Photon-counting single-pixel 3D imaging using a multimode-fiber-coupled fractal SNSPD

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Abstract: We demonstrate photon-counting single-pixel 3D imaging using a multimode-fiber-coupled fractal SNSPD and showcase 32×32-pixel imaging with reflectance and depth contrasts at the wavelength of 1560 nm.

1. Introduction

Faint-light imaging with high timing resolution and low noises plays an important role in fluorescence-lifetime microscopy [1] and remote sensing [2]. Superconducting nanowire single-photon detectors (SNSPDs) are good sensors for imaging at single-photon level, due to their high system detection efficiency (SDE), low timing jitter, low dark-counts rate, and broad spectral response with single-photon sensitivity. However, SNSPD arrays with many pixels still remain a challenge. On the other hand, single-pixel imaging is an alternative path to approaching single-photon-level imaging, using only one detector and a spatial light modulator [3–5]. In particular, researchers performed photon-counting single-pixel 3D imaging at the wavelength of 780 nm using a photomultiplier tube (PMT) as the photon counter [3]; in the longer wavelength range, recently, using individual SNSPDs, researchers demonstrated single-pixel imaging with the contrast of intensity [4,5] but without depth contrast.

In this paper, we report on photon-counting single-pixel 3D imaging at the wavelength of 1560 nm using a multimode-optical-fiber coupled fractal SNSPD. In the past, we demonstrated fractal SNSPDs with high SDE, very reduced polarization sensitivity and high timing resolution [6,7], and applied them in full-Stokes polarization LiDAR system [8]. But all these fractal SNSPDs were coupled with single-mode optical fibers. To enhance the collection efficiency of incident light, in this work, we implement a multimode-fiber (MMF)-coupled fractal SNSPDs for single-pixel imaging. The core diameter of the MMF is 50-μm and the photosensitive area of the fractal SNSPD is 22.9 μm $\times$ 22.9 μm. We achieve 43.5% SDE and 93-ps timing jitter. This system permits photon-counting single-pixel 3D imaging at the wavelength of 1560 nm.

2. Experiment and results

We first characterized the MMF-coupled fractal SNSPD. Figure 1 (a) presents a false-colored scanning-electron micrograph (SEM) of the detector. Similar to what were reported in Refs. [6,7], the device is configured as the cascaded superconducting nanowire avalanche photodetector (SNAP) structure, but with an expanded photosensitive area for ensuring good coupling efficiency with the MMF. The width of the nanowire is 50 nm. The fractal SNSPD was coupled with the MMF through dual-lens optical system [9] with beam compression ratio (the ratio of the mode-field diameters of the output and input beams) of 0.37. The device was mounted in a 0.1-W G-M cryocooler with a based temperature of 2.2 K. A cryogenic low-noise amplifier was mounted on the 40-K stage. Figure 1 (b) presents the output voltage pulse after amplification. The time constant of the falling edge is 24 ns. Figure 1 (c) presents the measured system detection efficiency (SDE) and false count rate (FCR) as a function of bias current at the wavelength of 1595 nm, which is peak wavelenth of the SDE spectrum, using the method of time-correlated single-photon counting (TCSPC). The maximum SDE is 43.5% at the bias current of 19.2 μA. The FCR was 1.4×10^4 cps at the bias current of 19.2 μA. Figure 1 (d) presents the measured timing jitter, the full width at half-maxima of the time-delay histogram, of the device as the function of bias current. The measurement was performed with a mode-locked femto-second fiber laser with the central wavelength of 1560 nm and an oscilloscope. The minimum timing jitter was measured to be 93 ps at the bias current of 19.6 μA.

Figure 2 (a) presents the experiment of the 3D single-pixel imaging with the MMF-coupled fractal SNSPD. A femto-second fiber laser with the central wavelength of 1560 nm, average power of 90 mW, and repetition frequency of 82 MHz, was used as the light source. After split by a 99:1 fiber directional coupler, one channel was coupled to a fast photo-detector to provide the start signals for the TCSPC module, and the other channel of light, after collimation, went through the diffuser and illuminated the object. The light scattered by the object was projected to the digital micro-mirror device (DMD) plane through a lens with focus length of 100 mm. The DMD

