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Review

Photon-Counting Spectrometers Based on Superconducting Nanowire Single-Photon Detectors

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Abstract — Optical spectrum analysis provides a wealth of information about the physical world. Throughout the development of optical spectrum analysis, sensitivity has been one of the major topics and has become essential in applications dealing with faint light. Various high-sensitivity optical detection technologies have been applied in optical spectrum analysis to enhance its sensitivity to single-photon level. As an emerging single-photon detection technology, superconducting nanowire single-photon detectors (SNSPDs) have many impressive features such as high detection efficiency, broad operation bandwidth, small timing jitter, and so on, which make them promising for enhancing the performance of optical spectral analysis. Diverse schemes for photon-counting spectrometers based on SNSPDs have been demonstrated. This article reviews these impressive works and prospects for the future development of this technology. Further breakthroughs can be expected in its theories, device performance, applications, and combinations with in-sensor computing, promoting it to be a mature and versatile solution for optical spectrum analysis on ultra-faint light.

Keywords — Superconducting nanowire single-photon detectors, Spectrometers, Single-photon detector, Photon counting.

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I. Introduction

Spectra of light carry abundant information of interactions between light and matter. Optical spectrum analysis is a significant way for human beings to explore and understand the physical world [1]–[3]. It has been developed for a long time and widely applied in various fields of science and technology, such as chemical industry [4]–[6], astronomy [7]–[9], agriculture [10], [11], remote sensing [12]–[14], biology and medicine [15]–[17], food safety [11], [18], military [19], and so on. In many applications, the light being measured is faint, even at single-photon level. For instance, optical spectra of astronomical light radiation have abundant information about celestial bodies, which are usually quite faint. Optical spectrum analysis with ultra-high sensitivity is a powerful tool in astronomical observation [7]–[9]. Another typical application is the spectral light detection and ranging (LIDAR) in the field of remote sensing. It obtains the optical spectra of the reflected light, which is quite weak, at each point in the measured three-dimensional (3D) point cloud [13], [20]. The sensitivity of optical spectral measurement determines the operation distance in this application. Biology is also a field requiring optical spectrum analysis on ultra-faint light. The light is emitted from a biological sample by either external excitation or self-emitting, carrying important information about life activities. Fluorescence spectroscopy [21], [22] and Raman spectroscopy [23], [24] are common ways to observe and characterize biological samples, in which high-sensitivity optical spectrum analysis is essential. Promoted by these applications, improving measurement sensitivity becomes an important topic for developing optical spectrum analysis.

Improving the performance of optical detection is a direct way to enhance the sensitivity of optical spectrum analysis. Especially, a sensitivity at single-photon level can be fulfiled by combining various optical spectrum analysis methods and single-photon detectors. Commonly used single-photon detectors include photomultiplier tubes (PMTs) [25], single-photon avalanche detectors (SPADs) [26] and superconducting nanowire single-photon detectors (SNSPDs) [27].

In these detectors, the small signal induced by absorbing a single photon would be amplified to a measurable signal. Hence, with proper electrical counters, they can be used to record single-photon detection events and realize photon-counting measurement [28]. Most high-performance single photon detectors are "bucket detectors". They do not have spatial resolution. When they are used in optical spectrum analysis, they are often combined with scanning narrow-band filters [29] or scanning interferometers to realize Fourier-transform spectroscopy [30], [31]. Besides, high-sensitivity image sensors have developed rapidly in recent years. Some of them support ultra-faint light detection at single-photon level, such as intensified charge-coupled devices (ICCDs) [32], [33], electron-multiplied CCDs (EMCCDs) [34], [35], and scientific complementary metal-oxide-semiconductor (sCMOS) cameras [36]. They can also be used to improve the sensitivity of optical spectrum analysis. Combined with spatial dispersion elements, pixels in the image sensors could be used to detect light at different wavelengths. Hence, the optical spectrum analysis can be realized by "a single exposure" without any scanning process. It is called "snapshot" optical spectrum analysis.

At present, the choice of optical detectors is different in different wavelength bands for high-sensitivity optical spectrum analysis. In the visible band and near-infrared band (400–1100 nm), thanks to the established technologies of silicon semiconductor, high-sensitivity image sensors such as ICCDs, EMCCDs, and sCMOSs have been applied to the snapshot-type spectral analysis, which has been widely used in astronomy [8], [37], fluorescence [38], [39], Raman spectroscopy [23], [40], and other fields requiring optical spectrum analysis on ultra-faint lights. SPAD arrays are also potential candidates, especially when high temporal resolution is required [24]. In the near-infrared band over 1100 nm (1100–1600 nm), SPADs based on indium gallium arsenide/indium phosphide (InGaAs/InP) semiconductor materials [41], [42] can be used to enhance the sensitivity of spectrometers. In the optical band with longer wavelength (>1600 nm), it is difficult for semiconductor optical detectors to achieve a single-photon-level sensitivity [43], [44]. Recently, the up-conversion single-photon detection was applied in mid-infrared spectrometers. It converts mid-infrared photons to visible photons through optical nonlinear processes, then detects the visible photons by traditional semiconductor detectors [45], showing a possible way to enhance the sensitivity of optical spectrum analysis in this wavelength range.

Notably, the mainstream optical detection technologies used in high-sensitivity optical spectrum analysis are based on various semiconductor detectors. Further development would like to see new technologies leading to breakthroughs in single-photon detection. As an emerging single-photon detection technology, SNSPDs have many attractive properties, such as high detection efficiency, low dark count rate, low timing jitter, high maximum photon count rate, and so on [46]. Since an SNSPD is a thin film of several nanometers in thickness, it is easy to be integrated with various micro/nano-structures [47]–[49], which provides a promising way to develop on-chip optical systems for quantum communication [50], quantum information processing [51], and optical sensing for ultra-faint light at single-photon level [52], [53]. Especially, it supports broad operation bands (from visible to mid-infrared band [54]), favorable for optical spectrum analysis. For these reasons, SNSPDs have been applied to spectroscopy and have shown great potential in developing photon-counting spectrometers. This paper reviews the latest progress in this emerging technology, especially the development of integrated photon-counting spectrometers combining SNSPDs and on-chip photonic structures for different schemes of optical spectrum analysis.

This paper is arranged as follows: Section II reviews the methods of optical spectrum analysis; Section III introduces the principle and progress of the SNSPD technology; Section IV presents the current development of photon-counting spectrometers based on SNSPDs; Section V provides a prospect on the development and application of this technology; Section VI is the summary.

II. Methods of Optical Spectrum Analysis

The technology of optical spectrum analysis has been developed for three hundred years since the time of Isaac Newton, who first discovered the compound nature of white light and proposed the concept "spectrum" to quantitatively describe different colors of light after the prism [55]. After that, many methods have been developed to measure optical spectrum [30], [56], [57]. Their principles could be described by a common theoretical model, which is simple but instructive. In the model, the input light illuminates a detector array through an optical system, as shown in Figure 1 (a). For the i-th detector in the array, considering that a monochromatic light with a frequency ν illuminates it, the ratio of its output signal to the power of the input light could be denoted by $\boldsymbol{R}_i(\nu)$, which is the spectral response of this detector. The spectral response $\boldsymbol{R}_i(\nu)$ of each detector is determined by both the characteristics of itself and the transmission of the optical system. If a detected light has many components with different frequencies and its spectrum is denoted by $\boldsymbol{P}(\nu)$, the measurement process can be expressed by equation (1), in which D_i is the measurement result of the i-th detector. Measurement results from every detectors form a vector denoted by $\boldsymbol{D}$. Usually, the optical spectrum is expressed on discrete sample points with equal frequency intervals. Accordingly, equation (1) could be discretized to a linear equation as (2). In (2), ν_j is the j-th frequency sample point, and $P(\nu_j)$ is the power spectrum density of the input light at frequency ν_j; $\Delta\nu_j$ is the detection bandwidth of the j-th frequency sample point; $\boldsymbol{R}$ is a matrix, in which each element $R_i(\nu_j)$ is the spectral response of the i-th detectors at frequency sample point ν_j. $\boldsymbol{R}$ could be obtained before optical spectrum analysis by detector calibrations. It can be seen that the optical spectrum analysis is an inverse problem of (2), i.e., how to obtain the information

