

## Multimode Fiber Coupled Superconducting Nanowire Transition Edge Sensor for Detection of Single-Photon at Optical and Near-Infrared Wave Lengths

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**Abstract:** We report the development of the multimode fiber-coupled superconducting nanowire transition edge sensor with high system detection efficiency at optical and near-infrared wavelength. The SNTES consists of an absorber, a sensitive thermometer, and a weak thermal link to a cold bath. For a SNTES optimized to detect single photons, the temperature change caused by the absorption of a single photon is read out by the thermometer, and the system resets by cooling through the thermal link. The graded index (GRIN) lenses were spliced to the end of the multi mode fiber with a 50  $\mu\text{m}$  diameter core, and the incident light spot diameter was focused to approximately 20  $\mu\text{m}$  at the active area, which is 28  $\mu\text{m}$  diameter, allowing a good optical coupling. We have achieved a nominal coupling efficiency of 91 % and system efficiency of 76 % by the SNTES at 1310 nm -1350 nm. The developed practical SNTES presented in this paper could open a new frontier for a wide range of applications at optical and infrared wavelength. *Copyright © 2015 IFSA Publishing, S. L.*

**Keywords:** Laser communication, Multi-mode fiber, Photon detector, Transition edge sensor, Detection efficiency.

### 1. Introduction

In recent years, Superconductor Nanowire Single-Photon detectors (SNSPDs) have been emerged as promising single-photon detectors for numerous applications [1] in various fields, as quantum information [2], free space optical communication, laser detection and ranging [3]. Their applicability to numerous areas can be attributed to their high System Detection Efficiency (SDE), high counting rate, Low Dark Count rate (DCR) and short timing jitter. So far, efforts have been made to improve the system performance of SNSPDs and SNTES, which are

optically coupled with single-mode(SM) optical fibers at telecommunication wavelength region [4-5]. However, the single-mode fiber coupled SNSPDs and single mode SNTESs are restricted to viable applications [6-7]. Development of the multimode fiber coupled SNTES system would enhance the usability in the satellite based quantum communication and in photon coupling. Many attempts tried to increase the detection area for developing multi-mode fiber coupled SNSPDs. A large active area benefits optical coupling but produces high kinetic inductance, which inevitably degrades the repetition rate of SNSPDs. In addition,

the fabrication difficulty increases exponentially as the detection area increases. Therefore the maximum detection area reported thus far is only  $40 \times 40 \mu\text{m}^2$  [16] for single nanowire, which is smaller than the core diameter ( $50 \mu\text{m}$ ) of standard multi-mode fibers. Thus, No multi-mode fiber coupled SNSPD and SNTESs has been reported previously. In the recent work by F. Marsili, *et al.* [2] achieved detection efficiency  $\eta \sim 2.6 - 5.5 \%$  in the wavelength range  $\lambda = 0.5 - 5 \mu\text{m}$  using SNSPD but the non integrating of the detectors in an optical cavity lead to decrease in detection efficiency. E. Reiger, *et al.* [6] approach is based on the fact that the size of the hotspot and is linearly dependent on the photon energy but the resolution of  $50 \text{ nm}$  is only achieved while W. Slys, *et al.* [7] experimented by  $\sim 100 \text{ nm}$  wide and  $4 \text{ nm}$  thick NbN SNSPD, operated at  $2$  to  $4.2 \text{ K}$  temperature range, the coupling efficiency up to  $33 \%$  is achieved due to the weak coupling between SNSPD and single mode optical fiber.

