Experimental study of high sensitivity infrared spectrometer with waveguide-based up-conversion detector[1]

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Abstract

We developed an up-conversion spectrometer for signals at single photon levels near the infrared region based on a tunable up-conversion detector which uses a periodically poled lithium niobate (PPLN) waveguide as the conversion medium. We also experimentally studied its characteristics including sensitivity, dark count rate, spectral scan speed, the signal transfer function of the waveguide, and polarization sensitivity. The overall single photon detection efficiency of the up-conversion spectrometer is about 32%. With its ultra high sensitivity the spectrometer can measure spectra for signals at a level as low as -126 dBm. We demonstrated its high sensitivity by measuring the spectrum of a greatly attenuated multimode emission from a laser diode at the 1310-nm band.

1. Introduction

An infrared (IR) spectrometer for weak light at single-photon level is a very important tool in many areas of research in physics, chemistry and biology, and may have applications in forensics. 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 or select light at different wavelengths and the selected light is then suitably detected. For UV, visible and wavelengths shorter than 1 µm, there are many choices for detectors with excellent performance. In this region the detection efficiency of silicon- based detectors (or arrays) is very high while their intrinsic noise is very low. For example, silicon avalanche photodiodes (Si-APDs) have its detection efficiency as high as 70% and a dark count rate of less than 100/second. However, the Si-APDs or other silicon-based detectors do not work in the IR region. The current IR detectors available either have high noise characteristics (no-cooling InGaAs array detectors), which limits its sensitivity, or need bulky cryogenic cooling system (liquid-nitrogen-cooled InGaAs array detectors).

To achieve highly sensitive detection for IR signals, the weak signal beam is introduced together with a strong pump source, at a fixed wavelength, into a periodically poled lithium niobate (PPLN) waveguide. The signal photons are up-converted (in terms of frequency) from the IR wavelength to a shorter wavelength by a sum frequency generation (SFG) process. The converted photons can then be efficiently detected by silicon detectors [1-5]. Only those photons, whose momentum and energy conservations requirements are satisfied with the phase-matching condition in the waveguide, can be converted and detected. Based on this principle, an up-conversion spectrometer can be constructed when a tunable pump source is used [6-8]. In this case, we can obtain a spectrum of the signal without

[1]The identification of any commercial product or trade name does not imply endorsement or recommendation by the National Institute of Standards and Technology.

using dispersive elements or tunable narrow-band filters. Furthermore, by using a pulsed pump, time-resolution spectroscopy can be conveniently realized [8].

We have developed an up-conversion spectrometer, which uses a tunable pump source around 1550 nm to convert signal photons at the 1310-nm band into the 710 nm in a PPLN waveguide. The converted photons are then detected by a Si-APD. In this paper, we will report on the up-conversion spectrometer and experimentally study its performance, including its sensitivity, maximum input signal intensity, scan speed, waveguide transfer function response, and polarization sensitivity.

2. System configuration

The configuration of the up-conversion spectrometer is shown in Figure 1. Similar to the up-conversion detector that we developed previously [4, 5], the spectrometer uses a 5-cm PPLN waveguide as a nonlinear medium to implement the SFG. A tunable CW laser near 1550-nm (New focus: TLB 6321) controlled by a computer via GPIB port provides a seed light. If needed, the seed light can be modulated into a pulse train for noise reduction or performing time-resolution measurements. Because the pump wavelength varies during the spectrum measurement, the modulator used here should be wavelength insensitive within the certain 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, of which the extinction ratio is 25 dB, are used to suppress noise around 1310 nm at the output of the EDFA. The amplified pump is then combined with a signal under test near 1310 nm in another WDM coupler. The combined signal and pump are coupled into the PPLN waveguide. The input polarization state of both the signal under test and the pump are adjusted by polarization controllers, PC1 and PC2 respectively, before the coupler. The output light of PPLN waveguide, including 710 nm (SFG), 1550 nm pump and its second harmonic generation (SHG) 775 nm, are separated by two dispersive prisms and the 710-nm photons are detected by a Si-APD (PerkinElmer: SPCM-AQR-14). An iris and a 20-nm band-pass filter (Omega Optical, Inc.: 3RD700-720) are used to reduce other noise, such as photons leaked from environment. The output count signal of APD is then sent back to the same computer. The computer controls the 1550-nm tunable laser to scan the pump light wavelength and also collects and processes the counts from Si-APD.