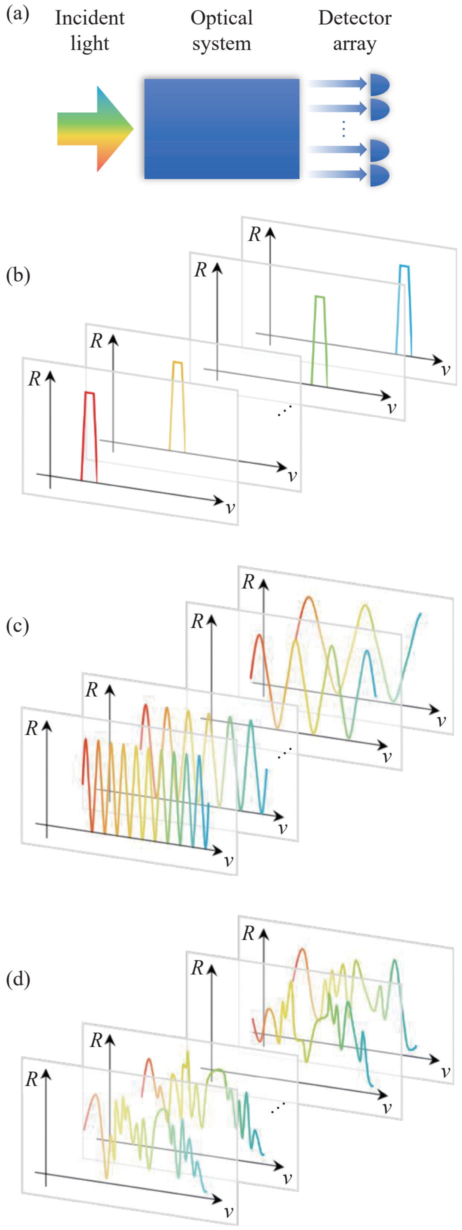

Figure 1 A common theoretical model of spectrometers. (a) Sketch of the common model. (b)–(d) Spectral responses of detectors in different types of spectrometers: (b) Spectrometers based on gratings or narrowband filters; (c) Fourier transform spectrometers; (d) Reconstructive spectrometers. R is the spectral response and ν is the frequency.

of $P(\nu_j)$ from the results of D_i.

$$D_i = \int \boldsymbol{R}_i(\nu)\boldsymbol{P}(\nu)\,\mathrm{d}\nu \tag{1}$$

$$\boldsymbol{D} = \begin{bmatrix} D_1 \\ D_2 \\ \vdots \\ D_i \end{bmatrix} = \boldsymbol{RP} = \begin{bmatrix} R_1(\nu_1) & R_1(\nu_2) & \cdots & R_1(\nu_j) \\ R_2(\nu_1) & R_2(\nu_2) & \cdots & R_2(\nu_j) \\ \vdots & \vdots & \ddots & \vdots \\ R_i(\nu_1) & R_i(\nu_2) & \cdots & R_i(\nu_j) \end{bmatrix} \begin{bmatrix} P(\nu_1)\Delta\nu_1 \\ P(\nu_2)\Delta\nu_2 \\ \vdots \\ P(\nu_j)\Delta\nu_j \end{bmatrix} \tag{2}$$

Obviously, the optical spectrum information $\boldsymbol{P}$ can be obtained directly from the results of D_i if $\boldsymbol{R}$ is a diagonal matrix. Many conventional schemes of optical spectrum measurement can be described in this way, such as monochromators based on optical gratings and scanning slits, as well as miniaturized spectrometers based on optical gratings and image sensors. Some schemes based on detector arrays and multiple narrow-band filters (or a single detector with switchable narrow-band filters) also can be classified into this case. The typical spectral responses of these schemes are shown in Figure 1(b). If $\boldsymbol{R}$ is not diagonalized but a full-rank matrix, the optical spectrum information can be obtained from D_i by the inverse of $\boldsymbol{R}$. The Fourier transform spectrometers [30] can be expressed in this way. In this scheme, the spectral responses of these detectors have sinusoidal patterns in frequency with different periods, as shown in Figure 1(c), leading to a full-rank $\boldsymbol{R}$. Usually, a variable optical interferometer is used as the optical system in a Fourier transform spectrometer. Its transmission spectrum is sinusoidal, and the period is scanned temporally. A bucket detector is used to measure the light at different times, and its spectral response is modulated by the interferometer.

In the above analysis, $\boldsymbol{R}$ is a full-rank square matrix. The optical spectrum information on the sample points can be fully obtained. But, a common situation in optical spectrum analysis is that the number of sample points may be much higher than the number of detectors, resulting in that $\boldsymbol{R}$ is not a square matrix. For example, in a spectrometer based on narrow-band filters, the space between the sample points could be smaller than the filter bandwidth. In this case, the resolution of the spectrometer is determined by the filter bandwidth, which means that the spectral information of these sample points would not be obtained completely.

In the last ten years, with the wide application of various algorithms of compressive sensing [58] and machine learning [59], reconstructive spectrometers have developed rapidly as an emerging technology of optical spectrum analysis. In a reconstructive spectrometer, as shown in Figure 1 (d), each detector in the detector array has a randomly modulated spectral response, which may come from the intrinsic property of the detector or the transmission of the optical system. The spectral responses of different detectors should be quite different, leading to a low correlation between the rows of the matrix $\boldsymbol{R}$. In a reconstructive spectrometer, the number of detectors is always far smaller than the number of the frequency sample points. Hence, $\boldsymbol{R}$ is a rectangle matrix. To obtain the information $P(\nu_j)$ from the results D_i, an optimization algorithm is required to reconstruct the optical spectrum under some prior knowledge. It is the process of compressive sensing [60]. Compared with conventional methods, reconstructive spectrometers significantly extended the implementation of optical spectrum analysis, especially promoting the development of on-chip integrated spectrometers [61]–[64].

III. Superconducting Nanowire Single-Photon Detectors

SNSPDs are small superconducting wires with a width of about 100 nm and a thickness of 5–10 nm. The commonly used superconducting materials include NbN, NbTiN, WSi, and some emerging materials, such as MgB_2 [65], NbReN [66], and so on. SNSPDs operate in a cryogenic environment at a temperature lower than the superconducting critical temperature of the superconducting material, under which the superconducting state of the wire is maintained precisely. A bias current is applied to the superconducting nanowire, which is close to its superconducting critical current. The superconducting critical current is defined as the maximum bias current under which the superconducting state of the wire could be maintained under the operation temperature. The mechanism of single-photon detection by the superconducting nanowires is complex. Several theoretical models have been proposed [67]. However, no one can explain all the phenomena reported in previous experiments. The hotspot model is a widely accepted model that could roughly describe the single-photon detection process of SNSPDs [68]. According to this model, the nanowire is initially in the superconducting state. The voltage on the nanowire is zero under the bias current due to its superconducting state. Since the energy of a photon is much greater than the binding energy of the Cooper pairs in the superconducting state, many Cooper pairs would be destroyed when an incident single photon is absorbed by the nanowire. A hotspot is formed in the nanowire due to this process. The hotspot increases the local current density around it, resulting in the hotspot spreading and the local current density on the wire continuing to increase. Finally, the hotspot leads to a resistance region on the nanowire. As a result, the current transfers to the load path, which connects in parallel with the SNSPD and has a lower impedance. Then, it generates a voltage signal for the single-photon detection event. After that, the nanowire gradually returns to the superconducting state under the cryogenic environment, waiting for next single-photon incidence. In this process, the voltage signal at the load path gradually reduces to zero as the current "transfers" to the nanowire again, and the nanowire recovers its superconducting state. Figure 2(b) shows a typical voltage signal when a single photon is detected. It is an electrical pulse with a sharp rise edge and a slow fall edge. It could be recorded by the time-correlated single-photon counting (TCSPC) system as a single-photon detection event.

