

Ultra sensitive NIR spectrometer based on frequency up-conversion detector¹

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ABSTRACT

We developed a spectrometer for signals at single photon levels in the near infrared (NIR) region based on a tunable up-conversion detector. This detector uses a 5-cm periodically poled lithium niobate (PPLN) waveguide to convert NIR photons to a shorter wavelength that are then detected by a silicon avalanche photodiode. The sensitivity of this spectrometer is -126 dBm, which is three orders-of-magnitude higher than any commercial optical spectrum analyzer in this wavelength range. Additionally, we use two PPLN waveguides to implement a polarization-independent up-conversion spectrometer, and use it to study a fiber-based quantum communication system.

Keywords: Frequency up-conversion, Single photon detector, Infrared spectroscopy.

1. INTRODUCTION

An infrared (IR) spectrometer for weak light at single-photon levels is an important tool for many areas of research in physics, chemistry, biology and forensics [1]. As quantum communication technology has developed to implement longer distance secure data transmission using the fiber communications windows, of 1310 nm and 1550 nm, a single photon level spectrometer in this range is an useful research tool.

A traditional optical spectrum analyzer (OSA) usually uses either dispersive elements, such as prisms or diffractive gratings, or a tunable narrow-band filter, to separate and select light at different wavelengths which is then detected and recorded. For ultra-violet light, visible light and light with wavelengths shorter than 1 μm , there are many choices for detectors with excellent performance. In these regions, the detection efficiency of silicon-based detectors (or arrays) is very high while their intrinsic noise level is very low. For example, silicon avalanche photodiodes (Si-APDs) have detection efficiency as high as 70 % and a dark count rate of less than 100/second. However, silicon-based detectors do not work in the IR region. Current IR detectors either have high noise characteristics (non-cooling InGaAs array detectors), which limits their sensitivity, or need a bulky cryogenic cooling system (e.g. liquid-nitrogen-cooled InGaAs array detectors).

To achieve a high sensitivity spectrum measurement in the IR range, one can apply sum frequency generation (SFG) using a strong pump laser to up-convert the frequency of the photons from their communication wavelength to a shorter wavelength, where they can be efficiently detected by silicon based detectors,. In this scheme, one can vary the pump wavelength over a given range to obtain signal spectrum and avoid the use of spatially dispersive elements or a tunable

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narrow-band filter. An up-conversion spectrometer has successfully been implemented to obtain chemical information in the near infrared range using a bulk nonlinear crystal [2-4]. To satisfy the higher sensitivity requirement for our quantum communication work, a waveguide-based up-conversion spectrometer was demonstrated [5-6].

Frequency up-conversion is a nonlinear optical process and its quasi-phase-matching condition makes it polarization dependent. Therefore, an up-conversion spectrometer with one conversion process is only able to measure the spectrum in one polarization orientation. However, in some applications, such as polarization based quantum communication systems, 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, a polarization sensitive up-conversion spectrometer may not always be suitable. To overcome this drawback, a polarization independent (PI) spectrometer is necessary.

We have developed an ultra sensitive up-conversion spectrometer, which uses a tunable pump source around 1550 nm to convert photons from the 1310 nm band into the 710 nm band in a PPLN waveguide and the converted photons are then detected by a Si-APD. We have further implemented a PI up-conversion spectrometer based on two waveguides. In this paper, we introduce these up-conversion spectrometers and their applications in quantum communication.