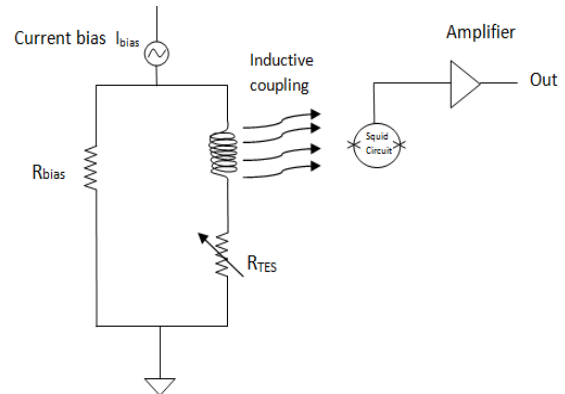
A part from the SNSPD detectors, the nanowire superconducting transition edge sensors where used for the detection of photon number. In recent times, Cryogenic particle detection by using Transition Edge Sensor with a single mode fiber coupling yielded for  $65 \%$  efficiency, K. D. Irwin, *et al.* [14] and Rosenberg D., *et al.* [5] report on the device characteristics of a new generation of tungsten TESs with greater than  $80 \%$  quantum efficiency at  $1550 \text{ nm}$  and has not discussed on the coupling efficiency.

This motivates to develop a multimode fiber (MM) coupled SNTES for good coupling efficiency, system efficiency and low noise which will increase the usability in different applications. Achieving efficient coupling with a multimode optical fiber gives a need to receive photons from free space. These applications [8] require a large detection area of the SNSPDs and SNTES, thus achieving an efficient coupling with MM optical fiber, which has a larger core diameter than that of the single mode fiber is proposed in this work.

In this paper, we report on the development of the MM fiber coupled Superconducting Nanowire Transition Edge Sensor (SNTES) for detection of single photons at optical and near-infrared wave lengths.

The proposed Superconducting Nanowires Transition Edge Sensor (SNTES) is highly sensitive microbolometers that can detect radiations from sub-mm wavelength to gamma -rays and they typically consist of an absorber, a sensitive thermometer, and a weak thermal link to a cold bath. For an optimized detection of single photons, the temperature change caused by the absorption of a single photo is read out by the thermometer, and the system resets by cooling through the thermal link but as low energies involved, detection of single photons at optical and near infrared wavelengths requires low heat capacity and extremely sensitive thermometry. The most successful optical SNTES sensors use device that operate below  $1 \text{ K}$ . However, higher operating

temperatures are being explored by sacrificing detector size [9]. For example, in devices made using tungsten the sensor is cooled below the superconducting critical temperature  $T_c$ , typically  $\sim 100 \text{ mK}$ . A voltage bias is applied so that the resultant Joule heating raises the electron temperature of the detector to a temperature in the superconducting-to-normal transition, where the device has some Non-zero resistance ( $RTES$ ). The negative feedback inherent in voltage biasing a device with a positive temperature coefficient of resistance ( $dR/dT > 0$ ) keeps the temperature stable; if the temperature increases (decreases), the resistance increases (decreases), resulting in a smaller (larger) amount of Joule heating thus when a photon is absorbed the temperature of the sensor increases, resulting in a change in the electrical resistance. This change can be measured using a sensitive current amplifier such as a SQUID in Fig. 1. The detector then resets as it cools through the weak thermal link. Because of the low operating temperature, and the need for a relatively stiff voltage bias, a small shunt resistor  $R_{bias}$  is placed in parallel with the TES detector, which is represented as  $RTES$  in the schematic. The value of  $R_{bias}$  is chosen to be much smaller than  $RTES$  at the operating point where the SNTES is properly biased to detect photons.



**Fig. 1.** Electrical schematic of the current bias and superconducting amplifier (SQUID) typically used to read out the signals from SNTES detector. A voltage bias is formed by choosing a bias resistor that is much less than the operating resistance of the SNTES detector.

The response of the SNTES is determined by two differential equations describing the electrical and thermal circuits. The thermal differential equation can be express as follow

$$C \frac{dT}{dt} = -P_{bath} + P_{Joule} + P_{photons}, \quad (1)$$

where  $C$  is the heat capacity of the device,  $P_{bath}$  is the power flowing from the electrons to the heat bath,  $P_{Joule}$  is the joule heating of the electrons, and  $P_{photons}$  is the power from photons being detected.