The principle of SNSPDs was proposed and demonstrated in 2001 [69]. Since then, their performance has been improved rapidly. Initially, most SNSPDs were designed to be operated at telecom band [70], [71]. At present, their operation wavelength range covers from the visible band to the mid-infrared band, according to the requirements of different applications [54], [72]–[74]. The detection efficiency of SNSPDs is quite high, close to 100% in some operation wavelength ranges [75]. Their dark count rate can be reduced to the order of 10^{-4} Hz [76], which is helpful to enhance signal-to-noise ratio when it is used to measure ultra-faint light. The timing jitter of SNSPDs is also quite small [77], leading to ultra-high temporal resolution. The maximum count rate of SNSPDs could be improved to the order of GHz [78], [79], showing a high dynamic range of single-photon detection. Thanks to these excellent performances, SNSPDs have been widely used in research on quantum communication and quantum information processing. As a type of high-sensitivity optical detector, their applications have been extended to many technical fields such as deep-space communication [80]–[82], LIDAR [83], gas sensing [84], [85], fluorescence imaging [86], [87], material analysis [88]–[90], and so on.

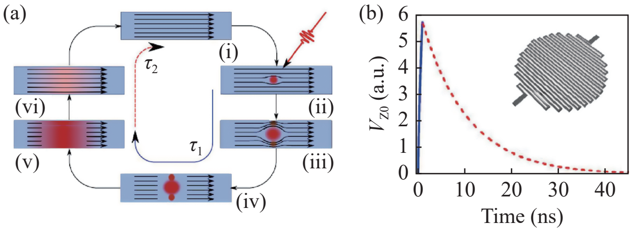

Figure 2 Hotspot model of SNSPDs [68]. (a) Schematic of the detection process; (b) A typical output voltage signal of an SNSPD upon a detection event. In (a), (i) the SNSPD is in its superconudcting state; (ii) a hotspot is generated and pushs the current aside; (iii) and (iv) the current exceeds the switching current and a resistive slot is formed accross the nanowire; (v) the slot expands along the nanowire; (vi) the slot starts to cool down because of stunt from a parallel resistor and the SNSPD is returing to superconducting state. τ_1/τ_2 is the rise/fall time of a typical voltage signal as shown in (b).

Commonly, SNSPDs are designed to detect photons incident on the surface of nanowires in the vertical direction. Promoted by the development of quantum photonic circuits, the technology of hybrid integration of SNSPDs and optical waveguides on chips has been developed. It has been achieved on various material platforms [91], such as GaAs waveguides [92], Si strip waveguides [93] and shallow ridge waveguides [94], SiN waveguides [95], diamond waveguides [96], lithium niobate (LN) waveguides [97], [98], etc., as shown in Figures 3(a)–(f). These hybrid-integrated chips have been used to achieve complicated functions of quantum photonics, such as the on-chip interferometers for quantum interference [95] and the central node of measurement device-independent quantum key distribution (MDI-QKD) [99]. In addition, to further improve the maximum count rate and temporal resolution of single-photon detection, SNSPDs were integrated with a variety of on-chip resonant structures, such as asymmetric nanobeam cavities and photonic crystal microcavities [100]–[102], which are shown in Figures 3(g)–(i). Recently, a photon-number-resolved measurement of more than 100 photons has been achieved by the SNSPD integrated on optical waveguides [103], showing the potential of hybrid integration of SNSPDs and on-chip photonic structures on realizing complicated functions of optical detection on ultra-faint light.

IV. Photon-Counting Spectrometers Based on SNSPDs

Thanks to their impressive performance, SNSPDs could be used to enhance the sensitivity of various optical spectrum analysis schemes. Besides, their wide operation wave-

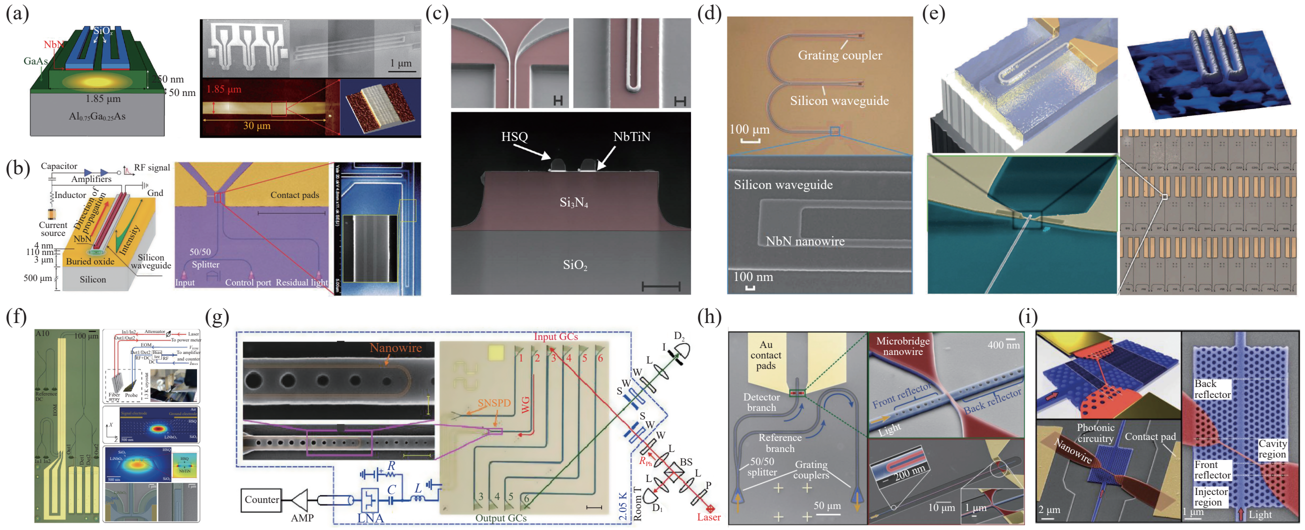

Figure 3 SNSPDs integrated on (a) GaAs waveguides [92], (b) Si strip waveguides (RF, radio frequency) [93], (c) SiN waveguides (HSQ, hydrogen silsesquioxane)[95], (d) Si shallow ridge waveguides [94], (e) Diamond waveguides [96], (f) LN waveguides (EOM, electro-optic modulator; DC, directional coupler)[98], (g) Asymmetric nanobeam cavities (AMP, amplifier; GCs, grating couplers; WG, waveguide) [100], (h) Perpendicular nanobeam cavities [101], and (i) Two-dimensional (2D) photonic crystal cavities [102].

length range and high temporal resolution could also be used for better optical spectral analysis. Before reviewing the recent progress on photon-counting spectrometers based on SNSPDs, we would like to provide an analysis of the sensitivity of single-photon detectors and high-sensitivity image sensors to show the advantage of SNSPDs on optical spectrum analysis.