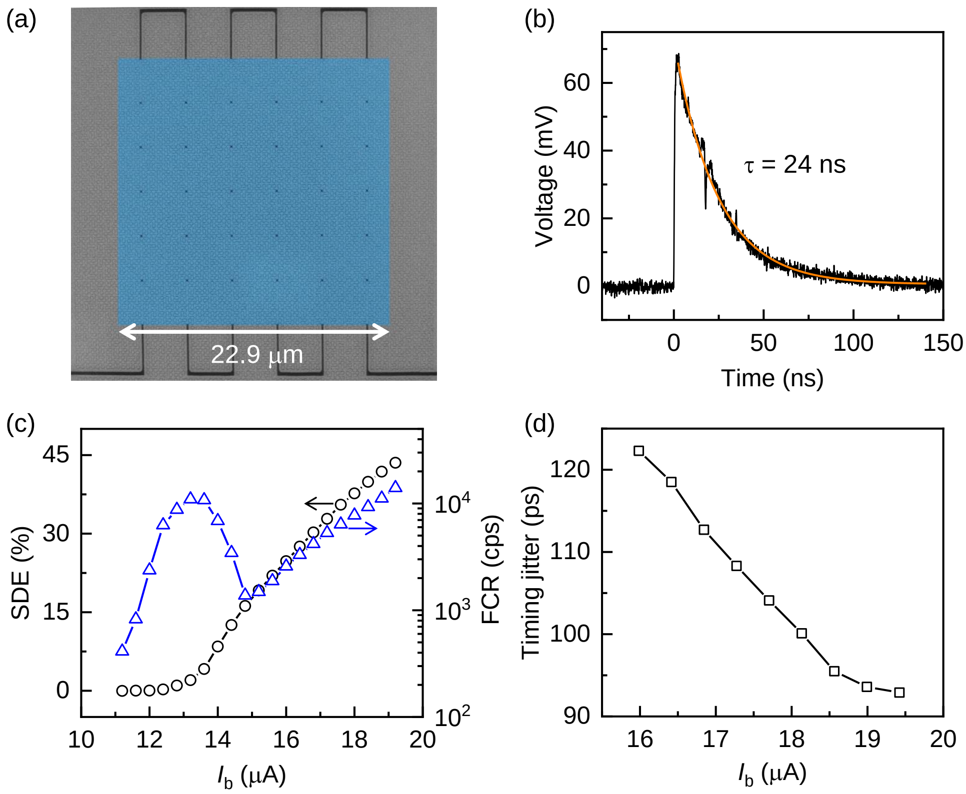

Fig. 1. Characterization of the multimode-fiber (MMF)-coupled fractal SNSPD. (a) A false-colored scanning-electron micrograph of the fractal SNSPD. The photosensitive area is 22.9 μm × 22.9 μm. (b) The output voltage pulse of the fractal SNSPD after amplification. The electrical time constant of the falling edge is 24 ns. (c) System detection efficiency (SDE) and false-count rate (FCR) of the MMF-coupled fractal SNSPD. The core diameter of MMF is 50 μm. (d) Timing jitter of the MMF-coupled fractal SNSPD.

consists of 1280 × 800 micro-mirror array. Every micro-mirror can be fixed in two discrete rotation angle: ±12°, relative to DMD plane. When we set "1" signal to the micro-mirror, the light reflected from the micro-mirror was fed into multi-mode fiber. When we set "0" signal, the light was reflected to another direction and was not received. The DMD driver was used to set "1" or "0" for every micro-mirror to perform spatial sampling with certain patterns, for example, raster-scan pattern or Hadamard pattern.

When the DMD started to work, the DMD driver output a square wave signal, which, after passing through a home-made RC circuit to change the waveform to a pulse, was fed into TCSPC module as the frame-start signal. The received light, after attenuation, was detected by the MMF-coupled fractal SNSPD. The output electrical pulses, after amplification, were sent to the TCSPC module as the stop signals. The distance between the facet of the MMF and the DMD plane was approximately 10 cm to ensure the field of view of multi-mode fiber to cover the DMD plane. In our experiment, the object is the upper body of a wooden doll with its arm positioned in front of it, as shown in Fig. 2 (b). The object was placed at a distance of approximately 90 cm from the project lens. To reconstruct the reflectance image and the depth image with 32 × 32 pixels, a complete Hadamard set of 1024 patterns and their inverse patterns were used. We first displayed each Hadamard pattern, followed by its inverse pattern, and took the difference of the measured photon counts as the data for image reconstruction. This method could remove the background noises, including the false counts of the fractal SNSPD. The frame rate was 100 Hz, and therefore, the dwell time for each frame was approximately 10 ms (in each frame, there was a 80 μs preparation time, and therefore, the actual dwell time was less than 10 ms.). The total time for data acquisition was 20.48 second. To avoid latching at high photon count rate during the measurement, we used a constant-voltage bias circuit to bias the fractal SNSPD.