2. CONFIGURATION OF UP-CONVERSION SPECTROMETER

The configuration of our up-conversion spectrometer is shown in figure 1. Similar to the up-conversion detector that we developed previously [7, 8], the spectrometer uses a PPLN waveguide (HC Photonics) as a nonlinear medium to implement the SFG. The waveguide is a reverse-proton-exchange PPLN waveguide with magnesium oxide doping. The waveguide is 52.3 mm long (50 mm uniform grating) and both ends have an anti-reflection (AR) coating for 1310 nm, 1550 nm and 710 nm. As opposed to the PPLN waveguide used in Ref. [5, 6], which had both the input and the output fiber coupled, the waveguide used in this spectrometer has only the input end fiber (SMF-28) coupled, and its coupling efficiencies are 64 % for 1310 nm and 71 % for 1550 nm. The output end of the waveguide is not fiber coupled, but is free-space with an AR coating. This configuration not only reduces the coupling loss at the output end, but also allows us to use dispersive prisms, instead of narrow band-pass filters, to suppress the noise. This improvement yields a higher detection efficiency than that reported in Ref. [7, 8]. A tunable CW laser near 1550 nm (New focus: TLB 6321) controlled by a computer via a GPIB port provides the pump seed light. If needed, the pump seed light can be modulated into a pulse train for noise reduction or for performing time-resolution measurements. Because the pump wavelength varies during the spectrum measurement, the modulator used here should be wavelength insensitive within that range. The light is then amplified by an erbium-doped fiber amplifier (EDFA) (IPG: EAR-0.5K-C). Two 1310/1550 wavelength division multiplexer (WDM) couplers, each with an extinction ratio of 25 dB, are used to suppress noise around 1310 nm at the output of the EDFA. The amplified pump is then combined with the 1310 nm signal beam being measured in a third WDM coupler. The combined signal and pump are then coupled into the PPLN waveguide. The input polarization state of both the signal and the pump are adjusted by the polarization controllers, PC1 and PC2 respectively, before the coupler. The output light of the PPLN waveguide, consisting of the newly generated photons at 710 nm (SFG), the pump at 1550 nm and its second harmonic generation at 775 nm, are separated by two dispersive prisms. The pump light (1550 nm) is clearly separated after the first prism and blocked by a beam block. Because the 775 nm is close to the signal wavelength at 710 nm, a second dispersive prism is used to further separate them and then an adjustable iris is used to block the 775 nm beam. Because all the light beams are linearly polarized and their polarization is aligned with the p-polarization direction of the prisms, there is almost no intrinsic loss when the incident angle of the 710 nm light is close to Brewster's angle. A 20 nm band-pass filter (Omega Optical, Inc.: 3RD700-720) is used to reduce other noise, such as photons leaked from the environment. The 710 nm photons are then detected by a Si-APD (PerkinElmer: SPCM-AQR-14) and output signal is sent to the computer. The computer counts the Si-APD pulses while controlling the wavelength of the tunable laser to obtain the signal spectrum in real time.

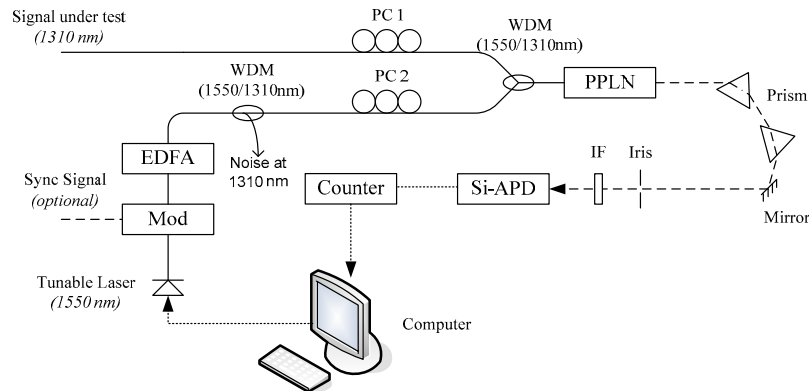


Figure 1. Schematic diagram of the up-conversion spectrometer. Mod: Wavelength insensitive modulator; EDFA: Erbium-doped fiber amplifier; WDM: Wavelength-division multiplexing coupler; PC: Polarization controller; PPLN: Periodically-poled LiNbO₃ waveguide; IF: Interference filter. Solid line: optical fiber; dash line: free space optical transmission; dot line: electrical line.

To implement PI frequency up-conversion, one can use two methods: double-passing the non-linear optical medium after rotating the polarization orientation of the light [9], or using two non-linear medium to convert the two orthogonal polarization components separately [10]. 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.

Our PI spectrometer uses two PPLN waveguides to up-convert both the horizontal and vertical polarization components of the signal to implement the spectrum measurement for a signal of arbitrary polarization orientation. The configuration is shown in Figure 2. The 1310 nm signals are transmitted through an in-fiber polarizing beam splitter (PBS), and the horizontal (H) and vertical (V) components are split into two separate fiber paths. Each component is then combined with the 1550 nm pump, which has been split into two fibers via a 3 dB fiber coupler, via a WDM coupler. Each signal component path has a separate up-conversion PPLN, prisms and Si-APD detector chains that feed into the computer.

