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# Single Photon Level Spectrum Measurement at Fiber Communication Band Using Frequency Up-Conversion Technology[1, 2]

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**Abstract**—We have developed a polarization independent (PI) spectrometer based on frequency up-conversion technology for single photon level spectrum measurement at the fiber communication band. To overcome the polarization dependence of the frequency up-conversion process, we use two periodically poled lithium niobate (PPLN) waveguides with a polarizing beam splitter. We experimentally study the sensitivity and resolution of the PI up-conversion spectrometer. We demonstrate the spectrometer by way of a spectrum measurement of a single photon level signal in the communication band.

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## 1. INTRODUCTION

Currently, quantum communication systems, like quantum key distribution (QKD) technology, have been developed to provide more secure communication. The systems use a single photon source, either a greatly attenuated laser source or an entangled photon pair source, to provide photons for secure transmission. In a fiber-based quantum communication system, the photon usually occupies one of two communication bands, 1310 or 1550 nm, in which the signal loss in the fiber is lowest. Therefore, single photon level spectrum measurement at these fiber communication bands becomes very important for quantum communication research.

Because of the limited performance of current single photon detectors in these wavelength ranges, such as InGaAs avalanche photo diodes (APD), spectrometers based on these technologies typically have lower sensitivity. A traditional spectrum measurement method using a tunable filter or grating to separate the components of light and an InGaAs APD to detect them is not suitable for week light because of the loss in the tunable filter or grating and the low efficiency of the detector.

To achieve a high sensitivity spectrum measurement at the communication bands, one can apply sum frequency generation (SFG) using a strong pump to up-convert the frequency of the photons from the communication wavelength to a shorter wavelength, where they can be efficiently detected by a single photon detector, such as a silicon APD, which has much higher detection efficiency and lower dark count rate than the detectors at the communications band. In this scheme, one can scan the pump laser wavelength to get the spectrum of the signal, and avoid the use of spatially dispersive elements or a tunable narrow-band filter. Previously, an up-conversion spectrometer has successfully been implemented to obtain chemical information in the near infrared range using a bulk nonlinear crystal [1–3]. To satisfy the higher sensitivity requirement for our quantum communication study, a waveguide-based up-conversion spectrometer is demonstrated [4, 5]. The sensitivity of a waveguide-based up-conversion spectrometer can reach as high as −126 dBm [4].

The frequency up-conversion is a nonlinear optics process and its quasi-phase-matching condition makes it polarization dependent. Until now, therefore, all up-conversion spectrometers were only able to measure the spectrum in one polarization orientation. In quantum communication systems, such as polarization based QKD system, the signal has many polarization states and therefore the polarization dependent up-conversion spectrometer cannot provide a full spectrum of the signal. Furthermore, since the polarization orientation of light usually changes during transmission through a fiber, the polarization sensitive up-conversion spectrometer may not be suitable. To overcome this drawback, we have developed a polarization independent (PI) up-conversion spectrometer for the fiber communication band. In this paper, we will report on the PI up-conversion spectrometer, experimentally study its sensitivity, resolution and transfer function response. We use the spectrometer to measure the spectrum of a single photon level signal at

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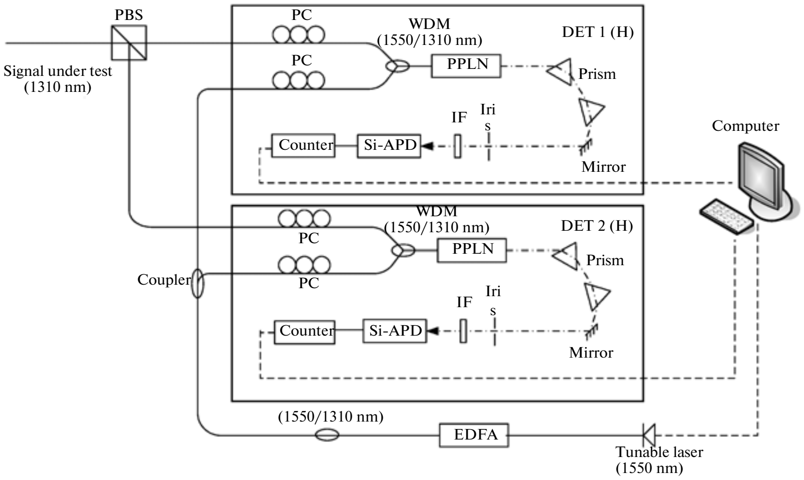