1. Advantage of SNSPDs on sensitivity

Sensitivity describes the ability of a spectrometer to measure faint light. It should be noted that there has not been a well-accepted definition of the sensitivity of spectrometers, nor a general method to evaluate it, since it highly depends on the methods to measure the light spectrum. The sensitivity also depends on the operation conditions for a specific type of spectrometer. For example, in spectrometers based on gratings and narrow slits, the sensitivity is different obviously at different spectral resolutions and operation wavelengths. For the same spectrometer, usually, higher sensitivity could be expected on a lower spectral resolution. Besides, the performance of the detector usually varies under different operation wavelengths. It is worth noting that the sensitivity also partly depends on the light to be measured. It is well known that a monochromatic light is easier to measure compared to a light with a broad spectrum under the same power level if it is ultra-faint [104]. Hence, it is difficult to compare the sensitivity of different spectrometers. On the other hand, for specific spectrometers with the same principle and optical design, the difference in their sensitivities is mainly due to the performance difference of the detectors employed. The sensitivities of optical detectors, i.e., the detectivity, could be well-described and comparable by the noise-equivalent power (NEP) [105], [106]. Therefore, in this part, we compare the performance of high-sensitivity detectors commonly used in optical spectrum analysis to show the advantage of SNSPDs in this application.

As mentioned in the introduction, the detectors used in high-sensitivity spectrometers can be categorized into two types: the high-sensitivity image sensors and the single-photon detectors. We compared the sensitivity of these detectors by picking typical products and calculating the signal-to-noise ratio (SNR) under different input photon fluxes and a specific measurement time (1 s) according to the noise model below. For high-sensitivity image sensors, the noise mainly comes from three parts. First, the shot noise is generated due to the quantum nature of photons, which is proportional to the square root of the number of detected photons. Second, the dark noise is produced in the detectors even when no light is input. It has different mechanisms for different detectors and may be amplified by internal gain. Third, the readout noise is present because of the thermal noise and flicker noise in the readout circuit and can be equivalently reduced by internal gain. Considering all these factors, when ultra-faint light is detected, SNR can be expressed by a simple, commonly used formula, which can be used to evaluate the sensitivity [107]:

$$\mathrm{SNR}=\frac{\mathrm{QE}\times S}{\sqrt{(\mathrm{QE}\times S+D)\times F^2+(N_{\mathrm{r}}/M)^2}} \tag{3}$$

where QE is the quantum efficiency of the detector; S is the number of the photons input on a pixel during one single exposure; D is the recorded electron number of dark noise in the pixel; F is the excess noise factor, which describes the amount of noise introduced in the internal amplification process. If there is no amplification, F is set to 1. N_{r} is the electron number induced by the readout noise and M is the internal gain.

This formula also provides a simple way to describe the sensitivity of single-photon detectors such as various PMTs, SPADs, and SNSPDs. These detectors present negligible readout noise, so the formula could be reduced to (4) [108], [73], where S and D are the number of photons input and the recorded dark count in a measurement process, respectively. Although some non-ideal effects are not considered in this formula, such as the after-pulse effect of SPADs and detection efficiency saturation effects when these detectors are operated under high count rates, it is convenient to compare the basic performance when single photon detectors and high-sensitivity image sensors are used in spectrometers to enhance their sensitivity.

$$\mathrm{SNR} = \frac{\mathrm{QE}\times S}{\sqrt{\mathrm{QE}\times S + D}} \tag{4}$$

For comparison, we selected some typical commercial single-photon detectors and high-sensitivity image sensors, calculated SNRs with increasing input photon flux by (3) and (4) according to their specifications. In these calculations, only the devices for visible light (using the specifications at 600 nm) and near-infrared light (using the specifications at 1550 nm) are considered, and the results are shown in Figure 4 by the solid and dashed color lines, respectively. The dash-dotted line shows the result of an ideal single-photon detector. It does not have dark counts, and its SNR is determined only by the shot noise. The data used in the calculations are from the product catalogs of Hamamatsu [109]–[111], Andor [112]–[114], IDQ [115], [116] and photon technology [117]. The integration time for all the detectors is 1 s.

Figure 4 shows that in the visible band, SNRs of most selected detectors are close to that of the ideal detector, except the PMT, under a high input photon flux. When the input photon flux reduces, the SNSPD, sCMOS, and EMCCD show similar performances, but the SNRs of the cooled CCD and SPAD decrease more rapidly than the above three. The minimum detectable signal of a detector can be characterized by NEP, which equals the input light power (the input photon flux in this paper) when the SNR is 1 [106]. It can be seen that the NEP of the SNSPD is close to the NEPs of the sCMOS and the EMCCD but obviously smaller than the cooled CCD, the SPAD, and the PMT. In the near-infrared band, the SNR of the SNSPD shows a similar performance to that of the SNSPD in the visible band. On the other hand, the performance of the InGaAs SPADs and the cooled photodiode (PD) array is far lower than that of the detectors at the visible band based on silicon material. Hence, the SNSPD outperforms them in all ranges of the input photon flux in this calculation. The NEP of the SNSPD is at least two magnitudes lower than the NEPs of the InGaAs SPADs and the cooled photon PD array, showing an obvious advantage of the SNSPD on the sensitivity in this band.

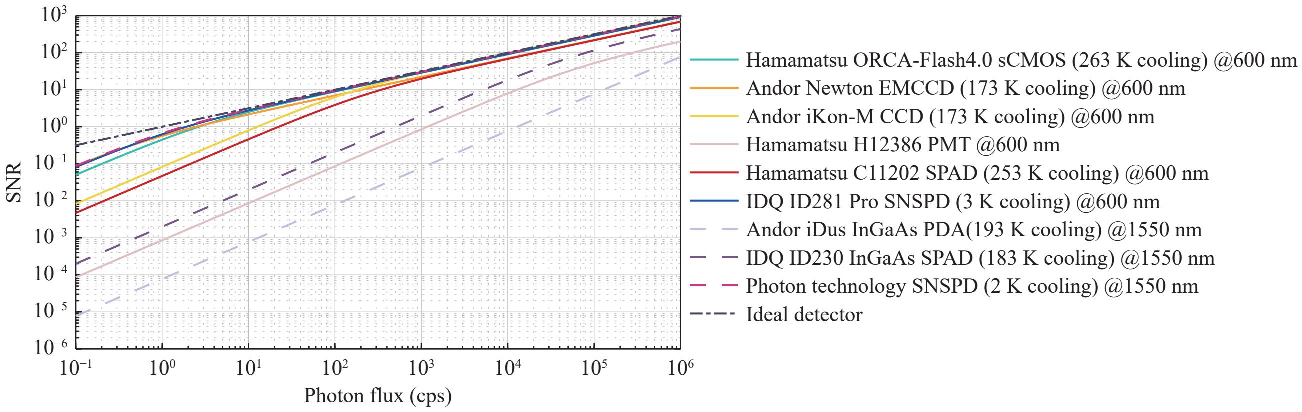

Figure 4 Calculated SNRs with increasing input photon flux for different detectors. Solid color lines: the devices for visible light (using the specifications at 600 nm); dashed color lines: the devices for near-infrared light (using the specifications at 1550 nm); the dash-dotted line: an ideal detector whose SNR is only limited by the shot noise. The data used in the calculation are from product catalogs of Hamamatsu [109]–[111], Andor [112]–[114], IDQ [115], [116] and photon technology [117]. The integration time for all the detectors is set to 1 s. cps: count per second.

Above comparisons indicate that a large sensitivity enhancement could be expected if SNSPDs are used in near-infrared spectrometers. In the visible band, SNSPDs do not have an obvious advantage on sensitivity compared with high-sensitivity image sensors such as sCMOSs and EMCCDs. However, as single-photon detectors, SNSPDs have an extremely small timing jitter when they record single-photon events. It is preferred in time-resolved measurement and could be used to reduce the impacts of dark counts and noise photons when pulsed lights are measured. It also provides new ways to simplify the implementations of the optical spectrum analysis.