The quasi-phase-matching (QPM) condition in the periodically poled structure of the PPLN limits the acceptance bandwidth of the signal for a particular pump wavelength and therefore acts as a filter in the frequency domain. In theory, the longer is the QPM structure (waveguide), the narrower the acceptance bandwidth. In our case (5-cm PPLN waveguide), the measured acceptance bandwidth is 0.2 nm. Because the line-width of the 1550-nm tunable laser is just 150 KHz, the up-conversion spectrometer resolution is determined by the QPM acceptance bandwidth (0.2nm) of the waveguide. According to the QPM condition, one can get the spectrum of the signal under test by scanning the pump wavelength.

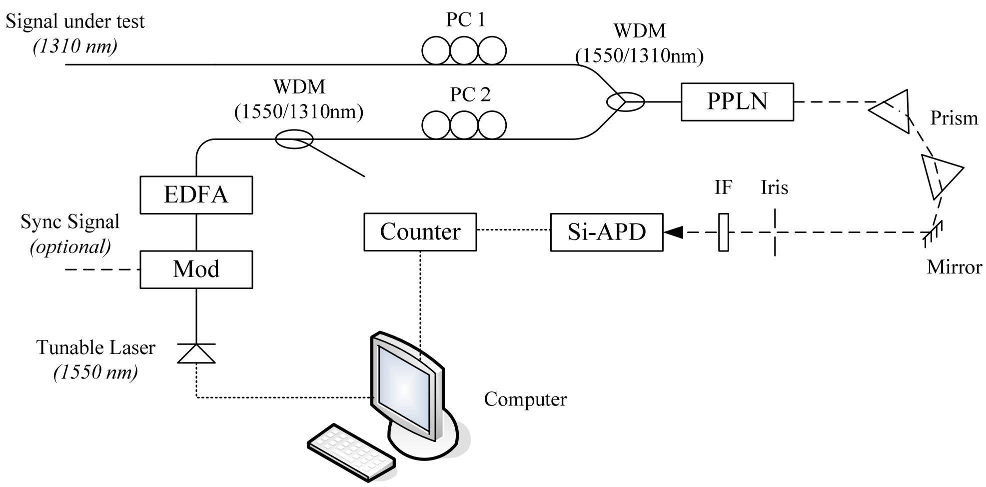


Fig. 1. Schematic diagram of the waveguide-based spectrometer. Mod: Wavelength insensitive modulator; EDFA: Erbium-doped fiber amplifier; WDM: Wavelength-division multiplexing coupler; PC: Polarization controller; PPLN: periodically-poled LiNbO3 waveguides; IF: Interference filter. Solid line: optical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

3. Performance of up-conversion spectrometer

3.1. Sensitivity of an up-conversion spectrometer

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 SFG conversion efficiency can be estimated by the following formula [1-3].

$$\eta = \frac{N_{710}}{N_{1310}} = \sin^2(\sqrt{\eta_{norm} \cdot P_{1550}} \cdot L) \tag{1}$$

Here N_{1310} denotes the number of input signal photons near 1310 nm and N_{710} denotes the number of output signal photons at 710 nm for detection. P_{1550} represents the pump power near 1550 nm and η_{norm} is a normalized internal conversion efficiency of the waveguide. The measured conversion efficiency over pump power is shown in Fig. 2 (a). The maximal overall detection efficiency is 32%, which corresponds to 100% of internal conversion efficiency after we exclude the component loss, waveguide coupling loss, and the 65% of detection efficiency of the Si-APD. The dependence of the detection efficiency on the pump power satisfies Eq. (1).