**Fig. 1.** Schematic diagram of the PI up-conversion spectrometer. PBS: polarizing beam splitter; EDFA: erbium-doped fiber amplifier; WDM: wavelength-division multiplexing coupler; PC: polarization controller; PPLN: periodically-poled $LiNbO_3$ waveguides; IF: interference filter. Solid line: optical fiber; dash-dot line: free space optical transmission; dash line: electrical line.

the 1310 nm band from a greatly attenuated laser diode and entangled photon source.

## 2. PI SPECTROMETER CONFIGURATION AND PERFORMANCE

### *2.1. Configuration*

To implement the polarization independent frequency up-conversion, one can use two methods: by double-passing the non-linear optical medium after rotating the polarization orientation of the light [6], or by using two non-linear medium to convert two orthogonal polarization components separately [7]. The first method requires the non-linear medium to transmit both polarization components of the light signal. Currently the most efficient devices for sum frequency generation (SFG) in IR range are proton-exchange based periodically poled lithium niobate (PPLN) waveguides, which are effective only for guiding the e-wave but not the o-polarized light. Therefore, we use the second method to implement our PI spectrometer.

As in our previous work [4], the PI spectrometer is also designed to measure the signal at the 1310 nm band, and PPLN waveguide is used to convert the signal at the 1310 nm band to 710 nm using a pump laser at 1550 nm. The 710 nm signal is then efficiently detected by a silicon avalanche photo diode (APD). In contrast to our previous work, the PI spectrometer uses two PPLN waveguides to up-convert both the horizontal and vertical polarization components of the signal respectively and implements the spectrum measurement for a signal of arbitrary polarization orientations. The configuration is shown in Fig. 1. The 1310 nm signals at transmitted through an in-fiber polarizing beam splitter (PBS), and the a horizontal (H) and vertical (V) components of signal are split into two fiber paths. Each component of the signal is then combined with a 1550 nm pump via a wavelength division multiplexing (WDM) coupler. The seed of the 1550 nm pump light comes from a tunable laser (New focus TLB 6328) and the light is then amplified by an erbium-doped fiber amplifier (EDFA) (IPG EAR-0.5K-C). Two 1310/1550 WDM couplers with a 25 dB extinction ratio are used to suppress the noise around 1310 nm at the output of the EDFA. The pump beam is split into two fibers via a 3 dB fiber coupler with half used for each polarization component. The input polarization state of both the signal under test and the pump are adjusted by polarization controllers respectively. The up-conversion unit is the same as implemented in [4], which uses a 5 cm PPLN waveguide (HC Photonics) as a nonlinear medium to implement the sum frequency generation (SFG). The output light of PPLN waveguide, including the 710 nm (SFG) converted signal, the excess 1550 nm pump and its second harmonic generation (SHG) at 775 nm, are separated using two dispersive prisms and the 710 nm photons are isolated and detected by a silicon APD (SPCM-AQR-14) [8]. The detection signals from the two APDs are sent to counting electronics controlled by a computer. A software program was developed to scan the 1550 nm tunable pump laser wavelength and at the same time collect the counts from the two APDs.

To measure the spectrum of two polarization components simultaneously, the quasi-phase-matching (QPM) condition in the periodically poled structure of the two PPLN waveguides should be same. In other words, for any particular frequency of the pump light, the two corresponding signal wavelengths from both polarization components being up-converted in the

