Near-infrared single-photon spectroscopy of a whispering gallery mode resonator using energy-resolving transition edge sensors

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Abstract
We demonstrate a method to perform spectroscopy of near-infrared single photons without the need of dispersive elements. This method is based on a photon energy resolving transition edge sensor and is applied for the characterization of widely wavelength tunable narrow-band single photons emitted from a crystalline whispering gallery mode resonator. We measure the emission wavelength of the generated signal and idler photons with an uncertainty of up to 2 nm.

Keywords: spectroscopy, transition edge sensors, crystalline whispering gallery mode resonators, spontaneous parametric downconversion

(Some figures may appear in colour only in the online journal)

1. Introduction

Near-infrared spectroscopy is an essential measurement technique in a large variety of research fields. Its applications range from physics to chemistry to biology and is also discussed as an application in forensics [1]. Fundamentally, spectroscopy identifies the amount of radiation intensity as a function of wavelength, frequency, or energy. Typically, spectrosopes consist of dispersive elements followed by either a movable slit and one photo-detector, or a detector array. Therefore, the wavelength range and the precision of this technology is mainly limited by geometry.

In this paper we demonstrate a method to directly measure the energy of the detected light at the single photon level without spectral discrimination. Due to the discrete nature of the photons, we can directly calculate the wavelength of the detected light. For the demonstration, we will calibrate the response of a transition edge sensor (TES) [2] and perform spectroscopy on a single photon test source, which in our case will be a widely wavelength tunable crystalline whispering gallery mode resonator (WGMR). To the best of our knowledge, this is the first time that a TES is used for spectroscopic measurements of a single photon source in the near-infrared wavelength regime.

The TES is a superconducting photon detector and operates as a microcalorimeter measuring the absorbed heat in the detection region. A number of experiments have demonstrated high energy resolution of a TES ranging from millimeter wave [3] to x-ray detection [4]. TES have shown remarkably good performance in spectroscopic measurements of the Crab Nebula, one of the first experiments using optical TES [5], and x-ray spectroscopy [6, 7]. In the x-ray
spectroscopy experiments the frequency resolution was limited by the TES single-shot energy resolution (0.2 eV), which is relatively large compared to the optical photon energy. Here, we use TES similar to devices with near-unity detection efficiency around 1550 nm [8–11] but optimized for optical frequencies in the visible to near-infrared regime [12]. The energy resolution is also around 0.2 eV, however, since photons from the WGMR are monochromatic, we can allow for averaging many detection outcomes and therefore improve the spectral resolution, i.e. we are not limited by single-shot operation.

Since the output signal of the TES is directly proportional to the amount of absorbed energy, this method enabled us to perform spectroscopic measurements at the single photon level without the use of additional wavelength dependent elements.

WGMRs combine high quality factors (Q-factors) with small mode volumes over the whole transparency range of the used material [13]. This makes them attractive for various experiments in nonlinear and quantum optics [14–18]. In the field of optical parametric oscillators, for example, crystalline WGMRs have demonstrated generation of parametric light at remarkably low optical pump powers [19, 20]. Furthermore, these systems enable controlled generation of signal and idler beams over a large wavelength range without sacrificing the intrinsic narrow bandwidth [21, 22]. Recently we have successfully demonstrated an efficient narrow-band heralded single photon source, readily tunable in bandwidth and wavelength based on a crystalline WGMR [23]. A similar source is used in this work to verify the performance of the TES-based spectroscopy.

By combining the TES with the crystalline WGMR we measure a wavelength shift of the idler over a wavelength range of 30 nm with a uncertainty of 2 nm. The corresponding signal photon shift is measured to be 15 nm. Both results agree well with the theory of the temperature dependent wavelength shift of the source.

2. Experimental Setup

The starting point of our setup is a continuous wave (cw) Nd:YAG laser, emitting light at 1064 nm. In order to simplify the future data analysis, a gated operation of the setup is preferred, where light from the WGMR is only impinging on the TES during predetermined time slots. Therefore, we generate temporal pulses from the initial cw light using a fast switching electro-optical modulator (EOM). The generated infrared pulses are subsequently frequency doubled using a periodically poled lithium niobate crystal (PPLn). This cascaded pulse generation improves the limited extinction ratio of the EOM.

With this technique we verified that no cw background at 532 nm could be observed. The pulse length was chosen to be 100 ns which corresponds approximately to twice the ring-down time of our WGMR. To minimize the effect of pulse pileup [8] during the TES recovery time of $t_{\text{recover}} \approx 12 \mu s$, the repetition rate was set to 80 kHz.

The 532 nm light is coupled to a single mode fiber and focused on the backside of a diamond prism using a gradient-index lens. By controlling the distance between the diamond prism and the WGMR, we control the optical tunneling between the beam’s footprint at the prism and the resonator.

The WGMR is manufactured from 5.8% Mg-doped $c$-cut lithium niobate crystal ($\text{LiNbO}_3$) with an equatorial radius of $R \approx 1.61 \text{ mm}$ and a polar radius of $r \approx 0.4 \text{ mm}$. The quality factor of the resonator at the pump wavelength of 532 nm is $Q \approx 3 \times 10^7$.

By changing the stabilized temperature of the resonator, we control the phase-matching between the extraordinary polarized pump and the ordinary polarized downconverted signal and idler photons (natural Type-I phase matching). The average pump power impinging on the coupling prism is $1.5 \mu \text{ W}$, which provides a sufficient signal to noise ratio on the pump monitor detector and simultaneously is still in the linear gain regime of the downconversion process [23].