The dark count rate has been extensively studied in frequency up-conversion technology [1-5]. The dark counts are contributed mainly by three parts: the intrinsic dark counts of the Si-APD, the linearly induced noise photons that leak through the filter from the pump, and nonlinearly induced noise photons due to scattering by the strong pump. The intrinsic dark count rate is a constant, about 100 c/s in our case [9]. The linearly induced dark counts are caused by the photons in the pump tail that reaches to the signal wavelength range. We use two WDM couplers to greatly suppress this noise. The nonlinear process generating the dark counts is widely believed to be the Raman scattering process, in which a photon is generated by the pump in the signal band and then up-converted to the detection wavelength, though this has not been strictly proven. In this spectrometer, we use a 1550-nm laser as a pump, whose wavelength is longer than that of the signal under test. Because the anti-Stokes component of the Raman process is much weaker than the Stokes component, the dark count rate of less than 2500 c/s is achieved when the conversion efficiency is maximized. Furthermore, the dark count noise itself has a spectrum. Fig. 2(b) shows the spectrum of the dark count nose from 1530~1570 nm and the peak is around 1550~1555 nm. From the spectrum, the dark count rate is 100 c/s (50 counts per 500 ms) when the pump is off, which is the intrinsic dark counts of Si-APD. From Fig. 2(a) we can see that the dark count rate increases with the pump power. 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 under test. In that case, only the deviation of dark counts affects the measurement result.

The sensitivity is jointly limited by the detection efficiency and the deviation of the dark count. As we measured, the detection efficiency is 32%. The dark counts have a shot noise behavior, whose deviation is equal to the square root of the average number of the counts. The maximum dark count rate in the measurement range is about 2500 c/s, and the maximum dark count deviation is 50 c/s. To get a clear spectrum, the signal counts should be one order of magnitude greater than the dark count deviation, or 500 c/s, which corresponds to 1563 photons/s or -126dBm of the signal when we take the detection efficiency of 32% into account.

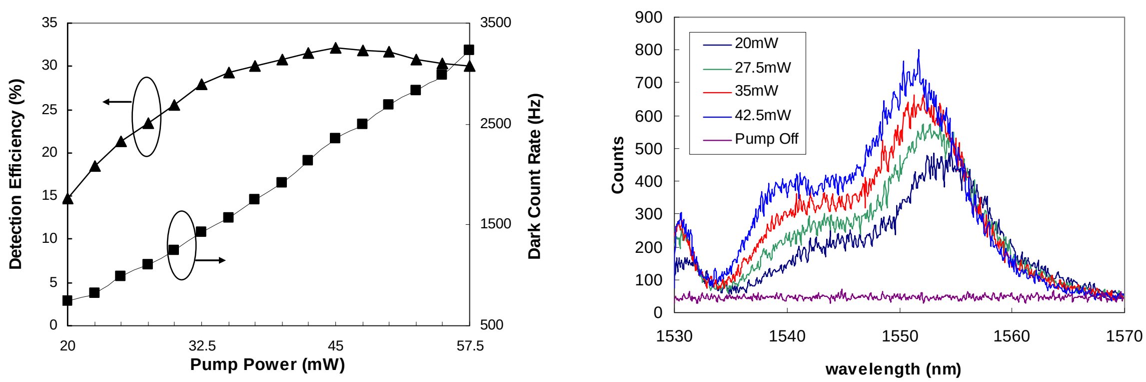


Fig. 2. (a) The detection efficiency and dark count rate as a function of pump power at the PPLN input. (b) The spectrum of dark counts at different pump powers and pump off. The integration time for each measurement step is 500 ms.

3.2. The detection "dead time" and maximum measurement intensity

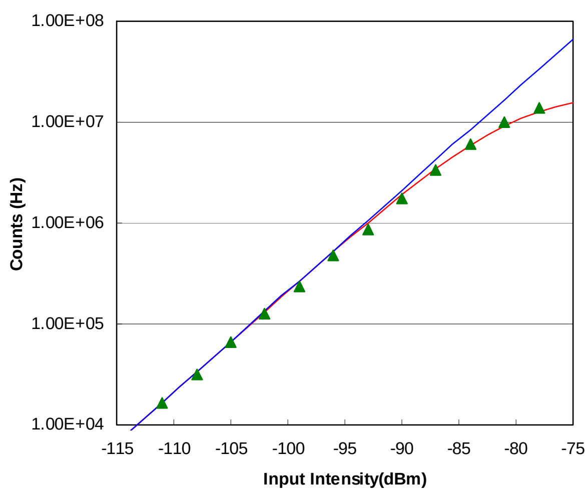
A major limitation to the maximum measurement intensity is imposed by the Si-APD and is referred to as "dead time". After the Si-APD receives a photon, the avalanche process generates an electrical output signal. The device then needs a certain amount of time (dead time, t_{dead}) to recover its initial operation state for detection of the next photon. During this period, the bias voltage across the p-n junction of the APD is below the breakdown level and no photon can be detected. This is especially significant when the intensity of the signal under test becomes stronger. When the input signal is coherent light and the photon arriving time satisfies Poisson distribution, the actual counts rate can be estimated by [4]