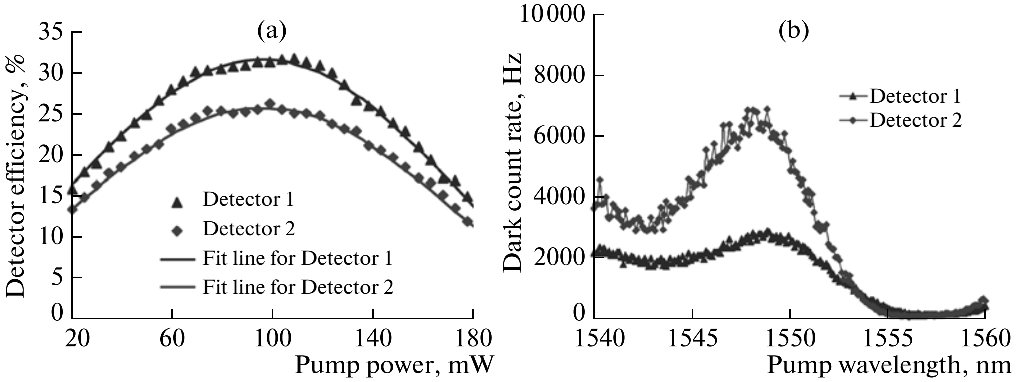

**Fig. 2.** (a) The detection efficiency as a function of CW pump power at the WDM coupler. (b) The spectrum of dark counts at different CW pump powers and with the pump turned off. The integration time for each measurement step is 500 ms.

two waveguides should be the same. To satisfy this requirement, the temperature of the two waveguides is tuned finely.

### *2.2. Sensitivity Study*

The sensitivity of an up-conversion detector is mainly determined by its detection efficiency and its dark count rate. The detection efficiency is determined by the total transmission loss, the internal conversion efficiency in the PPLN waveguides and the detection efficiency of Si-APD at the converted wavelength, which is 710 nm in our case. Detector 1 in the figure is the same as that described in [4]. The maximum total detection efficiency is 32%. The detector 2 uses another PPLN waveguide that has the same specification and comes from the same vendor. However, the second PPLN poling is not as good as the first one, and therefore its internal conversion efficiency can reach to only about 80%. As a result, the maximum total detection efficiency of detector 2 is only about 24%. The measured detection efficiency of the two detectors as a function of pump power is shown in Fig. 2a. Because the two PPLN waveguides are the same material and length, the pump power for the maximum conversion efficiency is similar at about 100 mW before the input to the WDM coupler. Considering the insertion loss of the WDM coupler and the connectors (20%), and the coupling loss between the fiber and waveguide (about 50%), the optimal internal pump power for both waveguide is about 40 mW. In our experiments, we set the EDFA to have the pump power of about 200 mW before the 3 dB coupler so that the two detectors work at their maximum efficiency. Compared to [4], a PBS is used before the signal photons enter into up-conversion detector, and therefore the PBS insertion loss will further reduce the total detection efficiency. The insertion losses of the inline PBS are 0.9 dB (H) and 0.4 dB (V), respectively. To somehow compensate for the imbalance of two detector's efficiency, we use detector 1 for the horizontal spectrum measurement, and detector 2 for the vertical measurement. Considering the loss of the PBS, the detection efficiency for two polarization orientations are about 26% (H) and 22% (V).

The dark count rate is another determining factor for the sensitivity of an up-conversion spectrometer. The dark counts are contributed mainly by three parts: the intrinsic dark counts of the Si-APD, dark counts caused by the noise in the pump tail at the signal wavelength, and dark counts caused by Raman scattering [4]. In addition, QPM-grating disorder may cause parametric fluorescence and thus an increase in the dark count rate [9]. Figure 2b shows the spectrum of the dark count noise of the two up-conversion detectors when the pump wavelength scans from 1540 to 1560 nm. Although the two detectors use the same type of waveguide, the same pump wavelength and Si-APDs, the dark count rate of detector 2 is much higher than that of detector 1. It is believed that the parametric fluorescence caused by the QPM-grating disorder of the waveguide in detector 2 contributes to the difference in noise. In the experimental set up, when the power and polarization of the pump are kept unchanged, the dark count spectrum is very stable. Therefore, we can subtract the dark counts from the measured spectrum of the signal. In that case, only the deviation of the dark counts affects the measurement result.