Signal and idler, as well as the residual pump light, exit the resonator via the diamond prism. The fact that signal and idler are orthogonally polarized to the pump allows the separation using a polarizing beam splitter (PBS). The residual pump light is monitored using a PIN detector for locking the frequency of the pump laser to the WGMR. The non-degenerate signal and idler photons are further separated using a dichroic mirror and are directed to two fiber-coupled TESs.

The TESs are operated at 20 mK, which is far below the critical temperature $T_c \approx 100 \text{ mK}$, using a commercial dilution refrigerator (DR). Both detectors are voltage biased and the electronic response of each is read out using a dc-superconducting quantum interference device (SQUID), which is also placed inside the DR. After an additional 100x amplification, each signal is recorded with a data-acquisition unit and post-processed to identify the energy of the detected photons. Examples of raw output pulses of the TES are shown in the inset of figure 2(a). Since these TESs were optimized for a
high photon number resolution, they have a low transition temperature, resulting in a relatively long recovery time of \( t_{\text{recover}} \approx 12 \mu s \) (compare inset figure 2(a)).

3. Energy calibration of the TES

In order to determine the energy of the detected photon pulses, one has to calibrate the voltage response of each TES. This was done by using an attenuated coherent state from a diode laser source, which was electronically pulsed with 10 ns pulse duration and a repetition rate of 35 kHz. For each trigger pulse, the TES response is recorded for 13 \( \mu s \). The integral of this TES response function is associated with the energy of each detected photon pulse. The inset of figure 2(a) shows typical TES responses for 1024 laser photon pulses. To improve the signal to noise ratio, each TES response is convolved with a predetermined characteristic TES master pulse [24]. Here, the master pulse is generated by building the average of 1024 individual TES single photon responses. The integral of this convolution is as well associated with the energy of each detected photon pulse. To quantify the amount of absorbed energy, in a first step we calculate the histogram of all convoluted TES responses (figure 2(a)). The combination of the discrete nature of photons with the knowledge about the laser’s emission wavelength of 1062.9 nm implies that each peak in figure 2(a) is a multiple of 1.16 eV. Therefore one can calibrate the histogram to the discrete amount of absorbed energy. The calibration is done by fitting Gaussian distributions to the individual histogram peaks and correlating the mean value of the individual fits with the corresponding energy (as shown in figure 2(a)). The standard deviation of each fit is 0.2 eV and corresponds the single shot resolution of the used TES. The background in-between the dominant peaks from the calibration laser originate from blackbody radiation, which scattered into the optical fibers and was guided to the TES. The mean values of the Gaussian fits are used to determine the scaling of the response integral depending on the incident energy (figure 2(b)). This results in the characteristic detector energy response function and is used further on to connect the TES response to the amount of energy absorbed. The linear detector response in figure 2(b) is expected, since the largest photon energy used for the calibration is far below the maximal directly resolvable photon energy of the used TES [25]. The fitting function used for the linear fit in figure 2(b) is \( f(x) = 3.31^{+0.04}_{-0.04} x - 0.01^{+0.04}_{-0.04} \). The errors represent the 95% low and upper confidence level of the linear fit.

4. Spectroscopy of the generated pair photons

We characterize the wavelength of the emitted signal and idler photon pulses originating from the crystalline WGMR as a function of the phase-matching temperature. For a given phase-matching temperature we accumulate a photon pulse energy distribution for the signal and idler, respectively, using the characteristic energy response function of each detector. Figure 3 illustrates two such energy histograms for two different phase-matching temperatures of the resonator, measured with the TES in the idler path. The inset of figure 3 shows a close-up of the region around 1 eV, which is used to recalculate the wavelength of the detected photons. One can clearly see that the energy of the detected idler photons decreases when the resonator temperature increases. Due to the energy conservation of the SPDC process, this relation is reversed for the signal photons. The standard deviation of each Gaussian fit is again 0.2 eV, and represents the single

Figure 2. Detector calibration (a) Photon pulse area distribution of a coherent state originating from the attenuated coherent diode laser source. The wavelength of the laser is 1062.9 nm. The inset shows 1024 TES output traces. (b) The pulse area of the TES response pulse dependent on the absorbed energy. The green dots are the mean values from the Gaussian fits from (a).
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This condition strongly depends on the bulk

region.

wavelength the theoretical prediction of the wavelength tuning in

and idler, which resulted in different amounts of averaging. For

difference was an imbalanced

±4 nm for idler and signal, respectively. The main reason for this

chromatic source, we achieved a

algorithm. By averaging many TES responses of the mono-

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Gaussian

one sigma interval of the mean-value determination using

error bars represent the

we observe a wavelength detuning of nearly 30 nm for the idler

result for the investigated temperature range for signal and idler

photons [29], this spectroscopy method offers the

possibility to characterize the quantum state of the detected

photons [30, 31] in combination with its wavelength.

5. Summary

We have used the energy resolution of superconducting TESs
to resolve the wavelength of near-infrared single photons
without the use of dispersive elements. The results were
obtained by measuring the output wavelength of the signal
and idler photons from a crystalline WGMR. We confirmed
the theoretically expected wavelength shift of signal and idler
photons based on a change of the phase-matching tempera-
ture. The presented uncertainty of 2 nm can be improved
further by an optimized fiber coupling and by accumulating
more photon counts. The absence of dispersive elements
should allow us to extend this spectroscopy method to a wide
wavelength range without increasing the measurement
uncertainty. Moreover, by exploiting the photon number
resolving ability [29], this spectroscopy method offers
the possibility to resolve the wavelength of near-infrared single photons [30, 31] in combination with its wavelength.

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