Review of Recent Superconducting Nanowire Single Photon Detector System Modeling Methods and Demonstrated Applications

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Abstract— In this review, two modeling methods that have been developed for superconducting nanowire single-photon detectors with efficient overall system performance has been described, with their design and simulation models at wavelengths near 500 nm for TE mode. The Merits and tradeoff of the methods for effective coupling at optical fiber cable, Electrical readout is described. In addition, the recent demonstrated examples in which SNSPDs is applied are reviewed.

Index Terms— Single Photon Counting Detector, Waveguide cavity, Racetrack Resonator, Polarization Mode, Time-Correlated Single –Photon Counting Module.

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1 INTRODUCTION

Single photon counting detector was used in communication links to enhance the receiver performance over the existing conventional photo detectors at the telecommunication window wavelengths [1]. As the maximum data rate demonstrated by the first generation InGaAs avalanche photodiode using these techniques are about 100kbits/sec to some tens of Mbits/sec [2, 3]. The limitation of the data rates are due to the resolution, reset time of the APDs and limitations of the laser transmitters/ receivers. Recently, a new technology based single photon detector made from a new material (niobium nitride) NbN nanowire [4] was demonstrated by G.N.Gol'tsman, which shows a higher performance in detection efficiency. With this there has been a remarkable advances in superconducting nanowire single photon detectors (SNSPDs) technology. Further, in addition to advances in detector capabilities, advances in low-losses at optical coupling, high performance readout circuits, and design optimization proved the demonstration of detector system which offers enhanced performance metrics of the detector. A number of different researchers used different engineering approaches to overcome challenges in the modeling, fabrication and performance metrics.

2 MODELING OF SNSPD IN A WAVEGUIDE CAVITY

In present SNSPD systems, light is focused on to the detection area of the meander nanowire [5]. Another method, intermingle the detector in the waveguide structure [6-7]. In such approach, the design is that the single photons move along the waveguide with an SNSPD and leading to a higher interaction length of photons and the meander nanowire of the detector. As the system efficiency is dependent on the absorption efficiency of the system which in turn is dependent on the length of the detection area, thus the detection efficiency can be higher. With that, efficiencies more than 80% to 90% have been reported with SNSPDs and SNTES as narrow as 20 μm to 30 μm [8-9].The available commercial top- coupled detectors have much higher length. The other advantage of waveguide model is that it is used in the photonic based circuits.

The application of the optical cavities shows improved efficiencies for top-coupled devices [10]. The optical resonator for waveguide integrated detector enhances the interaction length and decrease the long nanowire. Recently, integration of waveguide coupled SNSPD inside photonic crystal cavity have been reported [11].

3. DESIGN AND SIMULATION MODEL

Here SNSPD is examined for a cavity and the outcome can be authentic for any cavity. A race track resonator is familiar due to its easy manufacturing, compatibility. The cavity comprises of a wave guide racetrack resonator containing an integrated detector and a bus guide. Thus light is transmitted in and out of the cavity in the coupling area; meddling interfere the outcome of the bus waveguide at resonance frequency. The detection efficiencies reach high value at critical coupling. Some of the photons were trapped inside the resonator and are lost in waveguide or absorbed by the material of the detector, which leads to unity detection at resonance frequency. The resonator is used as a racetrack cavity having directional coupler in the coupling area. The fundamental quasi-TE mode is used in all simulations. Fig.1. Diagram represents the SNSPD in the wave guide racetrack resonator cavity. The Silicon-on-insulator (SOI) waveguides of 0.5 μm by 0.22 μm cross section, on a 1 μm thick SiO2 slab are considered in the design. For (TE) polarization mode Waveguide is optimized. The SNSPD considered here has two 4.5 nm thick, 100 nm wide parallel NbN wires separated by 100 nm and centered on top of the waveguide. The directional coupler allows selecting the transmissivity between 0 and 1 by altering the interaction length and by separating the bus waveguide and the cavity.

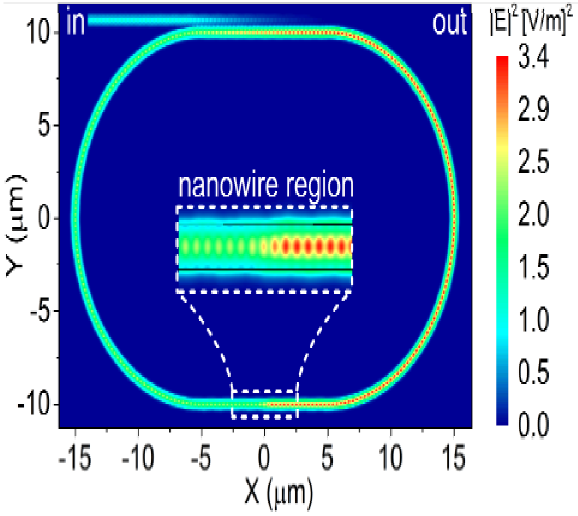

Fig. 1. Diagram of racetrack resonant cavity

The schematic in fig.1 is a model with the nanowire region lying inside the cavity. When Light in the input side Ein arrives at the coupling region of the resonator as a fraction is left in the bus waveguide after interfering with light, Eout , and some light goes into the racetrack, E0. Were EL is the light for one round trip of length L.

