition (DAQ) card through analogue input (AI) port and then processed by a computer. The generated feedback bias voltages from the analogue output (AO) ports are applied directly to the bias port of the modulators. The programmable function input (PFI) ports are used to generate internal clock signals for the pulse generator.

Compare with the internal modulation in which the laser diode is directly driven by electronic signals, the external modulation method presented here can generate light pulses with a longer coherence length which can minimize the interference deviation introduced by the path difference between the signal and local beams. Due to the poor coherence characteristics of internal modulation, the tolerance of the path difference is usually less than several millimeters.

B. The Method of Generating HER Light Pulses

For a LNMZ modulator, the output optical power in terms of the input optical power can be written as

$$P_{out} = P_{in} T \left[\cos(\theta) + 1\right]/2, \tag{1}$$

where T is the maximum transmission coefficient of the modulator taking into account the intrinsic insertion loss of the device, θ is the phase bias [5], [6]. When a bias voltage V_θ is applied, the output P_θ can be rewritten as

$$P_\theta = P_{in} T \left\{\cos\left[\pi \left(V_\theta - V_{\max}\right)/V_\pi\right] + 1\right\}/2, \tag{2}$$

where $V_{\max}$ is the voltage corresponds to a maximum transmission of modulator, and V_π is the half-wave voltage. The minimum transmission voltage $V_{\min}$ satisfies the following relationship

$$V_{\min} = V_{\max} + V_\pi. \tag{3}$$

In Fig. 2, the output power versus θ or V_θ is given in blue solid curve where $P_{in} T$ has been normalized to one and $V_{\max}$ is set to zero. When the voltage V_θ approaches to V_π, there will be a higher extinction ratio. For example, the voltages between $V_{3.122}$ to $V_{3.161}$ corresponds to an extinction ratio range of larger than 40 dB (below the grid line as shown inset of Fig. 2). For a half wave voltage of 7 V, the gap bandwidth is determined to be 87 mV. It is known that $V_{\min}$ is drifting with time and temperature slowly [9]–[12], which is about several millivolts per minute in our experimental environment. Under this situation, if the center voltage of the gap can be acquired and applied to the bias port, the extinction ratio can stay higher than 40 dB for more than ten minutes which determines the locking period of the bias locking technology proposed below.

In CV QKD, the power of LO pulse is around 10^8 photons per pulse and an extinction ratio larger than 80 dB is necessary to eliminate the leakage from LO pulse to signal pulse. Conventional LNMZ modulators have an extinction ratio less than 40 dB, therefore, two or more cascaded LNMZ intensity modulators are required. In this case, the extinction part of the light pulse from the second modulator will be extremely weak and it is a challenge to obtain the desired feedback signal. This hinders the suitability of various methods proposed so far [10]–[15]. Here, we proposed a bias locking method which is capable of locking two or more cascaded LNMZ modulators. The technique involve two parts, the first is the scanning and locking part which consumes about one hundred millisecond, the second is transmission part which lasts about one minute during which the quantum signals are transmitted.

The dynamic output voltage range of an ordinary photo-detector is usually less than 40 dB. For a HER modulator (40 dB or more), the output voltage around extinction point is almost dominated by the electronic dark noises of the detector. From above analysis, we can see that it is difficult to measure the voltage $V_{\min}$ accurately. To solve this problem, we propose to do a ten orders polynomial fitting to the measured voltage data. It is found that residue value of the fitting can be as small as 10^{-6} V^2. In this case, the fitting will provide an accurate and smooth curve similar to the blue curve in Fig. 2, and the voltage $V_{\min}$ with accuracy less than one millivolt can be inferred.