The sensitivity is jointly limited by the detection efficiency and the deviation of the dark counts. The detection efficiency for the two polarization orientations is 26% (H) and 22% (V). The dark counts have a shot noise behavior, whose deviation is equal to the square root of the average number of counts. The maximum dark count rate of the two detectors are 2500 and 6500 Hz, corresponding to 50 and 80 Hz shot noise respectively. To get a clear spectrum, the signal counts should be one order of magnitude greater than the dark count deviation. Therefore, the sensitivities for the two polarization orientations are –125 and

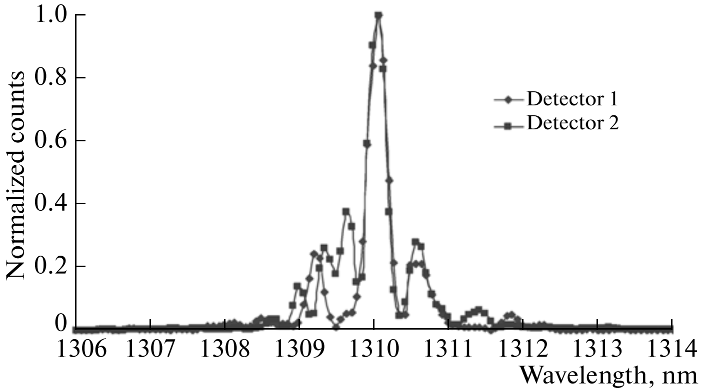

**Fig. 3.** The 1310 nm tunable laser spectrum as measured by the up-conversion spectrometer.

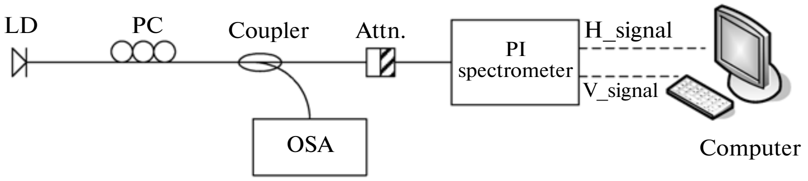

**Fig. 4.** Experimental configuration: LD: laser diode; PC: polarization control; OSA: optical spectrum analyzer; Attn.: optical attenuator.

–122 dBm. The total sensitivity of the spectrometer is –122 dBm.

### 2.3. Spectral Resolution and Transfer Function

As was discussed in [4], the resolution of the up-conversion is determined by the acceptance bandwidth of the PPLN waveguide. The bandwidth is mainly determined by the length of the waveguide: the longer the waveguide, the narrower the acceptance bandwidth. Figure 3 shows the measurement results of a 1310 nm tunable laser with a linewidth of 100 MHz by the two detectors. The results demonstrate that the acceptance bandwidths of the two PPLNs are the same at 0.2 nm (FWHM). The poling quality of a waveguide does not influence the resolution, as long as the waveguides are the same length. Therefore, the spectral resolution of the PI spectrometer is the same as that in [4], which is 0.2 nm.

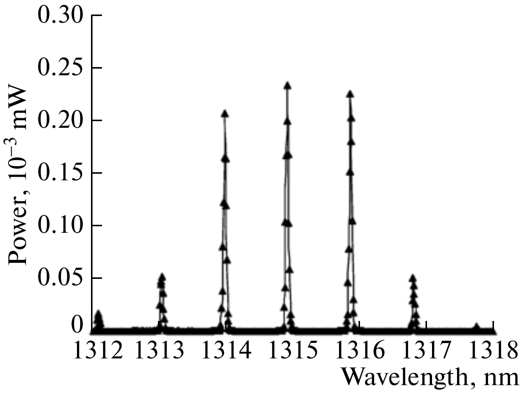

**Fig. 5.** The spectrum of laser diode (strong light) as measured by commercial OSA.

In contrast to traditional spectrometers using wavelength dispersive elements, the up-conversion spectrometer is based on the QPM condition. A ideal transfer function response of a finite-length uniform QPM grating is a sinc$^2$ function [10, 11]. This causes some side peaks in the spectrum measurement results from an up-conversion spectrometer. In addition, the imperfections in a waveguide, such as imperfect poling and period uniformity, will cause the side peaks to be larger and may even cause them to be asymmetric. From Fig. 3, the transfer function of detector 1 is similar to a sinc$^2$, while the transfer function of detector 2 has more, and larger, side peaks, which is caused by the imperfect poling of the waveguide. These sides peak will cause some "fake" small peaks in spectrum measurement. Uniform poling of the waveguide is therefore desirous to get a clear spectrum measurement.