The output field for racetrack resonator for a single wavelength, λ, is expressed [12] as

$$E_{out}(\lambda) = \frac{r-\alpha e^{i\theta(\lambda)}}{1-\alpha e^{i\theta(\lambda)}} E_{in}(\lambda) \ldots\ldots\ (1)$$

Where r represents the reflection coefficient of coupling region, α the transmission coefficient inside the racetrack and $\theta(\lambda)$ the phase accumulated for photon with wavelength λ during one cavity cycle. The results illustrate the potential of cavity –coupled photon detectors, in particular waveguide-coupled [13] Superconducting Nanowire Single Photon Detectors.

4. MODELING OF SNSPD WITH NON-PERIODIC DIELECTRIC MULTILAYER

A mechanism structure of SNSPD with a non-periodic dielectric multilayer (DML), which enables more designs for the wavelength dependences of the optical absorptance in meander nanowire. In Fig 2. The structure on non periodic DML is shown. The DML structure consists of two different dielectric materials with different refractive indices are placed on the substrate and the superconducting nanowire is kept on the DML. One can optimize the wavelength dependence of the optical absorptance by choosing the thickness of each dielectric layer. One can achieve both wider and narrow bandwidth by the SNSPD with non –periodic DML.as periodic DML have been used for SNSPDs as a mirror for shorter wavelengths to enhance the absorptance.

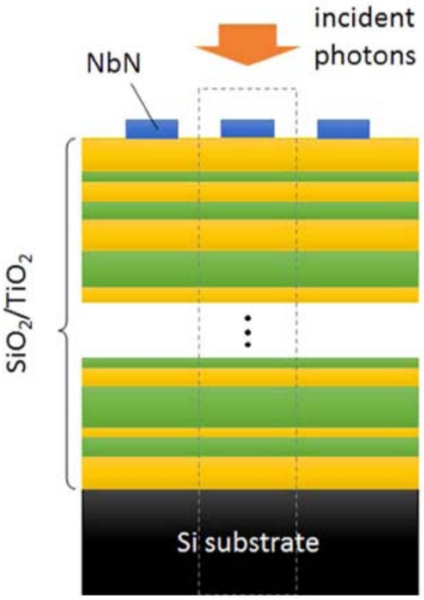

Fig. 2. Schematic of an SNSPD with non-periodic dielectric multilayer.

In study SiO2 and TiO2 are used as dielectric materials, and NbN was used for the superconducting nanowire [14]. From the optimization process, the thickness of each layer in the DML was 10-175 nm, and the total number of layers and thickness of the DML were 29 layers and 2.0 μm respectively.

Using the obtained thickness of the dielectric layers, we calculate the absorptance in the NbN nanowire assuming that the line and pitch of the unit cell were 150 and 250 nm respectively. High absorptance of ~80% was realized near a wavelength of 500 nm for the TE mode. Fig. 3. Shows the absorptance for the TE mode.

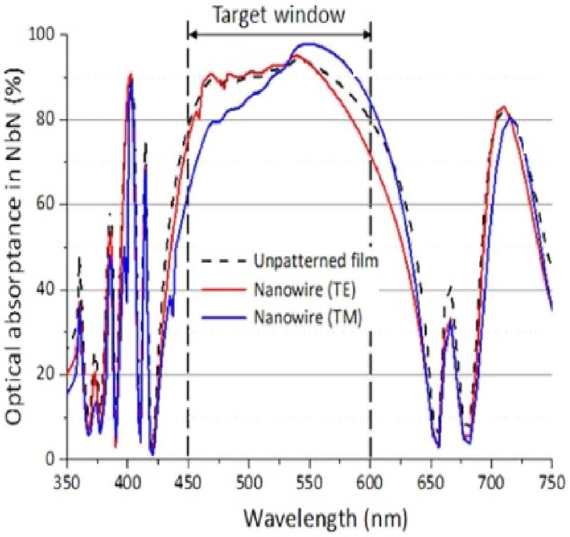

Fig. 3. Absorptance for TE mode

In the fig.3. it is clear that the te mode (red curve) is higher than that of the TM mode (blue curve). Thus the results obtained for detection efficiencies for each wavelength were consistent with the stimulated wavelength dependencies of the optical absorptance. The result shows that this is a powerful technique for precisely designing the spectral dependence of SNSPDs and will benefit more multidisciplinary applications including spectroscopy, atmospheric remote sensing and secure communication.