2. Photon-counting spectrometers using SNSPDs

Thanks to their impressive performance in the near-infrared band and longer wavelength range, SNSPDs can be used to enhance the sensitivity of various methods of optical spectrum analysis in these bands. For example, it has been used with a monochromator to detect the spectrum information over near-infrared and mid-infrared bands [85]. In this work, an F-P etalon was used as a monochromator to realize a scanning tunable narrow-band filter and a WSi

SNSPD was used to improve the detection sensitivity, as shown in Figure 5(a). The operation wavelength range covered 1.5–6 μm, and a temporal resolution of 1 ns was achieved. Based on the high sensitivity as well as the high temporal resolution of this spectrometer, the dynamic characteristics of the vibrational energy of carbon monoxide adsorbed to the surface of sodium chloride crystals were measured and reported [89], showing the potential of SNSPDs on optical spectrum analysis in the field of chemical analysis and material science. Another example is a photon-counting spectrometer with ultra-high wavelength resolution at telecom band [118]. In this work, a tunable on-chip lithium niobate micro-ring resonator was used as a tunable filter. Its resonance wavelength could be tuned by a thermal phase shifter. By scanning its resonance wavelength, the input light was filtered by the resonator, output from the chip, and detected by an SNSPD, as shown in Figure 5(b). It realized a spectral resolution as small as ~8 pm near 1572.02 nm. Based on this system, the solar absorption spectrum of carbon dioxide molecules in the atmosphere near 1572.02 nm was measured. It shows that the high sensitivity of SNSPDs is also desired for spectroscopy in atmospheric remote sensing.

Besides, the feature of small timing jitter makes SNSPDs suitable for highly time-resolved spectrometers for pulsed lights. Especially, optical spectrum analysis could be realized in the time domain by combining the high temporal resolution of SNSPDs and the large temporal dispersion of optical fibers. In 2015, Toussaint *et al.* [90] proposed a scheme to measure the spectrum of pulsed Raman signal light stimulated by an ultra-short pulsed pump light. In this scheme, a piece of optical fiber was used as a temporal dispersive component. The pulsed Raman signal light was injected into the fiber and then detected by an SNSPD after fiber transmission. The light pulses were broadened in the time domain due to the fiber dispersion, leading to the SNSPD recording the photons with different frequencies at different time delays. The temporal profile of the broadened pulses was measured by a TCSPC system, using the pulsed pump light as the trigger signal. This scheme could be described by the theoretical model shown in Figure 1. The time bins to record the photons in different time delays to the trigger signal were equivalent to a series of narrowband filters at different frequency sample points. The profile of the measured coincidence peak reflected the optical spectrum of the pulsed Ramans signal light, and the spectral resolution of the measurement was determined by the timing jitter of the SNSPD. A small temporal resolution of 20 ps was achieved in the measurement thanks to the low timing jitter of the SNSPD, resulting in a spectral resolu-

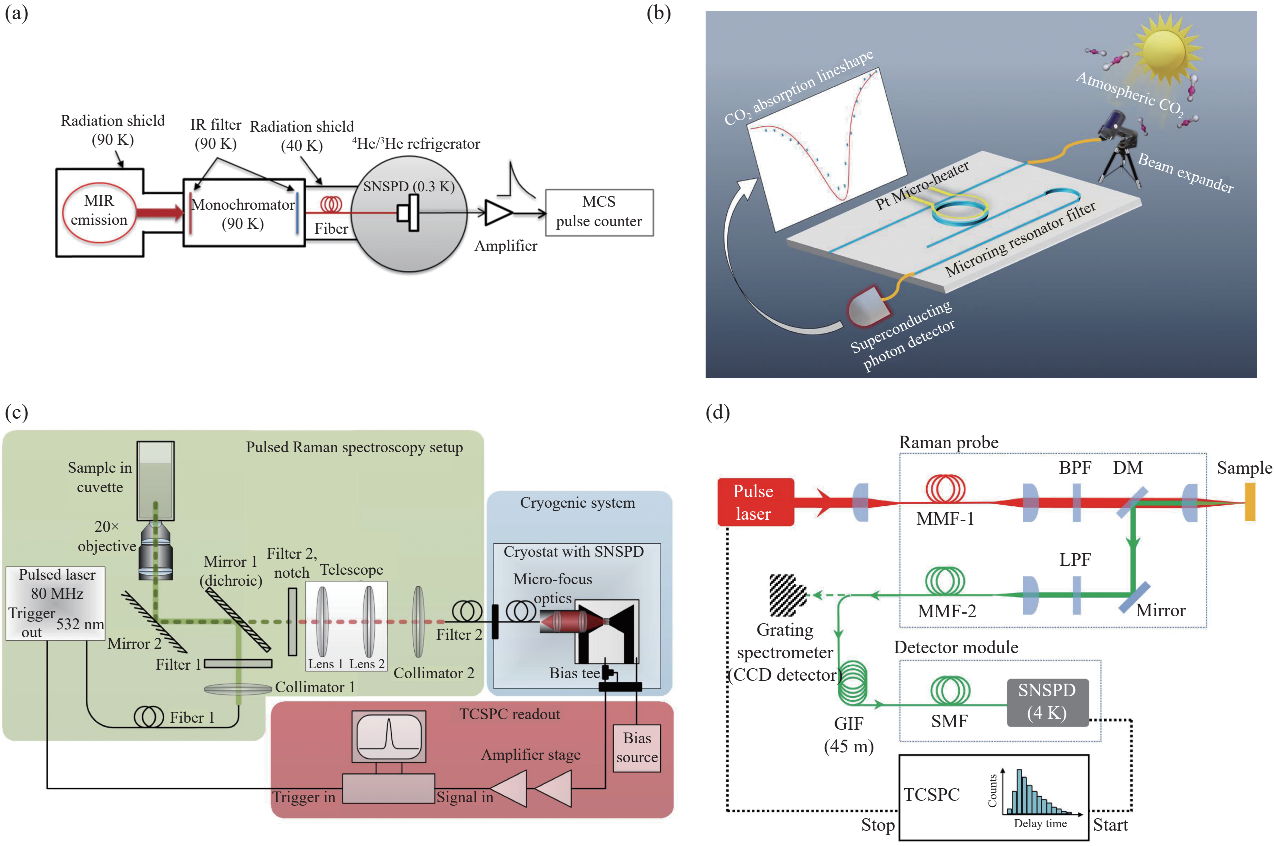

Figure 5 Photon-counting spectrometers using SNSPDs. (a) A monochromator with an SNSPD (MIR, mid-infrared; IR, infrared; MCS, multi-channel scaler) [85]; (b) A lithium niobate microring resonator used as a tunable narrowband filter with an SNSPD [118]; (c) and (d) A piece of optical fiber used as a temporal dispersion component with an SNSPD (BPF, band-pass filter; DM, dichroic mirror; LPF, long-pass filter; SMF, single-mode fiber; MMF, multi-mode fiber; GIF: graded-index fiber) [88], [90].

tion of 3.42 nm (wavenumber resolution of 149.25 cm^{-1}) at 629 nm. The wavenumber range of the measurement covered 0–4000 cm^{-1} (wavelength range of 532–676 nm) under a pump light at 532 nm. In 2021, Sidorova *et al*. [88] built up a system for Raman spectroscopy based on a similar principle with an improved spectral resolution. A wavenumber resolution of less than 5 cm^{-1} was achieved at 532 nm (a spectral resolution of ~0.2 nm) for an excitation wavelength of 532 nm, and a wavenumber resolution of 3–10 cm^{-1} (a spectral resolution of ~0.3–1 nm) for an excitation wavelength of 785 nm. The wavenumber range covered 0–4400 cm^{-1} in the measurements under both pump conditions (wavelength ranges of 532–695 nm and 785–1200 nm at the two excitation wavelengths, respectively).