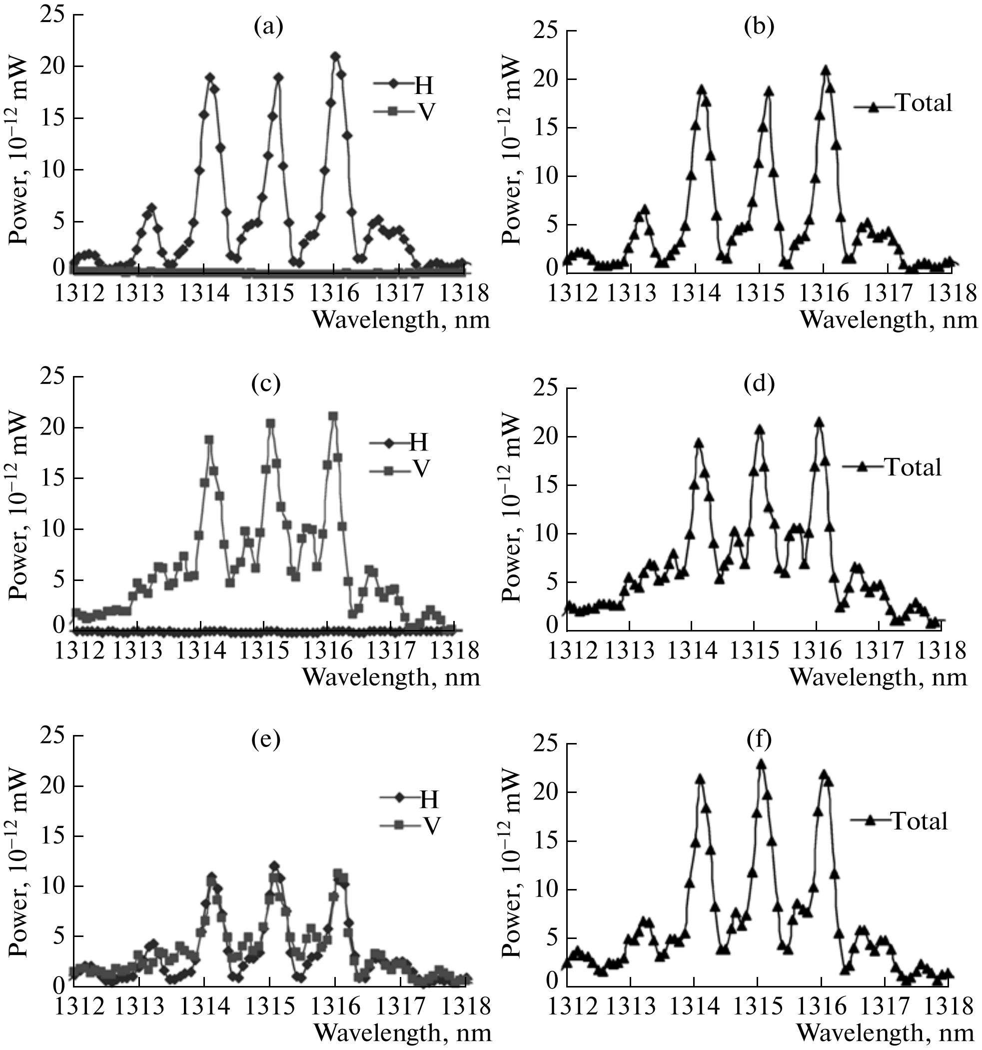

**Fig. 6.** The spectrums of greatly attenuated light with three different polarization orientations as measured by the up-conversion spectrometer. (a, b) Horizontal polarization, (c, d) vertical polarization, (e, f) 45 degree polarization.