To lock two cascaded LNMZ modulators, a successive scanning method is utilized. Firstly, M2 is set at the maximum transmission point and M1 is scanned to acquire the values of $V_{\min 1}$ and $V_{\max 1}$. Secondly, M1 is set at the maximum transmission and M2 is scanned to acquire the values of $V_{\min 2}$ and $V_{\max 2}$. Finally, the voltages of $V_{\min 1}$ and $V_{\min 2}$ are applied to the corresponding modulators, respectively. Repeating above steps at a time interval of minutes can maintain the two modulators in the state of bias locking in a long-term. Once the bias voltage is locked, the electronic pulses can be applied to the RF ports of the modulators to generate HER light pulses. This approach can also be extended to lock cascaded LNMZ modulators at any phase point by applying a voltage

$$V_{\theta} = V_{\max} + \theta V_{\pi}/\pi. \tag{4}$$

In order to acquire $V_{\max}$ and $V_{\min}$, the scan voltage range should be larger than V_{π}. To achieve a shorter scan time in the bias locking, a scan voltage interval about 20 mV and a scan rate of 250 kHz were adopted (the half wave voltage is about 7 V). The resulting scan voltage points are 350 and scan time is about 1.4 milliseconds. The fitting time depends on the scan voltage points, the less the scan voltage points are, the shorter the fitting time is. For 350 points, the fitting time is about 40 milliseconds.

C. Experimental Results of Bias Locking

To test the locking result of LNMZ intensity modulator, a power meter with a dynamic range of 70 dB is used. The output range and resolution of the DAQ card is ±10 V and 16 bits, respectively. This results in an output voltage precision of 0.6 millivolt which is enough for the bias locking.

The bias locking results for one LNMZ modulator is shown in Fig. 3 with a duration time of one hour. The blue square dot line is the extinction ratio curve without bias locking, i.e. there is only a constant bias voltage applied on the bias input port. The black circle dot line is the extinction ratio using directly the measured bias voltage. It is clear that there are significant fluctuations in the extinction ratio curve due to the limited accuracy of $V_{\min}$. The red star dot line is the extinction ratio result using the method of bias voltage fitting, and a HER larger than 45 dB can be achieved stably using one intensity modulator. The dynamic extinction ratio of HER light pulse using two cascaded LNMZ intensity modulators is measured with a specially designed setup which is introduced in part IV.

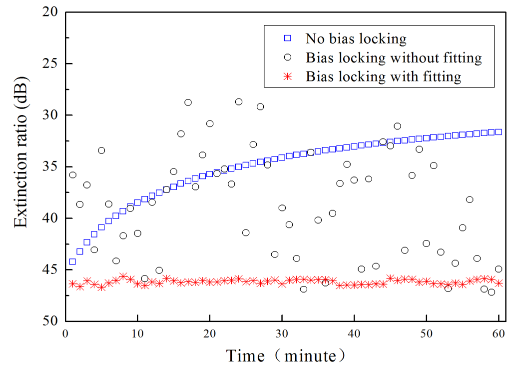

Fig. 3. The extinction ratio of the LNMZ intensity modulator with different locking methods or free running.

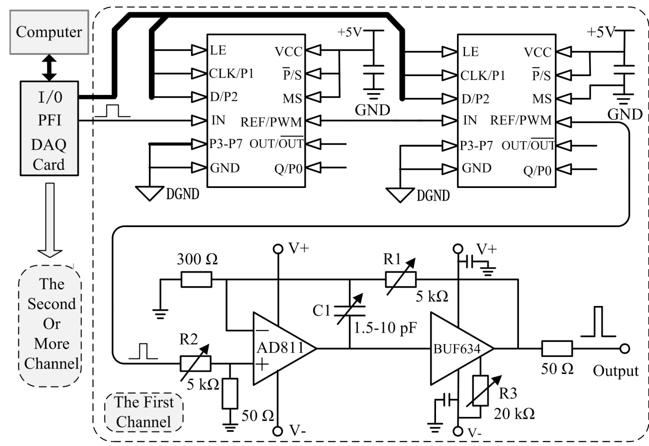

Fig. 4. Schematic diagram of the pulse generator.

III. Pulse Generator

With the above method of bias locking, the bias points of two or more cascaded LNMZ intensity modulators can be locked stably. In order to generate HER light pulses, a compact, low noise, and cost effective pulse generator with direct digital I/O control interface is designed to drive the modulator. The pulse generator is based on a hybrid design which includes a digital part and an analogue part.