3. Integrated photon-counting spectrometers based on SNSPDs

The development of hybrid integration of SNSPDs and on-chip photonic structures further extends the application of SNSPDs on optical spectrum analysis. Especially, it provides a promising way to develop integrated photon-counting spectrometers. In 2011, Cavalier *et al.* [119] proposed and demonstrated a stationary wave integrated Fourier transform spectrometer (SWIFTS) by hybrid integration of 24 SNSPDs with a silicon nitride single-mode ridged waveguide interferometer. In this device, the light to be measured was injected into the waveguide in both directions and formed a standing wave. Those 24 SNSPDs were fabricated under the waveguide interferometer with equal spacing to sample the intensity of the standing wave at different locations. Then, the optical spectrum was retrieved by the inverse Fourier transform of the measured results of the SNSPDs. The device featured a resolution of 170 nm. It is the first work of an integrated photon-counting spectrometer based on SNSPDs. However, the number of detectors limited its performance. Since then, integrated photon-counting spectrometers based on SNSPDs have been developed rapidly with the emergence of various hybrid integration schemes of SNSPDs and on-chip photonic structures, which can be mainly categorized into two types.

The first type is along the traditional methods of optical spectrum analysis. By integrating SNSPDs on the same photonic chip with dispersion components or optical filters, the information of the optical spectrum can be obtained from the photon-counting results of SNSPDs, achieving an integrated photon-counting spectrometer. In 2017, Zhao *et al.* [120] proposed that when a superconducting nanowire delay line absorbed a single photon, the arrival times of the induced electrical pulses at the two ends of the delay line were different. The time difference depended on the position at which the photon was absorbed and the hotspot was generated. Therefore, the incident position of the photon along the delay line could be obtained by measuring the difference between the two arrival times. By this way, a single superconducting nanowire delay line could be used to retrieve spatial information of incident photons with about 590 effective pixels. Based on this method, a broadband SNSPD-based spectrometer was reported by Cheng *et al.* [121] in 2019, as is shown in Figure 6(a) . In this device, an in-plane echelle grating dispersed the photons coupled into the chip, and the photons with different wavelengths were diffracted to different positions along a superconducting nanowire delay line. Similarly, by measuring the difference in arrival times at the two ends of the nanowire, the incident positions of the photons could be obtained, indicating the wavelength information of the photons. The device operated over a broad wavelength range (400–2000 nm) with an estimated spectral resolution of ~7 nm. The device for the telecommunication band was also fabricated, showing a wavelength range of 1420–1680 nm and a spectral resolution of 2.5 nm.

Arrayed waveguide grating (AWG) supports on-chip narrow-band filter arrays, which also could be used to develop integrated spectrometers. In 2017, Kahl *et al.* [122] realized a monolithic device integrating an AWG and eight SNSPDs. The spectroscopy setup for the device as well as the structure of the device is shown in Figure 6(b). The AWG was fabricated on a silicon-nitride-on-insulator substrate. The incident light was coupled to the chip and diffracted by the AWG. The photons with different wavelengths were sent to different output waveguides, and an SNSPD was fabricated on each output waveguide to detect the output photons. This device had eight output waveguides, supporting eight detection channels for different wavelengths. Two prototype devices were fabricated and tested. One had a center operation wavelength of 740 nm with a measurement wavelength range of 60 nm and a spectral resolution of 6.4 nm. The other had a center operation wavelength of 1550 nm with a measurement wavelength range of 24 nm and a spectral resolution of 2.2 nm. Thanks to the small timing jitter of the SNSPDs, which were less than 50 ps, the time-resolved fluorescence lifetime spectroscopy on silicon-vacancy color centers in diamond nanoclusters was measured.

The other type of integrated photon-counting spectrometers using SNSPDs is based on the principle of reconstructive spectrometers. Some representative works of this type is shown in Figure 7. As mentioned in Section II, reconstructive spectrometers reduce the number of detectors by compressive sensing. On-chip photonic structures could be used to achieve complicated modulations on spectral responses of the detectors, providing a promising way to miniaturize photon-counting spectrometers. In 2013, Redding *et al.* [123] proposed a scheme of reconstructive spectrometers based on an in-plane random scattering structure. The light was injected into the random scattering structure through a waveguide and output through an output waveguide array. In the array, the output waveguides were connected at different positions to the random scattering structure. The random scattering structure modulated the transmission spectra differently for the output waveguides at different positions. Then, the spectrum of the input light can

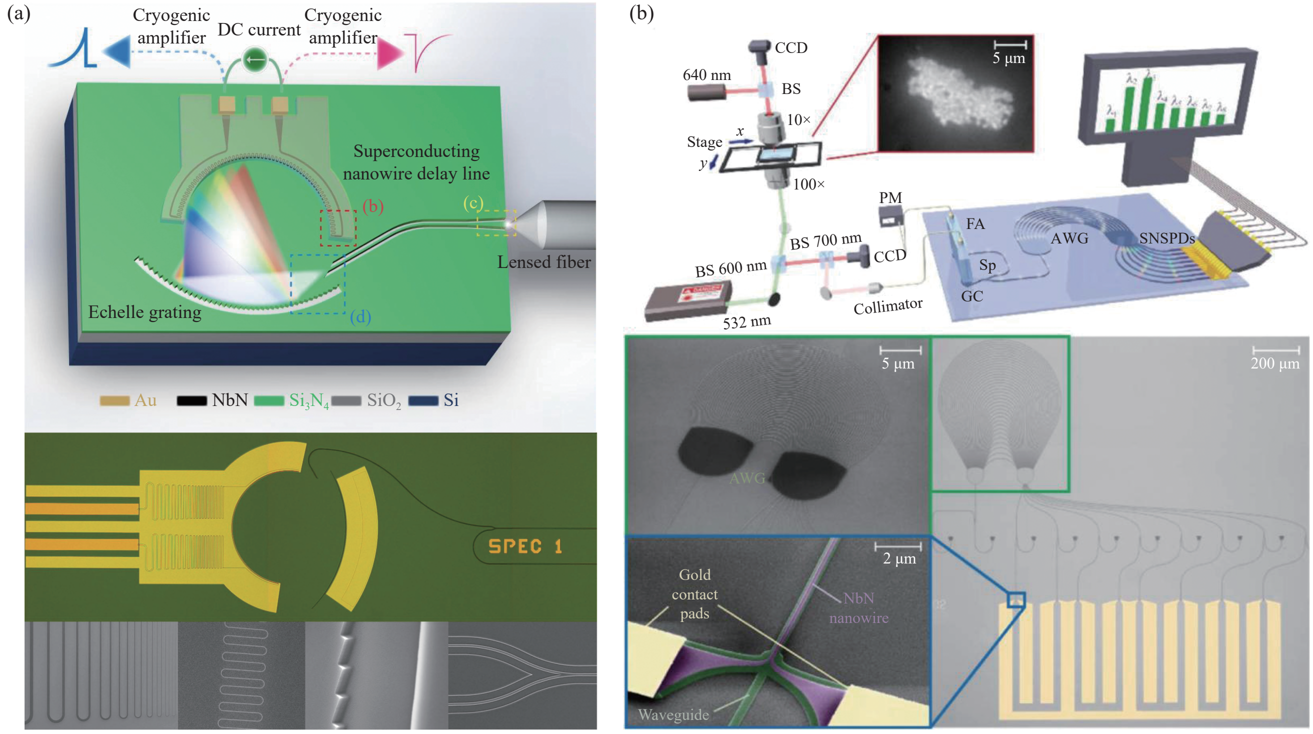

Figure 6 Integrated photon-counting spectrometers based on SNSPDs with (a) Echelle gratings [121] and (b) Arrayed waveguide gratings (AWG) (FA, fiber array; BS, beam splitter; PM, power meter; Sp, splitter; GC, grating coupler; *x* and *y* stand for the two moving direction of the piezostage) [122].

