A Single-Photon-Sensitivity Spectrometer Based on Metasurfaces

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Abstract: We demonstrate a single-photon-sensitivity spectrometer based on metasurfaces and superconducting nanowire single-photon detectors with 1.5% ~ 9.5% total detection efficiency at 1100 nm ~ 1700 nm. © 2022 The Author(s)

Optical spectroscopy of single-photon-level weak light has important applications in the quantum information, fluorescence spectroscopy, remote sensing and astronomical observations. The conventional solution for optical spectral measurement of weak light is based on tunable narrow-band filters such as monochromators or acousto-optic tunable filters, together with single-photon detectors, to achieve photon counting measurement at different wavelengths [1]. However, the utilization of photons in these solutions are quite low, since the tunable narrow-band filter would block photons outside its transmission band. Hence, the measurement time is determined by the photon counting process at each wavelength points and wavelength scanning, which is quite long. In recent years, computational spectral reconstruction has developed rapidly due to its potential on realizing miniaturized spectrometers. We believe that it also has an important advantage on enhancing the photon utilization in the optical spectral measurement of weak light. In addition, as an ideal broadband detection technique of single-photon-level weak light, superconducting nanowire single-photon detectors (SNSPDs) have great potential on realizing single photon sensitivity spectrometers. Several related works have been reported based on conventional solutions and computational methods [2-5]. However, the detection efficiencies of these devices still limit their further applications.

In this paper, we report a single-photon-sensitivity spectrometer based on metasurfaces, on which superconducting nanowires are fabricated to realize photon counting measurement. It is well-known that different metasurface structures have different transmission or reflection spectra for incident light. Hence, a spectrometer can be realized by combining different metasurfaces with SNSPDs based on computational spectral reconstruction. If the spectrum of the incident photon flux density to be measured is denoted as $f(\lambda)$ and the spectral response of the i-th detection unit is denoted as $h_i(\lambda)$, $i = 1,2,\ldots,N$, where N is the number of the detection units, λ is the wavelength, the photon counting rate (PCR) $c_i(\lambda)$ of the i-th unit can be expressed by $c_i(\lambda) = \int_{\lambda_{min}}^{\lambda_{max}} f(\lambda)\, h_i(\lambda) d\lambda$. In practice, spectra are discretized via wavelength sampling and the number of discrete wavelength points is M. In our spectrometer, N is smaller than M and an algorithm of compressive sensing needs to be used to reconstructed the incident spectrum $f(\lambda)$.

We fabricated a spectrometer sample with 12 detection units and demonstrated its performance experimentally. Fig. 1 (a) schematically shows one detection unit with the SNSPD arranged on the metasurface. Niobium nitride (NbN) is used as the material of the SNSPDs, which is deposited on a SOI (Silicon-On-Insulator) substrate with a 340-nm-thick silicon layer. Then the nanowires are patterned via electron-beam lithography (EBL) and etched by reactive-ion etching (RIE). Next, the electrodes of the nanowires are also formed by the NbN film using ultra-violet lithography and RIE process. Finally, the metasurfaces are defined by EBL and etched by the inductively coupled plasma reactive-ion etching (ICP-RIE) at the 340 nm silicon layer. Fig. 1 (b) shows a scanning-electron micrograph, which has 4 of the 12 detection units in total of the fabricated spectrometer sample. The sample is mounted in a cryostat, coupled with an optical fiber under a temperature of 2.1K.

In order to calibrate the spectral response $h_i(\lambda)$ of each detection unit, we use a broadband supercontinuum laser as the light source, an acoustic-optical tunable filter (AOTF) for wavelength points sweeping, an optical power meter to measure the incident light power and a counter connecting with the detection units for the PCRs at each wavelength sampling point. The detection efficiency spectra of the 12 detections units and their normalized spectral responses are shown in Fig. 2 (a) and (b), respectively. The wavelength region of the measurement was from 1100 nm to 1700 nm. Then the total detection efficiency spectrum of the spectrometer is calculated and shown in Fig 2.