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 the same. In another words, for any particular frequency of the pump light, the two corresponding signal wavelengths from both polarization components being up-converted in the two waveguides should be the same. To satisfy this requirement, the temperature of the two waveguides is finely tuned.

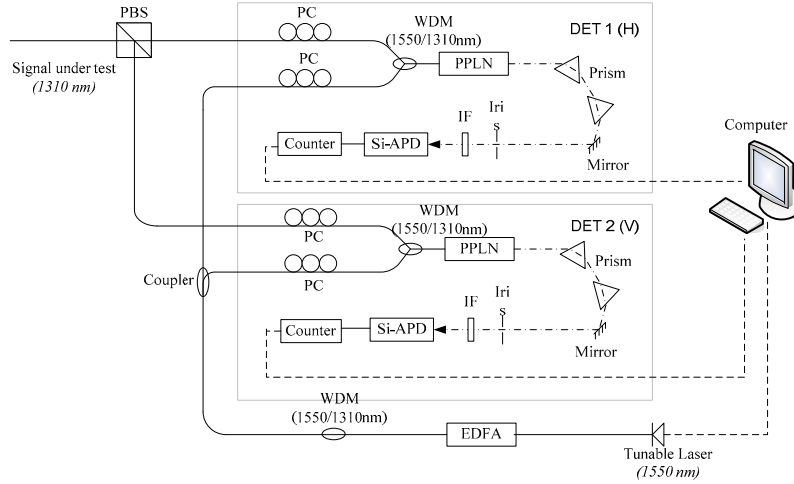


Figure 2. Schematic diagram of the PI up-conversion spectrometer. PBS: Polarizing beam splitter; others are same in Figure 1.

3. UP-CONVERSION SPECTROMETER PERFORMANCE

3.1. Sensitivity study

High sensitivity is the main objective of the up-conversion spectrometer. The sensitivity is mainly determined by the detection efficiency and the dark count rate. The detection efficiency can be estimated by the following formula [11-13]:

$$\eta_o = \eta_{loss} \cdot \eta_{det} \cdot \eta_{con} \approx \eta_{loss} \cdot \eta_{det} \cdot \sin^2(\alpha \cdot \sqrt{P_{pump}} \cdot L) \quad (1)$$

where η_o is the overall detection efficiency of the up-conversion detector; η_{loss} is the total loss in the detector, including the component insertion loss and waveguide coupling loss; η_{con} is the internal conversion efficiency in the PPLN, which can be estimated as shown in Eq. (1); η_{det} is the detection efficiency of Si-APD at the converted wavelength, which is 710 nm in our case. According to the specification of the Si-APD, η_{det} is about 65%. P_{pump} represents the pump power near 1550 nm, α is a constant, and L is the length of the waveguide. The maximum overall detection efficiency of detector 1 is 32 %, which corresponds to 100 % of internal conversion efficiency after we exclude the component loss, waveguide coupling loss, and the detection efficiency of the Si-APD. Although detector 2 uses another PPLN waveguide that has the same specification and comes from the same vendor, 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 Figure 3(a).

The dark count rate is another determining factor for the sensitivity of an up-conversion spectrometer. Dark counts have three main sources: 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 [7]. In addition, QPM-grating disorder may cause parametric fluorescence and thus an increase in the dark count rate [14]. Figure 2 (b) shows the spectrum of the dark count noise of the two up-conversion detectors when the pump wavelength is varied from 1540 nm 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 our 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 these known 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. Our measured maximum overall detection efficiency is 32 % and 25%, as shown in figure 3(a). For the PI spectrometer, a PBS is used before the signal photons enter the up-conversion detectors, 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 partially compensate for the imbalance of the two detector's efficiency, we feed detector 1 with the higher loss horizontal component, and detector 2 with the lower loss vertical component. Combining the loss of the PBS and the detectors for the two polarization components result in about 26 % (H) and 22 % (V) efficiencies. 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 Hz and 6500 Hz, shown in Figure 3(b), corresponding to 50 Hz and 80 Hz shot noise respectively. An up-conversion spectrometer based on the first PPLN waveguide, can result in a sensitivity limit of -126 dBm. For our PI up-conversion spectrometer, the sensitivity limit reduces to -122 dBm because of the PBS loss and low performance of the second PPLN waveguide. This sensitivity is at least three orders of magnitude better than any commercial spectrum analyzer in this wavelength region.