## 3. EXPERIMENTAL RESULT

To demonstrate and verify the functionality of the PI spectrometer, we used it to measure a spectrum of a single photon level signal from a greatly attenuated laser diode and from an entangled photon source. We first measured the spectrum of the greatly attenuated light from a multi-longitude-mode laser diode (LD) at the 1310 nm band with different polarization orientations. The experimental configuration is shown in Fig. 4. A beam from the LD is coupled into a single mode fiber with its polarization orientation adjusted by a polarization controller. A 1 × 2 fiber coupler splits the beam: half the light being sent to a commercial OSA (Ando AQ-6315A) to measure the spectrum, and the other half greatly attenuated by 70 dB and then measured by the PI up-conversion spectrometer. The horizontal and vertical components are measured by two detectors and the signals are sent to a computer for processing. The spectrums of the horizontal and vertical orientation are calculated by subtracting the dark count spectrum and by factoring in the detection efficiency of the detectors. The total polarization independent spectrum is obtained by adding the two spectrums together.

Figure 5 shows the measured spectrum of the laser diode by the commercial OSA, and the spectrum does not change with the polarization state. There are three main peaks within the 1314~1315 nm range and several other small peaks in the spectrum. In the other optical path, the light is greatly attenuated by 70 dB, and its spectrum is then measured by the up-conversion spectrometer. The polarization state of the light was aligned to horizontal, vertical and 45° orientations. The results are shown in Fig. 6. The three main peaks are clearly shown in the total measurement, which is independent of the polarization state. In the

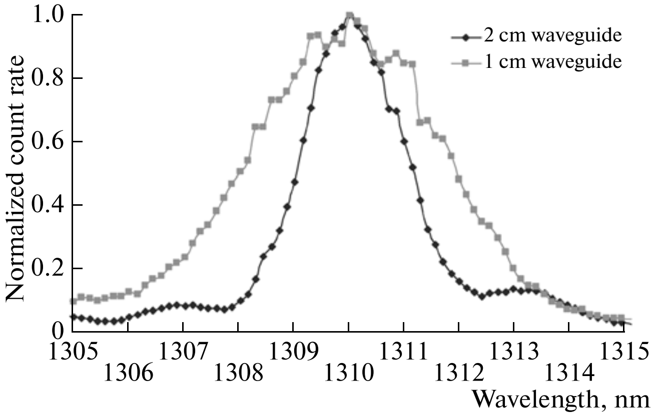

**Fig. 7.** Measured spectra of 1310 nm SPDC photons for 1 cm and 2 cm long PPKTP waveguide.

meantime, the spectrometer can also provide the spectrum in two orthogonal orientations (horizontal and vertical). However, due to the side peaks associated with the transfer function of the waveguide, especially in the detector 2, the small peaks in the spectrum are not clear. This result emphasizes the importance of uniform poling in reducing the side peaks of the transfer function and providing a clearer spectrum measurement.

We further use the spectrometer to measure the spectrum of the 1310 nm photons from an entangled photon source. The entangled source uses a PPKTP waveguide and generates 1310 and 895 nm photons by spontaneous parametric down conversion (SPDC) from 532 nm [12]. Figure 7 shows the linewidth for 1310 nm SPDC photons from different length PPKTP waveguides. According to the quasi-phase matching condition, the longer the SPDC waveguide, the narrower of the linewidth of the spectrum. The measurement results in Fig. 7 shows that the linewidth (FWHM) of the spectrum from a 1 cm waveguide is about 4 nm, and the linewidth from a 2 cm waveguide is about 2 nm, which is in good agreement with the theoretical estimation. In addition, due to the very high sensitivity of the spectrometer, the spectrum measurement process takes less than 1 min. The fast spectrum measurement also plays an important role during research by quickly finding the optimal working condition when tuning temperature and the pump wavelength of the waveguide. It demonstrates that the high sensitivity spectrometer is an efficient and important tool for research on single photon level systems, such as quantum communication.

## 4. CONCLUSION

We have developed a PI up-conversion spectrometer with two up-conversion detectors for single photon level spectrum measurement at the fiber communication band. We have experimentally studied the sensitivity and resolution of the PI up-conversion spectrometer. The sensitivity of the spectrometer is −122 dBm and the resolution is about 0.2 nm. The spectrometer not only can provide polarization independent spectrum measurement, but also can give the spectrums in two orthogonal orientations. Poling quality of waveguide is an important factor for this kind of spectrometer as many of the artifacts in the results can be traced back to the lack of poling uniformity. We used the spectrometer to measure the spectrum of a single photon level signal at the 1310 nm band from a greatly attenuated laser diode and an entangle photon source.

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