A. Digital Part of Pulse Generator

The digital part is mainly composed of delay line chips DS1023. This kind of chip has two modes. It can be used not only as a delay line chip to delay pulse signals, but also can be used as a pulse width modulation chip to generate pulses with programmable pulse width. Fig. 4 is the schematic diagram of our pulse generator. High logic level on the ms pin enables two DS1023-100 chips to work in the pulse width modulated mode. The clock signal from the PFI port of the DAQ card can trigger the DS1023-100 chip to generate pulse width modulation through input pin IN. Low logic level on the MS pin enable the DS1023S-500 chip to work in the delay mode. High Logic level on the $\overline{P}/S$ pins makes the DS1023 chip to work in the serial mode. The pulse width and delay time can be programmed by 8-bit value using the clock input pin CLK, data input pin D, and input latch enable pin LE. Unused input pins (P3-P7) are connected to the GND to avoid electric disturbance. They aren't allowed to float since the DS1023 is a CMOS design. The pin Q/P0 that outputs the serial data signal of pin D should float if unused. To achieve a low noise performance, the digital ground DGND and analog ground GND are connected with a 0 Ω resister, and the bypass capacitors that connected to the pin VCC are close to each chip.

The digital pulse width can be adjusted from 1 ns to 255 ns with a precision of 1 ns for the chip DS1023-100, which means the digital part is capable of achieving a pulse repetition rate as high as 1 GHz. The pulse can be delayed from 0 to 1275 ns with a precision of 5 ns. A longer delay time and higher precision can be obtained by cascading two or more different types of DS1023 chips. Each pulse generator channel has a similar structure, and the number of channels can be extended easily according to the number of modulators. In our experiment, two channels are used and their delays differs 15 ns which will compensate the optical delay of 3 meters pigtail fiber between the two LNMZ modulators. It is noted that the voltage and current of the output electronic pulse from the digital part of the pulse generator is not high enough to drive the LNMZ modulator. The Analog amplifiers are required to amplify the output signal of the digital part.

B. Analog Part of Pulse Generator

The schematic of the analog part is shown in the lower part of Fig. 4. Two chips are included, a high speed buffer BUF634, and a low noise, wide bandwidth operation amplifier AD811 which works in the noninverting amplifier mode. The BUF634 is embedded inside the feedback loop of the AD811 to increase the output current, meanwhile, the BUF634's offset voltage and other errors are corrected by the feedback of the AD811. A variable capacitor is used to ensure that the BUF634's phase shift remain small throughout the loop gain of the circuit and improve the stability of the amplifier. In order to make the circuit works in a stable condition and avoid excessive ringing, the total gain should be larger than four. The variable resistors R2 and R3 are used together to change the output voltage while keep the gain intact. For example, when a lower output voltage is desired, one can adjust the resistor R3 to a smaller value, at the same time the resistor R2 is also required to be adjusted to ensure the gain is larger than 4. It means that the output voltage could be changed without changing the total gain. Furthermore, the gain could be adjusted without changing the output voltage. When the gain varies, the bandwidth of the analog circuit also changes since the gain bandwidth product is constant. It will affect the slope time and electronic noise of the output pulses. So the variable resistors R2 and R3 can also be combined together to tune the rise or down slope time of the output pulses. For example, a longer slope time can be achieved by decreasing the bandwidth of the analog circuit, and the electronic noise is also decreased simultaneously. The slope time can also be tuned via adjusting the bandwidth of BUF634. In CVQKD, proper slope time of the pulse can improve the stability of the homodyne detector and decrease its electronic noise [4], [16], [17].

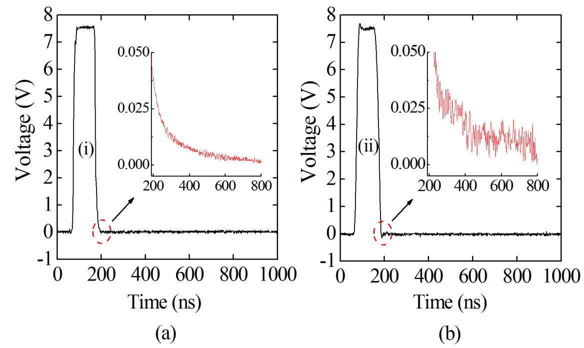

Fig. 5. The electric pulses generated by the pulse generators. (a): the results of our pulse generator; (b): the results of commercial pulse generator. The insets show the details of the falling edge of the pulse.