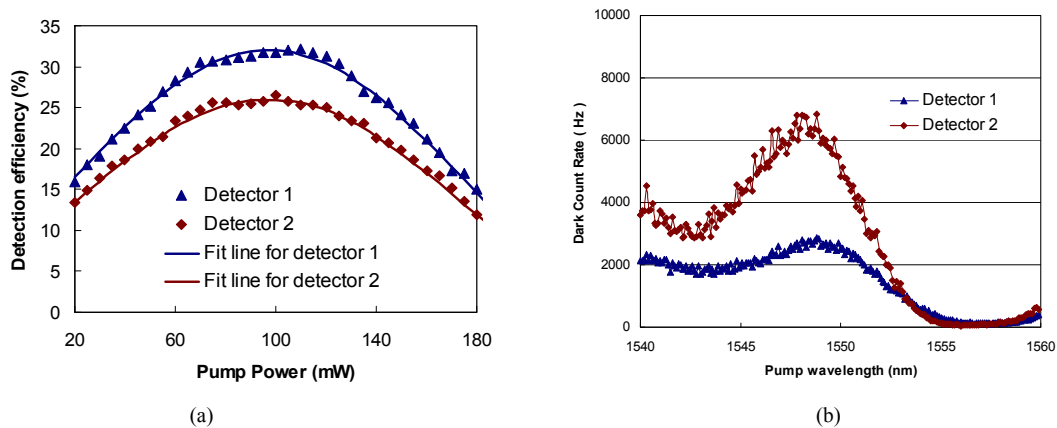


Figure 3. (a) The detection efficiency as a function of CW pump power at the WDM coupler. (b) The spectrum of dark counts at different CW pump powers and with the pump turned off. The integration time for each measurement step is 500 ms.

3.2 Waveguide transfer function and Spectral resolution

While a traditional spectrometer uses wavelength dispersive elements, our up-conversion spectrometer is based on the QPM condition. The transfer function response of a finite-length of uniform QPM grating is a sinc^2 function as given in the following equation [15, 16]:

$$P_{SFG}(\Delta k) \propto P_{pump} \cdot P_{signal} \cdot \text{sinc}^2(\Delta k \cdot L / 2) \quad (2)$$

where P_{SFG} , P_{pump} , P_{signal} are the power of SFG, pump, and signal light, L is the waveguide length, and Δk is the wave-vector-mismatching and can be calculated by the following equation:

$$\Delta k = 2\pi \times \left(\frac{n_{SFG}}{\lambda_{SFG}} - \frac{n_{pump}}{\lambda_{pump}} - \frac{n_{signal}}{\lambda_{signal}} - \frac{m}{\Lambda} \right) \quad (3)$$

where λ_{SFG} , λ_{pump} and λ_{signal} are the SFG, pump, and signal wavelengths; n_{SFG} , n_{pump} , and n_{signal} are the indices of the nonlinear material for the corresponding wavelength. Λ is the poling period for the m^{th} order quasi-phase-matched condition of the nonlinear PPLN waveguide.

The resolution of the spectrometer is determined by spectral bandwidth and length of each tuning step of the pump laser as well as the QPM acceptance bandwidth of a waveguide. The linewidth of the tunable pump laser is 300 kHz, corresponding to a spectral bandwidth of 2.4×10^{-6} nm. The tuning step of the pump laser used in the experiment is 0.02 nm (FWHM). The acceptance spectral width for the 5 cm long PPLN waveguide is measured to be 0.2 nm, and dominates the resolution of the up-conversion spectrometer because it is much larger than the spectral bandwidth and tuning resolution of the pump laser. According to Eq. (2) and Eq. (3), the bandwidth of QPM crystal is inversely proportional to the waveguide length L . Therefore, a longer waveguide will result in a better spectral resolution. Due to fabrication tolerances, it is difficult to get a PPLN waveguide longer than 5 cm. In our experiments, the two waveguides are the same length, 5 cm, and thus the spectral resolution of our up-conversion spectrometer is limited to about 0.2 nm under current technological conditions, as shown in figure 4. A better spectral resolution can be realized when longer QPM structures are available.

In addition, the sinc^2 transfer function causes some side peaks to appear in the spectrum measurements. Waveguide imperfections, such as imperfect poling and period uniformity, will cause the side peaks to be larger and may even cause them to be asymmetric. From Figure 4, 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 side peaks will cause some small “fake” peaks in spectrum measurements. Uniform poling of the waveguide is therefore desirable to get a clear spectrum measurement.