Figure 2 (c) presents an example of the measured histograms of five frames. The size of each time bin is 4 ps. While the typical single-pixel imaging schemes use the total counts per frame to reconstruct a 2D image [4, 5], our scheme, similar to Ref. [10] but at faint-light level, used the counts per time bin per frame to reconstruct a series of 2D images versus depth. The depth image was obtained by finding the depth, which is corresponding to the maximum reflectance in these 2D images at the same pixel point. A hard threshold of reflectance at each pixel was set to filter out some noises, which otherwise may result in a random depth in depth image. Fig. 2 (d) presents the reconstructed image of reflectance. The arm and the head of the wooden doll can clearly be recognized. Figure 2 (e) presents the reconstructed image of depth. The arm and the head can also be recognized clearly.

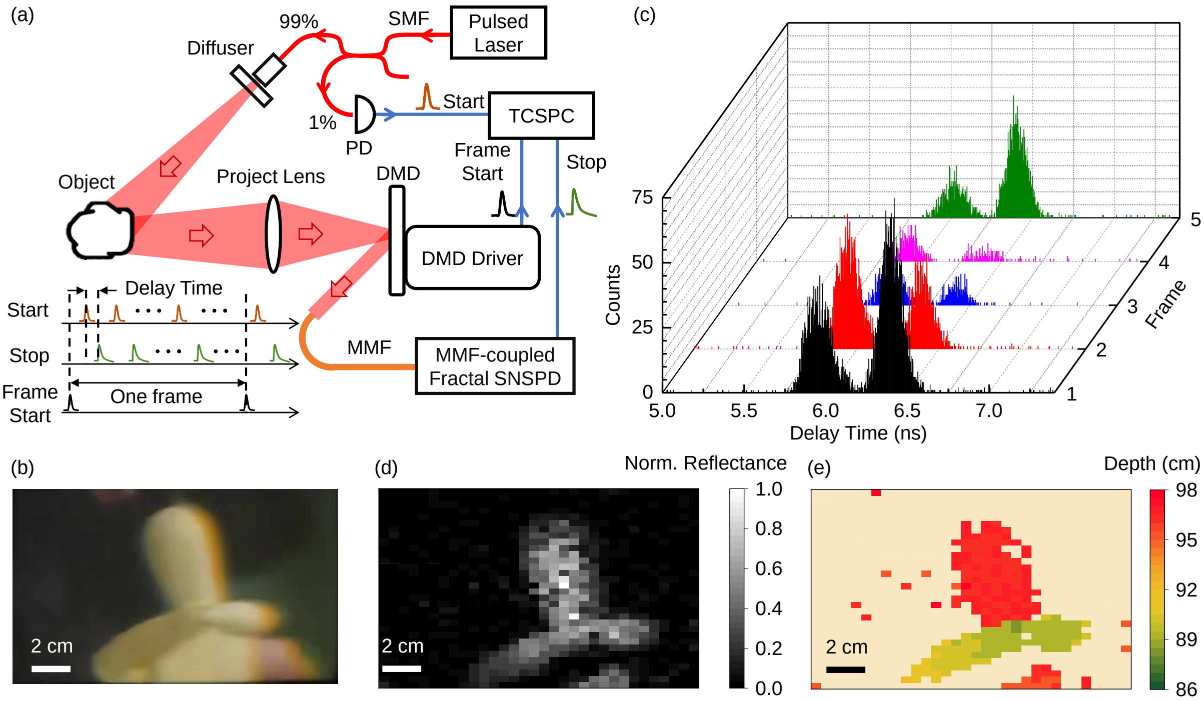

Fig. 2. Photon-counting single-pixel 3D imaging using a MMF-coupled fractal SNSPD. (a) The schematic drawing of the experimental setup and time sequence of the signals. SMF, single-mode fiber; PD, photo-detector; DMD, digital mirror device; TCSPC, time-correlated single photon counting; MMF, multi-mode fiber. (b) Photograph of the objects, containing the head and arms of the wooden doll. (c) The histograms of the photon counts of the first five frames. (d) The reconstructed image with reflectance contrast. (e) The reconstructed image with depth contrast.

3. Conclusion

We have demonstrated a MMF-coupled fractal SNSPD system with 43.5% SDE and 93-ps timing jitter. The core diameter of the MMF is 50-μm and the photosensitive area of the fractal SNSPD is 22.9 μm × 22.9 μm. Using this system, we have demonstrated photon-counting single-pixel 3D imaging with 32 × 32 pixels and reflectance and depth contrasts at the wavelength of 1560 nm. In the future, we consider further optimize the MMF-coupled fractal SNSPD, increase the frame rate and extend the distance of the 3D single-pixel imaging camera.

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