$$R = 1/(t_{dead} + 1/R_1) \tag{2}$$

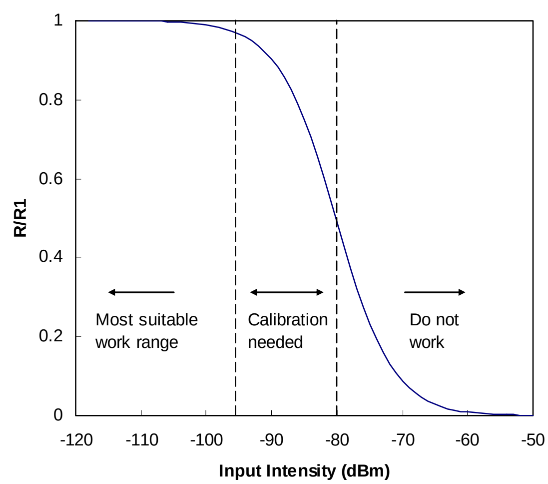
where t_{dead} is 50 ns for the Si-APD used in the spectrometer. R_1 is the detection count rate for the Si-APD assuming t_{dead} is zero, which can be calculated by:

$$R_1 = \eta \cdot I_{input} / E_{photon} \tag{3}$$

Where η is the detection efficiency, which is 32% in this spectrometer; I_{input} and E_{photon} are the intensity and photon energy of the signal under test. We used an attenuated light from a 1310-nm tunable laser (Santec: TSL-210V) to measure the count rate as a function of input intensity. The calculated value is given by Eq. (2~3) and the measured value are shown in Fig. 3(a). When the signal intensity is lower than -90dBm, the influence of the dead time to the count rate is small and negligible, but when the intensity further increases, the influence will be significant. Fig. 3 (b) shows the calculated ratio of R/R_1 as a function of the signal intensity. When the signal intensity is lower than -95dBm, the ratio is larger than 0.96 and we do not need to consider the influence of the dead-time. When the signal intensity is between -95dBm to -80dBm, the influence of the dead time is significant and the measured spectrum should be calibrated using the ratio curve (in Fig.3(b)) to recover the actual spectrum. When the signal intensity is larger than -80dBm, more than half of the signal photons are lost due to the dead time and, additionally, the Si-APD is saturated, so it is not suitable to use the spectrometer to measure the signal directly. Therefore, the most suitable measurement intensity range of the spectrometer is from -126dBm to -95dBm while the signal between -95dBm to -80dBm should calibrated to remove the influence of the dead-time. Any signal above -80dBm should to be attenuated before using the up-conversion spectrometer.



(a)



(b)

Fig. 3. (a) The count rate as a function of input intensity. Blue line is the calculated value assuming t_{dead} is zero, R_1; red line is the calculated value by Eq. (2), R ; the green triangle is the measured result. (b) Ratio of R/R_1 as a function of input intensity.

3.3. Waveguide transfer function

While a traditional spectrometer uses wavelength dispersive elements, the up-conversion spectrometer is based on the QPM condition. The transfer function response of a finite-length uniform QPM grating is a sinc^2 function like the following [10,11]

$$I_{SFG}(\Delta k) \propto I_{pump} \cdot I_{signal} \cdot \mathrm{sinc}^2(A \cdot \Delta k \cdot L) \tag{4}$$

where I_{SFG}, I_{pump}, I_{signal} are the intensity of SFG, pump, and signal light, A is a constant, L is the waveguide length, and Δk is the phase-mismatching and can be calculated by the following equation:

$$\Delta k = \frac{n_{SFG}}{\lambda_{SFG}} - \frac{n_{pump}}{\lambda_{pump}} - \frac{n_{signal}}{\lambda_{signal}} - \frac{m}{\Lambda} \tag{5}$$

Where λ_{SFG}, λ_{pump} and λ_{signal} are 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.