For tungsten-based TES detectors  $P_{bath}$  is given by the following equation:

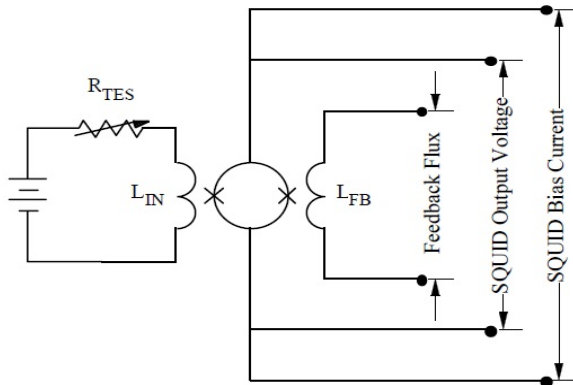
$$P_{bath} = k \cdot V \cdot (T_e^n - T_{ph}^h), \quad (2)$$

where  $k$  is the electron-photon decoupling constant,  $V$  is the volume of the device, and the exponent  $n$  is usually 5 for tungsten SNTES detectors.

In SNTES detector, the power applied to raise the SNTES into its transition region is nearly constant. This has the effect that the response becomes linear to better than 1 %, substantially better than the typical linearity achieved with semiconducting thermistors, because the sensitivity of a SNTES is so large ( $\approx 200$  for the flim), a voltage – biased SNTES is stabilized by strong eletrothermal feedback. In this mechanism, an increase in temperature yields a sharp increase in resistance, which reduce the current flowing through the SNTES, lowering the bias power and decreasing the temperature [10]. This enables the devices to be very fast (time constants of  $\approx 1$  ms) and a nominal coupling efficiency of 91 % and system efficiency of 76 % was obtained by the SNTES at 1310 nm - 1350 nm.

## 2. SQUID Amplifier

The superconducting SNTES is well matched by a superconducting SQUID amplifier [11] (Fig. 2). A SQUID amplifier acts as a magnetic flux to voltage converter, with very low output voltage noise. A voltage – biased SNTES in series with a pickup inductor placed near a SQUID [11] will be inducing a change in flux through the SQUID when the RTES resistance changes. A single detector can be read out using eight wires.



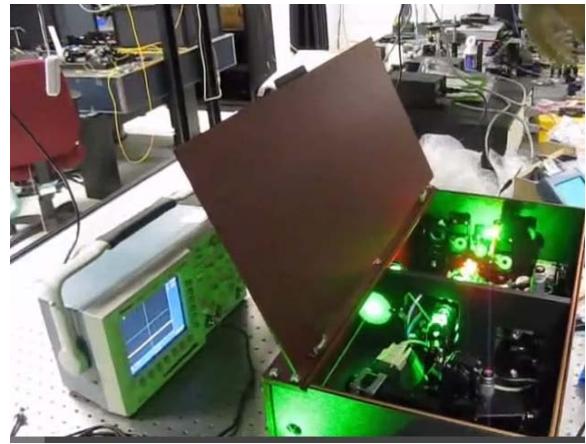
**Fig. 2.** A single SQUID amplifier circuit. eight wires are connected to readout one detector, assuming separate returns.

## 3. Coupling Efficiency-multimode Fiber

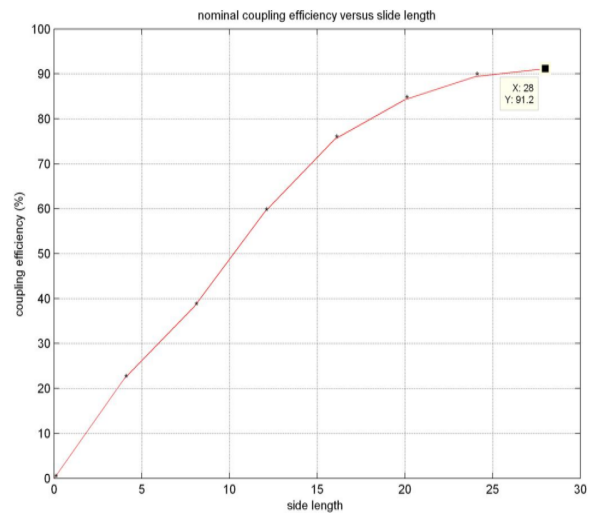
### 3.1. System Coupling Efficiency and Detection Count Rate