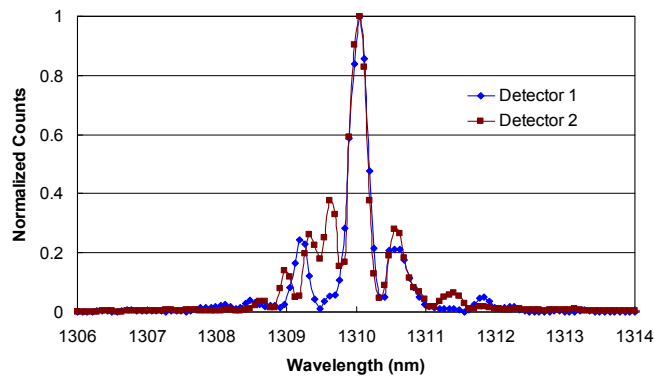


Figure 4. The 1310 nm tunable laser spectrum as measured by the up-conversion spectrometer.

4. Experiment result

To demonstrate and verify the functionality of our spectrometer, we used it to measure the 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 Figure 5. A beam from the LD is coupled into a single mode fiber with its polarization orientation adjusted by a polarization controller. A 1x2 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 known dark count spectrum and by factoring in the different detector efficiencies. The total polarization independent spectrum is obtained by adding the two spectra together.

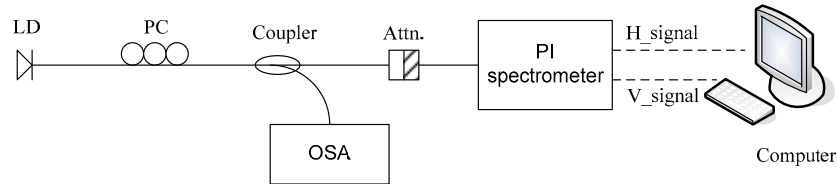


Figure 5. Experimental configuration: LD: Laser diode; PC: Polarization control; OSA: Optical spectrum analyzer; Attn.: Optical attenuator.

Figure 6 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 to 1316 nm region 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 the horizontal, vertical and 45° orientations. The results are shown in Figure 7. The three main peaks are clearly shown in the total measurement, which is independent of the polarization state. In the 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 in providing a clearer spectrum measurement.

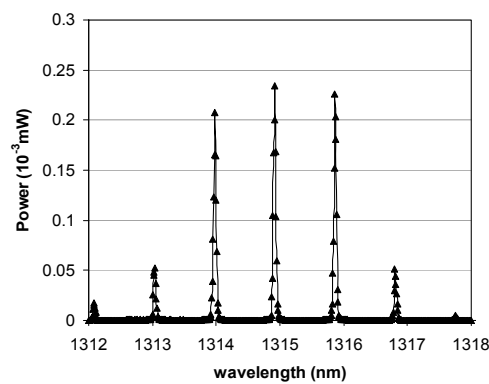


Figure 6. The spectrum of laser diode (strong light) as measured by commercial OSA.