From Eq. (4) and Eq. (5), for a certain signal wavelength (near 1310 nm in our case), the SFG spectrum over pump wavelength will be a sinc^2 function instead of a single peak. It will cause some "fake" side peaks in spectrum measurement results when the spectrometer is used to measure a signal with a narrow linewidth. In theory, the two main side peaks are as large as about 5% of main peak, while in practice, the imperfections in the waveguide, such as imperfect poling and period uniformity, will cause the side peaks to be larger than the theoretical ones and they can also be (very) asymmetric.

The measured spectrum can be seen as the convolution of the waveguide transfer function and the measurement noise. In order to reduce the "fake" side peaks in the spectrum of a signal with narrow linewidth a procedure of deconvolution can be performed. The relation can be expressed by the following formula:

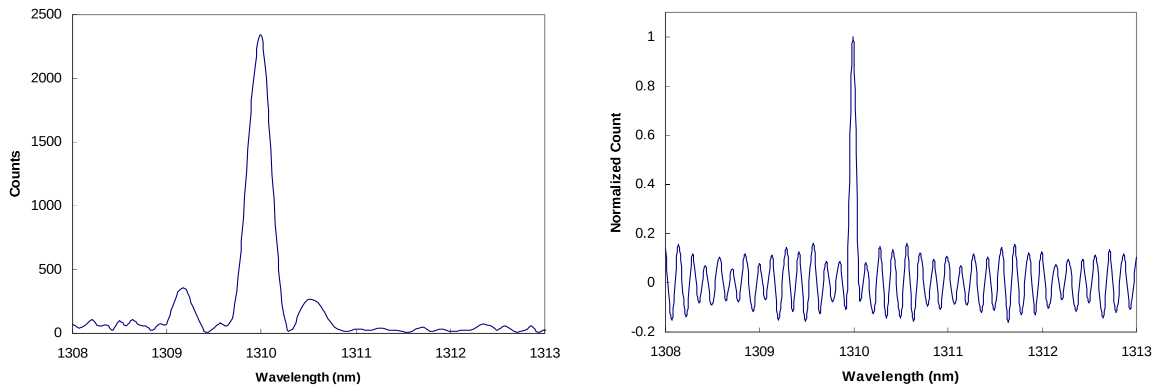
$$S_{measured} = F * S_{signal} + \varepsilon \tag{6}$$

Where $S_{measured}$ and S_{signal} are the measured spectrum and the actual signal spectrum. F is the transfer function of the waveguide, which can be measured using strong light from a tunable laser. ε is the total measurement noise, including the dark counts and other measurement noise.

When the measurement noise, ε, is small, we can deconvolve the measured spectrum, $S_{measured}$, to recover the actual signal spectrum, S_{signal}. However, the measurement noise is also deconvolved by F and then added into the result in the process. The lower the signal-to-noise ratio of the measurement is, the worse the estimation of the deconvolved signal will be. Therefore, to do the recovery by deconvolution, the measurement result must have high signal-to-noise ratio.

A 1310-nm tunable laser (Santec TSL-210V) with a linewidth of 100MHz was used as the signal. After been greatly attenuated (about 100dB), a spectrum of the laser light was measured by the up-conversion spectrometer, shown in Fig.4 (a). In the measured spectrum, there are two small side peaks around the main peak due to the transfer function of the waveguide. The measurement result can be deconvolved by the transfer function, and the result is shown in Fig. 4 (b). After deconvolution, we can see a clear peak at 1310 nm, the two side peaks are removed, but the deconvolution of the noise causes some ripples in the other wavelength. The algorithm used to get the result in Fig. 4(b) is just the most simple and straightforward deconvolution calculation using fast Fourier transform function. Currently, many advanced deconvolution algorithms have been developed to improve the recovered results in a low signal-to-noise ratio situation. For example, if we have some knowledge of the type of noise in the measurement (shot noise or white noise), we may be able to further improve the recovered results by using some advanced algorithms such as Wiener deconvolution[12].

The transfer function response of a finite-length uniform QPM grating causes some small “fake” peaks in the measurement results when the spectrometer is used to measure a signal with a narrow linewidth . Deconvolution can be used to remove this influence when the signal-to-noise is sufficiently high. However, in low signal-to-noise situations, more advanced algorithms may be needed to get more accurate results.



(a) (b)

Fig. 4 (a) The 1310-nm tunable laser spectrum measured by the up-conversion spectrometer. (b) The 1310-nm tunable laser spectrum recovered by deconvolution.

3.4. Spectral resolution and scan speed.

Spectral resolution and scan time are other important parameters for a spectrometer.