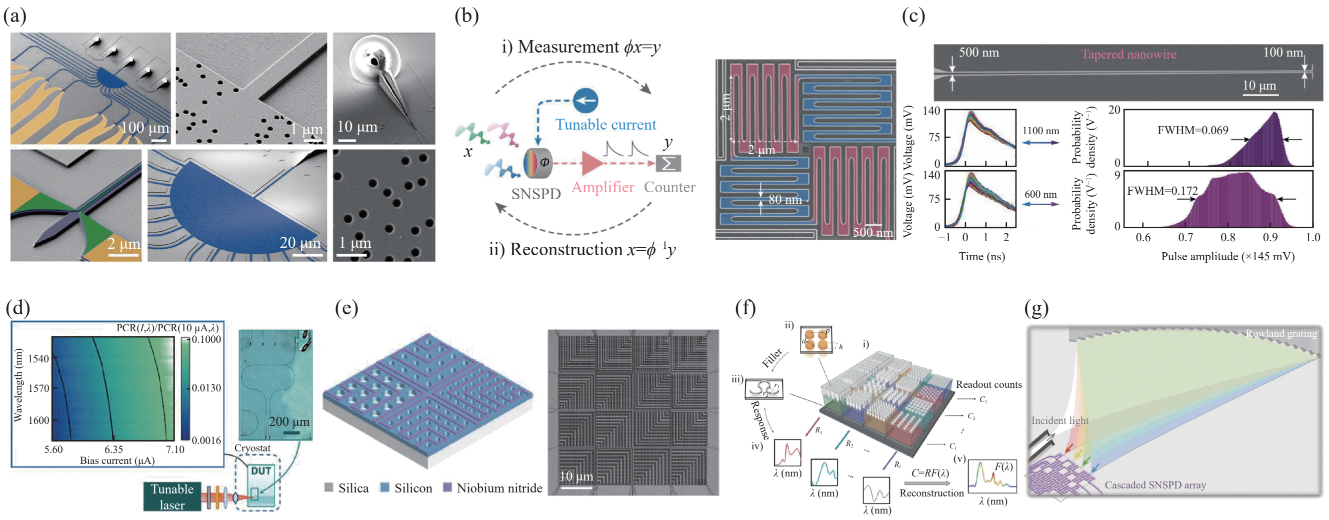

Figure 7 Reconstructive integrated photon-counting spectrometers based on (a) A random scattering structure and an SNSPD array [124]; (b) Spectral response difference under different bias current of an SNSPD (*x* and *y* stand for the measurement results and the spectrum to be reconstructed)[125]; (c) Spectral response difference under different output pulse amplitudes of a tapered SNSPD (FWHM, full width at half maximum)[126]; (d) Spectral response difference under different bias current of an SNSPD integrated on thin film lithium niobate (TFLN) waveguides (DUT, device under test; PCR, photon counting rate; λ, wavelength of input light)[127]; (e) Metasurface filters and an SNSPD array [128]; (f) 3D-printing photonic crystal filters and an SNSPD array (p, period of the cylinder arrays; d, diamter of the cylinders; h, height of the cylinder; r_1/r_2, the inner/outer radius of the fractal nanowires; R_i, the spectral response of the i-th detection channel; C_i, the response count of the i-th detection channel)[129]; and (g) A Rowland circle grating and a cascaded SNSPD array [130].

be reconstructed by the detected light powers of different output waveguides and their transmission spectra. In 2020, this scheme was applied to an integrated photon-counting reconstructive spectrometer based on SNSPDs [124]. In this work, the random scattering structure was a region with randomly distributed holes on the silicon-on-isolator (SOI) substrate, and stripe silicon waveguides were used as the input and output waveguides. The SNSPDs were integrated on the top of output waveguides, and the number of detection channels was 16. The device achieved a spectral resolution of 30 pm in the operation range of 793–808 nm and 4 nm in the operation range of 1530–1580 nm. The minimum input power required to reconstruct the spectrum was as low as −115 dBm.

In 2021, Kong *et al*. [125] realized a reconstructive spectrometer using only one SNSPD. This device exploited the feature of SNSPDs that the spectral response of a superconducting nanowire varies under different bias currents, which could be used as the bases of spectrum reconstruction. The device covered an operating wavelength range of 660–1900 nm, with a spectral resolution of 6 nm in the range of 1480–1640 nm. Furthermore, they developed a multispectral LIDAR system based on the device. However, the scheme could not support snapshot spectrum analysis since the bias current must be scanned across different values during the measurement. In 2022, the same research team reported that the amplitude of the output electrical pulses from a tapered superconducting nanowire had different probability distributions for photons with different wavelengths [126]. Based on this feature, they proposed and demonstrated another spectrometer scheme using only one SNSPD. The device achieved a spectral resolution of 100 nm in the wavelength range of 600–1700 nm, while only a few hundred photons were needed to achieve this spectral resolution [126]. The spectral response variation under different bias currents was also investigated for superconducting nanowires integrated on thin film lithium niobate (TFLN) waveguides in 2023 [127]. A resolution of 4 nm was achieved over the whole C- and L-band by properly selecting bias currents to establish the measurement bases.

In 2023, Zheng *et al*. [128] proposed a photon-counting reconstructive spectrometer combining optical metasurface arrays and SNSPD arrays. This scheme utilized the wavelength sensitivity of the local light field distribution on the surface of the metasurface structure. The SNSPDs were fabricated between the air nanoholes on the metasurfaces with different structure parameters. Hence, the spectral responses of the SNSPDs were modulated differently according to the different structure parameters of the corresponding metasurfaces. The spectrum of the input light could be reconstructed by the detection results of these SNSPDs and their spectral responses. The prototype device was fabricated and demonstrated, showing an operation wavelength range of 1350–1629 nm. A spectral resolution of 2 nm was achieved at 1500–1600 nm. Moreover, the spectrum analysis of an attenuated sweeping laser was demonstrated, showing its feasibility for real-time measurement of the light with a dynamically varied spectrum [128]. Almost at the same time, Xiao *et al*. [129] realized another photon-counting reconstructive spectrometer combining photonic crystal filter arrays and SNSPD arrays. In this device, the photonic crystal filters with different structure parameters were fabricated by 3D printing on the top of SNSPDs. The spectral responses of different SNSPDs were modulated by different photonic crystal filters, realizing the bases for the spectrum reconstruction. The polarization dependency of the device was reduced by introducing the fractal structure of superconducting nanowires [129]. The prototype device showed a resolution of 5 nm in the wavelength range of 1200–1700 nm.

In 2023, Zheng *et al*. [130] proposed another scheme of photon-counting reconstructive spectrometer combining on-chip Rowland circle grating and SNSPDs. In this device, the light to be measured was coupled to the input optical waveguide and guided towards the Rowland circle grating. The photons with different wavelengths passed through different spatial positions in the converging region of the Rowland grating. A total of 16 SNSPDs were set side by side across this region. Each of them had a specific zigzag pattern. They would have stronger absorption at the region where the zigzag pattern resulted in a higher density, which provided an effective way to modulate the spectral response of the SNSPD. Since the photons that passed through the converging region would be absorbed by one of the cascaded SNSPDs, the spectral responses of these SNSPDs could be designed flexibly by the zigzag patterns, considering the cascaded absorption effect. In this scheme, the additional photon loss due to filtering structures for spectral modulation was avoided in principle. The feasibility of this scheme was demonstrated by a prototype device, showing a spectral resolution of 0.4 nm in the operation range of 1495–1515 nm.