(c). It can be seen that the efficiency is in a range of 1.5% ~ 9.5% at different wavelength points, which is much higher than previous related works. The performance of the computational spectral reconstruction of monochromatic lights at different wavelengths is shown in Fig 2. (d), demonstrating that the sample can realize optical spectrum measurement over broad wavelength region. It can be expected that the performance of this device has great potential on further improvement.

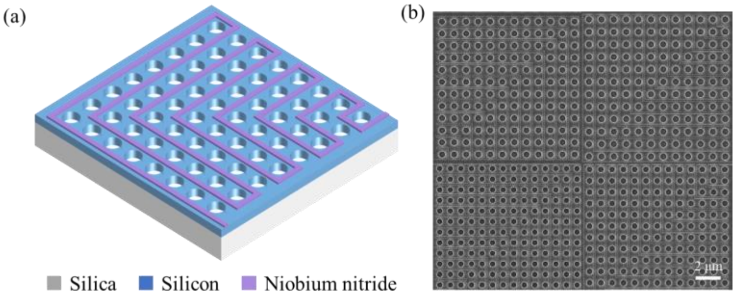

Fig. 1. Design and fabrication of the single-photon-sensitivity spectrometer based on metasurfaces and SNSPDs. (a) Schematic optical structure of the detection unit in the spectrometer. (b) A scanning-electron micrograph of 4 detection units.

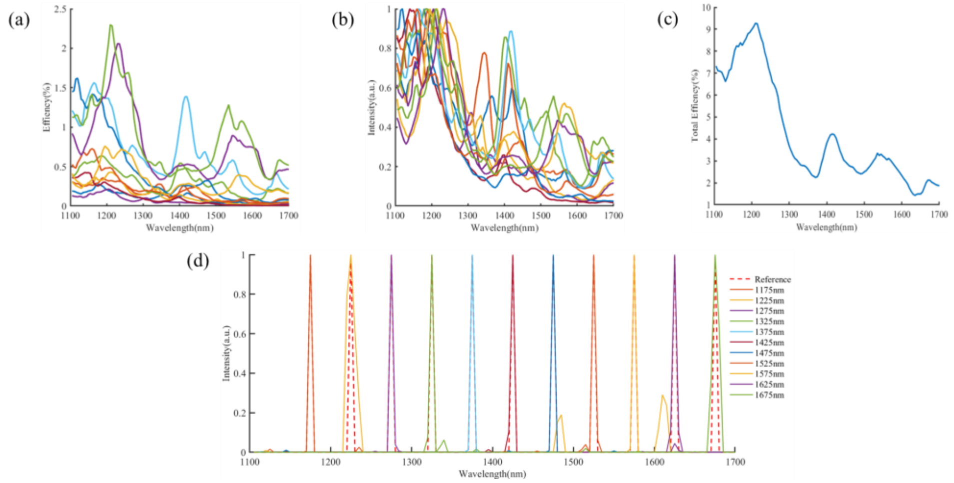

Fig. 2. Demonstration of monochromatic spectral measurements. (a) detection efficiency spectra of the 12 detections units. (b) corresponding normalized spectral responses in (a). (c) total detection efficiency spectra of the spectrometer. (d) Reconstructed spectra of monochromatic light at different wavelength.

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References

[1] C. Li, *et al*., "Ultra-sensitive mid-infrared emission spectrometer with sub-ns temporal resolution," Opt. Express **26**, 14859-14868, (2018)
[2] O. Kahl, *et al*., "Spectrally multiplexed single-photon detection with hybrid superconducting nanophotonic circuits," Optica **4**, 557-562, (2017)
[3] R. Cheng, *et al*., "Broadband on-chip single-photon spectrometer," Nat Commun **10**, 4104 (2019).
[4] W. Hartmann, *et al*., "Broadband spectrometer with single-photon sensitivity exploiting tailored disorder." Nano Lett. **20.4**, 2625-2631, (2020).
[5] L. Kong, *et al*., "Single-Detector Spectrometer Using a Superconducting Nanowire." Nano Lett. (2021).