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 spectral bandwidth 2.4 x 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 the Eq. (4) and Eq. (5), the bandwidth of QPM is in reverse proportion with the waveguide length L .So a longer waveguide will result in a better spectral resolution. Due to fabrication tolerances, it is hard to get a PPLN waveguide longer than 5 cm, which is used in this experiment. Therefore, the spectral resolution of an up-conversion spectrometer is limited to about 0.2 nm under current technological conditions. A better spectral resolution can be realized when a longer QPM structure is available or other experimental arrangements are implemented.

The scan speed of the up-conversion spectrometer can be estimated by the following equation.

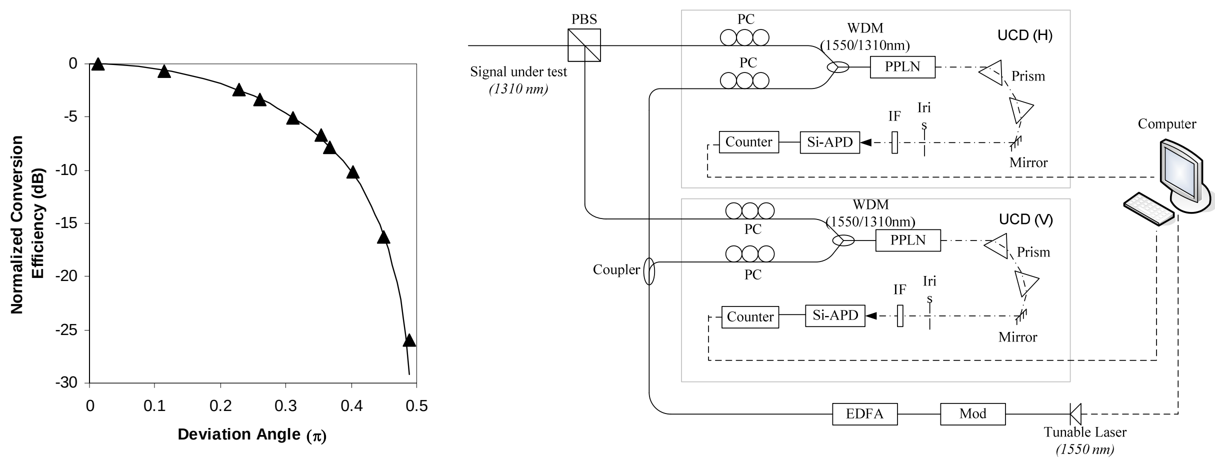
$$v_s = \frac{v_t}{1 + n \cdot t_{in} \cdot v_t} \tag{7}$$

Where v_s is the spectrometer scan speed, v_t is the tuning speed of pump laser (12 nm/s in our case), n is step number in each nm and t_{in} is the integration time for each step. n can be selected according to the desired measurement resolution. In the case of our up-conversion spectrometer, n = 10 (each step = 0.1 nm) is chosen for a good resolution since the waveguide has an acceptance spectral width of 0.2 nm. t_{in} can be selected by the intensity of the signal under test, usually 50~500 ms. In that case, the scan speed of the spectrometer is about 0.2~1 nm/s.

3.4. Polarization sensitivity

One of the QPM conditions of the PPLN waveguide, conservation of momentum, determines that the device is polarization sensitive. Fig. 5(a) shows the dependence of the conversion efficiency on the deviation (shifting) angle of the 1310-nm input polarization state. The deviation angle is the angle (in Jones space) between the given input polarization state and the state at which the conversion efficiency is maximized. The conversion efficiency is normalized by the maximum value to 1. As shown in the figure, the polarization extinction ratio of the PPLN waveguide is more than 25 dB. We also compared the measurement results with the polarization sensitivity of an ideal polarizer, in which the transmittance as a function of deviation angle θ equals to $\cos^2(\theta)$. The high polarization extinction ratio of PPLN waveguide provides a unique characteristic for up-conversion spectrometers, which acts as the combination of a polarizer inserted at the front of a traditional spectrometer. Then the measurement result is the spectrum of the signal at a certain polarization orientation. When the signal under test is polarized at a certain direction, by using an up-conversion spectrometer we can carry out its full spectrum and reduce the noise in other polarization orientation. The up-conversion spectrometer is especially suitable for some applications, in which a polarization spectrum is of interest.