The pulse generator could provide maximum voltage of 12.5 V (larger than the half wave voltage of modulator) and maximum current up to 250 mA with a 50 ohm load. The minimum rise and fall time of the pulse generator can reach 10 ns and the minimum pulse width that the analog part can generate is 20 ns. Thus the maximum repetition rate of the pulse generator is 50MHz. The pulse width can be tuned from 20 ns to 255 ns and the delay range can be tuned from 0 to 1275 ns with a precision of 5 ns. The size of pulse generator is 11cm×4cm×1cm.

C. The Electric Pulse Generated by Our Pulse Generator

Fig. 5(a) illustrates the output electric pulses generated by our pulse generator, which are recorded by an oscilloscope with 1 GHz bandwidth. For comparison, the output of a commercial pulse generator (AV-1000-C, Avtech Electrosystems Ltd.) is also given in Fig. 5(b). The full width at half maximum of the two pulses is both 100 ns. The flat top part of pulse (i) in the left figure is flatter than that of pulse (ii). The electronic signal after the pulse is given in detail in the inset of each figure; it is obvious that our pulse generator exhibits a lower electronic noise.

The pulse generator is specially designed for CV QKD system with emphasis on its performance of repetition rate, programmable pulse width and delay, output voltage and current, low electronic noise, small size, easy integration and low cost. Furthermore, shorter pulse width and higher repetition rate can be achieved by using faster slew rate amplifier and buffer. However, the electronic noise will increase correspondingly due to higher bandwidth.

IV. Experimental Generation and Measurement of Stable and HER Light Pulses

In order to detect the dynamic extinction ratio of the light pulses generated by two cascaded LNMZ intensity modulators, the setup of part (ii) in Fig. 1 is replaced by the setup of part (iii) in Fig. 6. The HER light pulses are injected into three cascaded 30 dB LNMZ intensity modulators followed by a single photon detector (IDQ 201, ID Quantique) operated in a gated mode. Here the intensity modulators applied with a constant bias voltage are employed to block the strong light

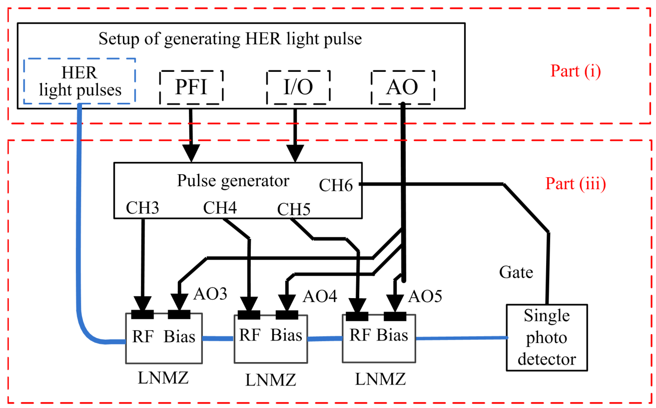

Fig. 6. Schematic diagram of the setup to detect the extinction ratio of light pulses.

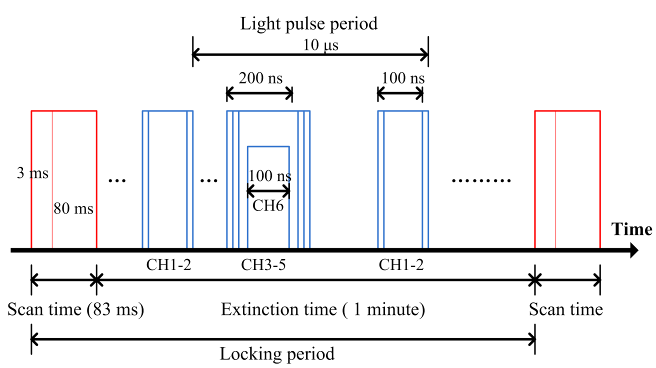

Fig. 7. Schematic diagram of the time structure.