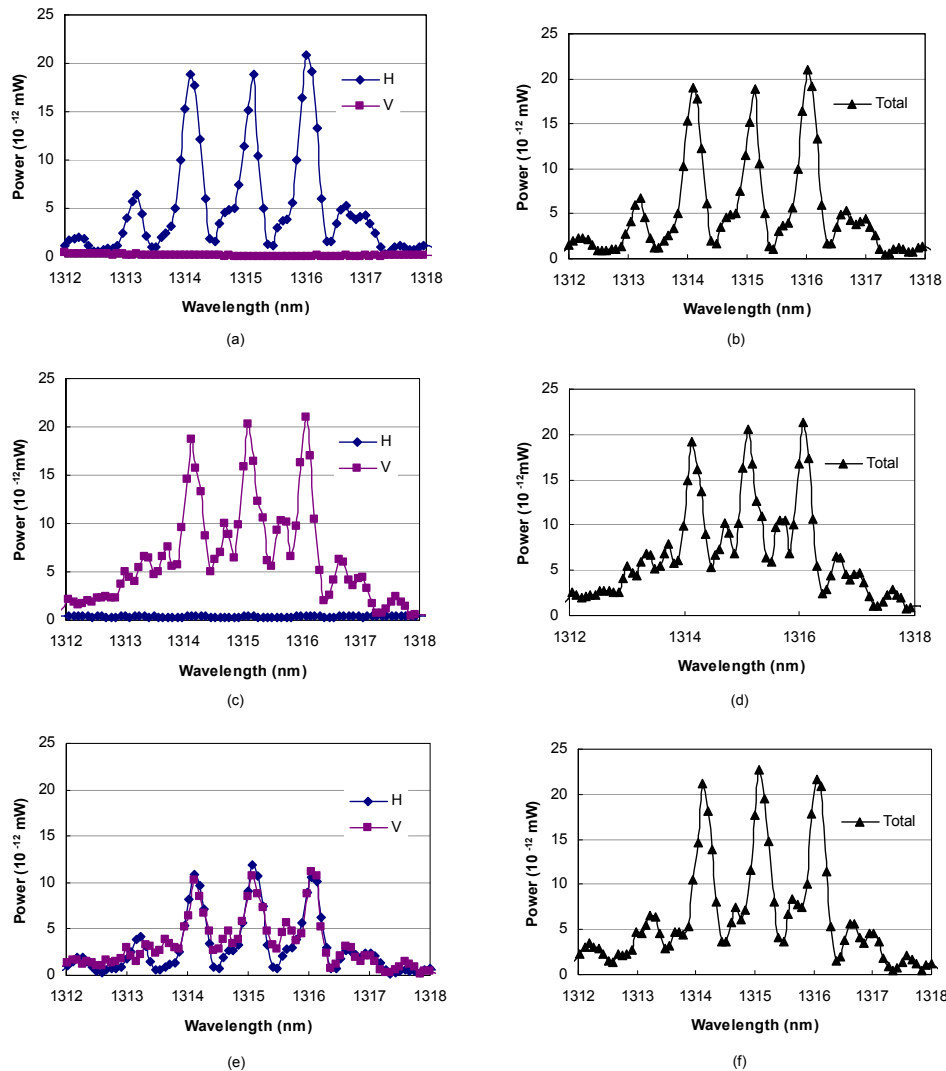


Figure 7. The spectra of greatly attenuated light with three different polarization orientations as measured by the up-conversion spectrometer. (a) and (b): horizontal polarization, (c) and (d): vertical polarization, (e) and (f): 45 degree polarization.

We further used 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 nm and 895 nm photons by spontaneous parametric down conversion (SPDC) from 532 nm [17]. Figure 8 shows the linewidth for the 1310 nm SPDC photons from different length PPKTP waveguides. According to the quasi-phase matching condition, the longer of the SPDC waveguide, the narrower of the linewidth of the spectrum. The measurement results in Figure 8 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 minute. This 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 systems.

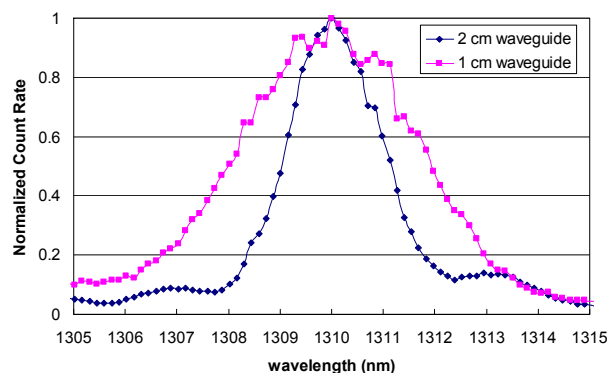


Figure 8. Measured spectra of 1310 nm SPDC photons for 1 cm and 2 cm long PPKTP waveguide.

5. CONCLUSION

We have developed an ultra sensitive up-conversion spectrometer with a PPLN waveguide for single photon level spectrum measurement. The sensitivity of the spectrometer can be as much as -126 dBm. We further implemented a PI up-conversion spectrometer. Because of the loss of a PBS and the low performance of our second PPLN waveguide, the sensitivity limits of our PI spectrometer reduces to -122 dBm, but it is still much better than any commercial spectrometer in this wavelength range. The PI spectrometer not only can provide polarization independent spectrum measurements, but also can record spectra in any one of two orthogonal orientations. Poling quality of the 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 spectra of single photon level signals at the 1310 nm band from a greatly attenuated laser diode and an entangled photon source.

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