In many cases, polarization-insensitive spectra are needed. The up-conversion spectrometer also can be implemented by combining two detection units, shown in Fig. 5 (b). A polarizing beam splitter (PBS) is used to split the components of two orthogonal polarization orientation into two up-conversion detection units. The two signals are aligned with the polarization of the respective PPLN waveguide to obtain the maximum counts, and then the counts are combined in a computer. In this configuration, the spectrum of light at all polarization orientation can be obtained.

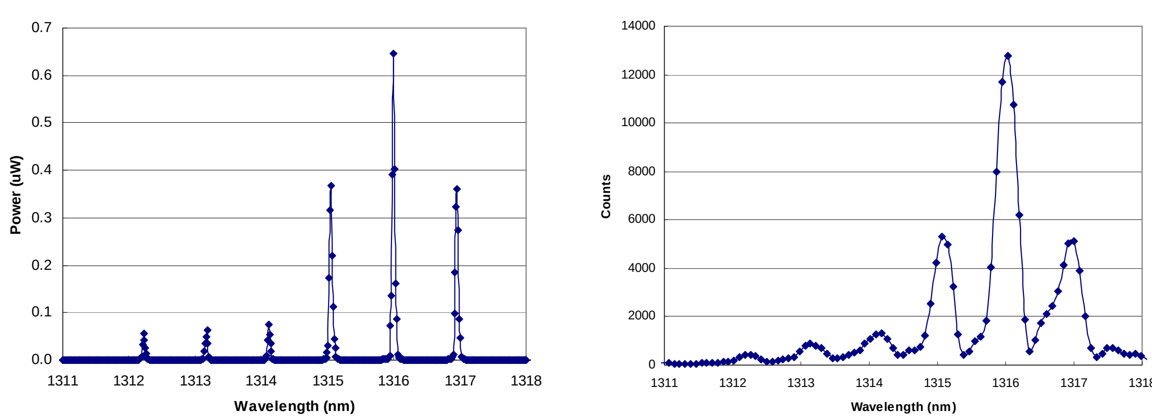


(a) (b)

Fig.5 (a) The normalized conversion efficiency as a function of polarization angle of input signal. (b) Schematic diagram of polarization insensitive up-conversion spectrometer. PBS: Polarizing beam splitter and other notations are the same as in Fig. 1.

4. Experimental result

To demonstrate and verify the functionality of the spectrometer, we used it to measure a spectrum of a multi-longitude-mode structure near 1310 nm emitted from a laser diode. For a comparison, an optical spectrum analyzer (OSA, Ando AQ-6315A) was used first to record the spectrum, as shown in Fig. 6(a). The spectrum shows one main peak with an amplitude of -33 dBm at 1316 nm, two side peaks (-35dBm) at 1315 and 1317 nm, and some smaller peaks (less than -40 dBm) at the 1312 ~ 1314 nm range. Then we used the up-conversion spectrometer to measure the spectrum of the light after we greatly attenuated it by 75 dB. The scan range of the pump laser is set from 1540 to 1550nm with a scanning step of 0.1 nm. The integration time for each step is 500 ms. The measured six peaks are clearly shown in Fig. 6(b)., The intensity of all six peaks is less than -110 dBm and the intensity of the smallest peak is as weak as about -120 dBm. The total time used to record this spectrum is about 1 minute. This experiment demonstrates the ultra high sensitivity of the up-conversion spectrometer. The resolution of the up-conversion spectrometer is limited by the QPM condition, about 0.2 nm, which can be improved by increasing the length of waveguide.



(a) (b)

Fig.6. (a) The spectrum of strong light measured by a commercial OSA. (b) The spectrum of greatly attenuated light measured by the up-conversion spectrometer.

5. Conclusion

We have developed an up-conversion spectrometer based on a periodically poled lithium niobate (PPLN) waveguide. We also experimentally studied the up-conversion spectrometer, including its sensitivity, maximum input signal intensity, scan speed, the waveguide transfer function response, and polarization sensitivity. The detection efficiency of the up-conversion spectrometer is about 32% and its sensibility can reach to -126dBm. Its working wavelength range is from -126 dBm to -80 dBm. We experimentally demonstrated its ultra high sensitivity by measuring a greatly attenuated light from a laser diode near 1310 nm.

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