pulses to avoid damage of the single photon detector, at the same time to open a window to the extinction part of the HER light pulses. A pulse generator with four channels is designed in which three channels provide the electronic pulses for the intensity modulators, and the forth channel acts as an external trigger signal for the single photon detector. The power of the HER light pulse with a width of 100 ns is adjusted to 10^8 photons per pulse. The insertion losses of the two HER LNMZ intensity modulators, fiber couplers, and three LNMZ 30 dB intensity modulators are 9.1 dB, 1.6 dB, and 10.2 dB, respectively.

To illustrate the measurement method clearly, a schematic diagram of the time structure is given in Fig. 7. The duration of the scan time is 83 ms, which mainly includes two parts: the part of voltage scanning (3 ms) and the part of of bias voltage fitting and applying (80 ms). The duration of the extinction time is 1 minute. In this period the HER light pulse with a repetition rate of 100 kHz (limited by the repetition rate of the single photo detector) is generated. The width of the electronic pulses output by CH1 and CH2 is 100 ns, the pulses from the two channels have a time difference of 15 ns to compensate the light path of the pigtail fiber between the two HER LNMZ modulators. The 200 ns electronic pulses output by CH3, CH4 and CH5 (there are also time differences between them to compensate the light paths of the pigtail fibers between the modulators) are used to open a window for the single photon detector which works in the external gated mode.

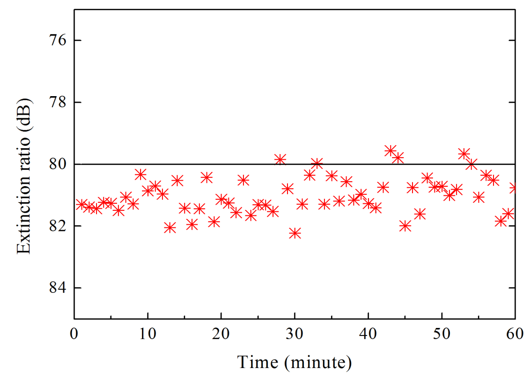

Fig. 8. The extinction ratio of the light pulses generated by two cascaded LNMZ intensity modulators.

The width of the trigger signal generated by CH6 is 100 ns, which is in the middle of 200 ns window. The gate width of the single photon detector is set to 100 ns and the photon detection probability is 10%.

The extinction ratio can be calculated according to the measured photon counts per second, the expression can be written as

$$R = 10\,\mathrm{Log}_{10}\,[N_{LO} \cdot P \cdot F \cdot T/(N_{count} - N_{dark})], \qquad (5)$$

where R is the extinction ratio, N_{LO} is photon number per pulse of the LO beam (10^8), P is the photon counting probability of single photon detector (10%), F is the repetition rate of light pulse (100 kHz), which is mainly limited by the maximun repetition rate of single photo detector, T is total transmission efficiency of the fiber couplers and three 30 dB LNMZ intensity modulators ($10^{-1.18}$), N_{count} is measured photon counts per second with a mean value of 735, N_{dark} is the number of dark counting per second with a mean value of 198. The measured extinction ratio of the HER light pulses is plotted in Fig. 8. We can see that the dynamic extinction ratio of the HER light pulse can reach 80 dB.

V. Conclusion

As a conclusion, we propose and demonstrate the generation of high extinction ratio light pulses. Firstly, a high precision bias control technique is developed which can reduce the locking time greatly and achieve the desired bias voltage with a high accuracy. Then, based on delay line chips, a low noise, cost effective, easily integrated pulse generator is designed and constructed. Combine these method and device with the LNMZ intensity modulators, light pulses with very high extinction ratio (larger than 80 dB) can be generated in a stable fashion. The presented technique and device can meet the unique demands of CV QKD system. We believe they can also find potential applications in other areas.

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