5. DEMONSTRATED APPLICATIONS

5.1. Measurement of temperature

Owing to their excellent detection efficiency and timing resolution, the SNSPDs can be utilized for measurement of temperature by the coherent antistoke Raman scatterings and coherent stoke Raman scatterings. The difference in the time required for light of different wavelengths to travel through an optical fiber to obtain spectra by measuring the wavelength dependent arrival time with a time-correlated single –photon counting module (TCSPC). As the arrival time is extremely small we need a detector with high timing resolution. As shown in the Fig. 4, the author demonstrated the basic concept of the CARS and CSRS by using an SNSPD, achieved at 1550nm wavelength [15]. The sensing fiber is a standard low loss single mode fiber with a diameter of 10.1µm and attenuation less than 0.2 dB/km.

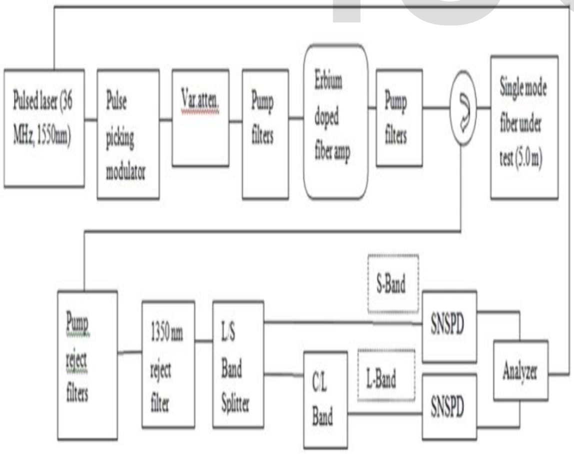

Fig. 4. Measurement sset up for wavelength analysis of coherent anti-stoke Raman scattering and coherent stoke Raman scattering in the fiber under test

5.2 Ultra-low- temperature switch

As the low temperature superconducting circuits have become most widely applied in many scientific applications. However, there are no high current –capacity switches with low power dissipation for sub-Kelvin operations, the alternative sub-Kelvin switch is cryotron, a device in which the superconductivity of a wire is suppressed with a magnetic field. The author has demonstrated a cryotron switch suitable for sub-Kelvin temperatures [16].these switches can eliminate the crosstalk in the time division SQUID multiplexing. These switches can reduce the actuation current from that of the previous cryotron devices. The author demonstrated cryotron switch with a maximum $I_{sig} = 900\mu A$ in its closed state $(I_{con} = 0\ A)$ and leakage current $I_{sig}{\sim}500\mu A$ in its open state$(I_{con} = 2\ mA)$ that can operate at sub-Kelvin temperatures.

5.3 satellite laser ranging.

An application with the superconducting nanowire single photon detector at a wavelength of 532 nm designed for satellite laser ranging (SLR).the author used a NbN SNSPDs with a sensitive area diameter of 42 µm. the device is couple to a multimode fiber (φ = 50 µm) with a maximum detection efficiency of 75% at an dark count rate of <0.1 Hz [17]. The PC structure is shown as in Fig. 5. The author has demonstrated with a sensitive area chosen to be 42 µm for $\sim 99\%$ coupling efficiency of the incident photons. The results shows a ranging resolution of 8 mm for the satellite LARES, which is $\sim 3,000\ km$ away from the ground-ranging station.

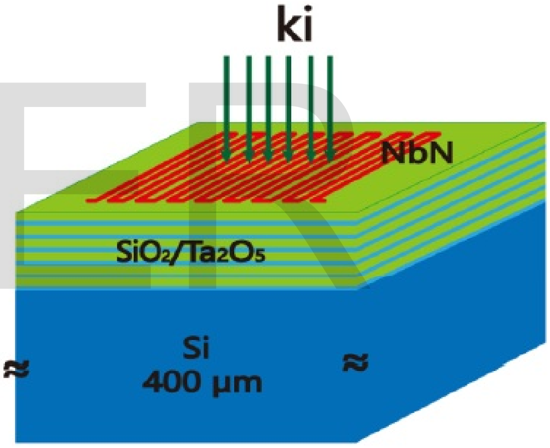

Fig.5. the common optical film materials comprised the PC structure

The results show that the PC structure effectively acted as a cavity to enhance the absorption of incident photons.

6. CONCLUSION

In this review, we have introduced the recent modeling systems which have been demonstrated with the superconducting nanowire single photon detector and reviewed few demonstrated application of the SNSPDs. As described, with the enormous research work on SNSPDs, the overall performance have reached to a practical level and utilized in many areas of applied research. As the next step in the development of these systems, the detection efficiency, modeling of the system is an important issue. By selecting multi-element structures one can enhance the modeling systems signal processing technology is needed for realizing high counting rate. In addition, the development of highly efficient SNSPD in the near infrared region is expected to have more prominence in various research fields.

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