It is worth noting that the sensitivity of reconstructive photon-counting spectrometers is still a topic under investigation, and most works above did not touch it. It could be indicated by the minimum input photon number to realize a reliable optical spectrum analysis. A simple but instructive way to analyze the minimum photon number was proposed in our previous work [128] and applied on the spectrometer in the work under specific broadband light. The root mean square error (RMSE) between the reconstructed spectrum and the ground truth was used to evaluate the quality of spectrum measurement. The theoretical analysis and experiment results showed that the RMSE was reduced with increasing input photon number, with a nonzero floor when the photon number was high due to the limitation of compressive sensing. At the same time, the standard deviation of the RMSE of multiple measurements was also reduced with increasing input photon number. If a specific value of RMSE was defined as the criteria of a reliable measurement, and a confidence level of the reliable measurement was set, the minimum input photon number could be calculated according to the relations between the RMSE (and its standard deviation) and the input photon number. Although the analysis was based on input light with a specific spectrum, it provided a reasonable method to estimate the sensitivity of reconstructive photon-counting spectrometers quantitatively.

V. Prospects

All the works introduced in this paper are summarized in Table 1 for a clear comparison. It can be seen that the research of photon-counting spectrometers based on SNSPDs is in its early stage, focusing on exploring device schemes and demonstrating their feasibility. The existing works have shown the great potential of SNSPDs on optical spectrum analysis on ultra-faint light. We would like to provide some prospects that may extend the research and application of this emerging technology.

1. Developing theories of photon-counting spectrometer

Single-photon detection has been used in optical spectrum analysis for a long time. It brings new features that need to be considered, such as statistics of photon flux, temporal resolution of single-photon detection, and various nonideal performances of real single-photon detectors. It also impacts the evaluation criteria of spectrometers, requiring new parameters to describe the photon-counting characteristics. However, comprehensive theories to describe and evaluate the photon-counting spectrometer are still under investigation, especially for the schemes based on spectrum reconstruction. Notably, a photon-counting spectrometer is specifically developed for applications under ultra-faint light. Therefore, the minimum input photon number required to realize a reliable optical spectrum analysis is a meaningful question. It indicates the sensitivity of the spectrometer and determines the measurement time of photon-counting spectrometers in applications. The related research is still in the initial stage. It can be expected that theories of photon-counting spectrometers will develop continuously by exploring different methods to combine single-photon detection and various optical spectrum analysis methods. As a result, the theoretical instruction would promote the performance of photon-counting spectrometers based on SNSPDs and extend their applications.

2. Improving device performance of integrated photon-counting spectrometers

Table 1 shows that the system efficiencies in the reported works of photon-counting spectrometers using SNSPDs are quite low. It is partly due to the intrinsic efficiency of the SNSPDs used in these works, partly due to the losses introduced by the optical system in the spectrometer, and the optical coupling when the light is coupled to the input fibers for sending the photons to the SNSPDs from the optical system. The low system efficiency would significantly limit the sensitivity of the spectrometer. A possible way to improve the system efficiency is the hybrid integration of SNSPDs and the optical system on the same chip, which may improve the transmission of the optical system and reduce the coupling loss of SNSPDs. According to the works of integrated photon-counting spectrometers shown in Table 1, their system efficiencies also have a large room for improvement to take full advantage of SNSPDs. New optical spectrum analysis methods and optical system design for integrated spectrometers are expected. Besides, the hybrid integration technology of SNSPDs and on-chip photonic structures should be further improved to enhance the performance of integrated SNSPDs.

3. Developing devices according to the requirement of applications

In the early stage of the research, the existing works have shown the feasibility and characteristics of photon-counting spectrometers based on SNSPDs. It can be expected that the following research will focus on developing practical

Table 1 Comparison of reported photon-counting spectrometers based on SNSPDs

Category	Scheme/Principle		Material of SNSPDs	Bandwidth	System efficiency	Resolution	Reference
Photon-counting spectrometers using SNSPDs	Monochromator with an F-P etalon		WSi	1.5–6.0 μm	4×10^{-6}	N/A	[85]
	LN ring resonator as a scanning filter		N/A	1571.65–1572.10 nm	N/A	6 pm	[118]
	Temporal dispersion of fiber		NbN	532–676 nm	<1% (QE)	3.42 nm	[90]
			NbN	532–695 nm 785–1200 nm	<1%	0.2 nm	[88]
Integrated photon-counting spectrometers based on SNSPDs	SWIFTS		NbN	N/A	N/A	170 nm	[119]
	Dispersion of an on-chip grating		NbN	600–2000 nm 1420–1680 nm	<0.1% <0.3%	7 nm 2.5 nm	[121]
	AWG as a narrow band filter array		NbN	720–770 nm 1536–1556 nm (approx.)	1.97%	6.4 nm 2.2 nm	[122]
	Reconstructive spectrometer	Disordered scattering structure	NbN	793–808 nm 1530–1580 nm	N/A	30 pm 4 nm	[124]
		Bias current	NbN	660–1900 nm	10^{-6}	10 nm	[125]
		Amplitude mapping	NbN	600–1700 nm	N/A	100 nm	[126]
		Bias current	NbTiN	1520–1630 nm	10^{-8}	4 nm	[127]
		Metasurface	NbN	1350–1629 nm	1.4%–3.2%	2 nm	[128]
		PhC filter	NbN	1200–1700 nm	1.6%–4.7%	5 nm	[129]
		A grating + cascaded SNSPDs	NbN	1495–1515 nm	0.03%–0.05%	0.4 nm	[130]

devices based on the unique features of SNSPDs, according to the requirements of real applications. We would like to note some possible applications that are appropriate for this technology. First, the operation wavelength range of SNSPDs is ultra-broad and could be designed from the ultraviolet band to the mid-infrared band. Thus, it provides a promising way to develop broadband or multi-spectral band spectrometers for some applications in remote sensing. Second, as single-photon detectors, SNSPDs could record the arrival time of a single photon with a small timing jitter. This feature can be used to develop photon-counting spectrometers to acquire both the optical spectrum information and the arrival time of each single-photon detection event. Combined with time-of-flight (TOF) measurement, these devices could realize LiDARs with spectrum analysis. They also can be used in time-resolved fluorescence spectroscopy, which is a useful tool in biology, medicine, chemical, and material analysis. Finally, it has been shown that SNSPD is easy to be integrated on metasurfaces, which are powerful tools for manipulating optical fields. By properly designing the metasurfaces, the devices can obtain more information about the optical field besides the optical spectrum. It is an interesting topic to develop devices achieving multi-freedom optical field detection by combining SNSPDs and metasurfaces.

4. Exploring new methods for in-sensor computing

In recent years, artificial intelligence algorithms, namely neural networks, deep learning, etc., have provided new ways for efficient information processing. To decrease the computation costs, parallel computing of neural networks using optical methods has attracted widespread attention and has become a hot topic. It is worth noting that the measurement process of the reconstructive spectrometer can be regarded as a linear layer of a neural network. In cooperation with the subsequent electrical neural network computation, it is expected to complete complex spectral sensing tasks. Hence, how to develop a neural network computing architecture that features in-sensor computing and combines software and hardware would be a significant research direction.

VI. Conclusion

This paper reviews recent progress on photon-counting spectrometers based on SNSPDs, which realize optical spectrum analysis on ultra-faint light in a wide operation wavelength range. Besides, these spectrometers could also record the arrival time of the single-photon events. These features make them promising in many applications requiring optical spectrum analysis with single-photon level sensitivity and inspire new spectral analysis applications requiring time-resolved measurement. This paper briefly reviews the methods of optical spectrum analysis. Then, the principle and development of SNSPDs are introduced. The main part of this paper reviews the development of photon-counting spectrometers based on SNSPDs, especially the integrated devices combining SNSPDs and various on-chip photonic structures. Finally, the prospects of this emerging technology are provided. The research of photon-counting spectrometers based on SNSPDs is still in the early stage, focusing on exploring the device scheme and their feasibility demonstration. According to its great potential shown in the existing works, this technology has a large space to develop by improving its theory and device performance, developing devices according to the requirements of applications, and introducing the concept of in-sensor computing. It can be expected that optical spectrum analysis will benefit from the excellent features of SNSPDs, extending its application in scenarios under ultra-faint light.

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