The device was mounted in a fiber coupled package optimized for front side illumination with a multimode fiber. The graded index (GRIN) lenses

were spliced to the end of the multimode fiber with a 50  $\mu\text{m}$  diameter core, and the incident light spot diameter was focused to approximately 20  $\mu\text{m}$  at the active area [12], which is 28  $\mu\text{m}$  diameter, allowing a good optical coupling. The reflectance of the dielectric mirror was designed to be less than 25 % at a 1310 nm wavelength. The optical alignment was done precisely by monitoring an illuminated 1310-nm-wavelength spot from the side of the chip [13]. The final packed SNTES is then installed in the GM cryocooler system [14] with the operating temperature of 2.2 K. The bias circuit used is as show in the Fig. 1. And the experimental set up is as show in the Fig. 3. The nominal coupling efficiency versus slide length of the detection area with the focused beam is shown in Fig. 4.



**Fig. 3.** The experimental setup of the multimode coupling of the superconductor nano wire transition edge sensor for measurement of single photon near-infrared wavelengths.

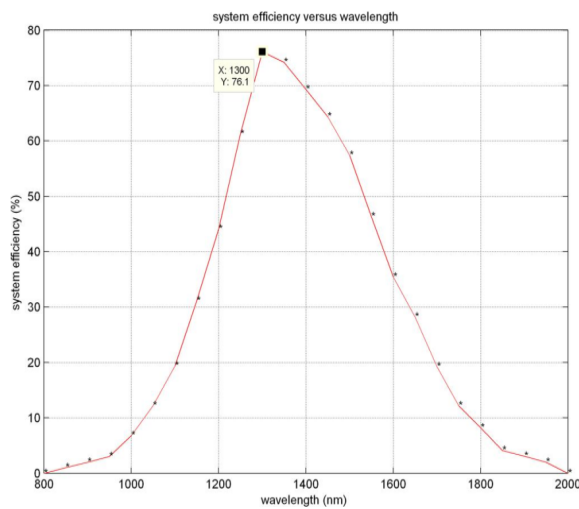


**Fig. 4.** Nominal coupling efficiency Vs slide length; with the detection area of 28  $\mu\text{m}$  – coupling efficiency of 91 % is achieved for the multimode fiber coupling.

While measuring the system detection efficiency (SDE), a continuous laser source with several

different wave lengths was used as the photon source. A 4-channel attenuator was used to adjust the photon power to be  $P_1$  and then a calibrated attenuation of  $P_2$  is added to the incident light, so that the power  $P_1$ - $P_2$  equaled to the power of the flux of  $10^6$  photons/s at a specific wave length. We follow the method defined in the international standard of IEEE 61300-3-5; which requires an external cavity laser source(tunable from 1300 to 1400 nm), Although the optical losses of the optical fibers in the cryocooler system [14] were measured to be 0.1-0.3 dB and they were not included in the calibration of the input photon flux.

When measuring the System Detection Efficiency (SDE), the SDE curve shows saturation trend when the bias current approaches the  $I_{SW}$ ; the SDE reaches its highest value at 76 % as shown in Fig. 5.

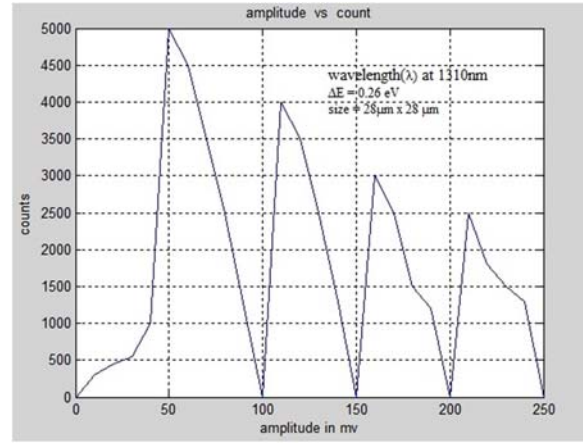


**Fig. 5.** System detection efficiency Vs wave length.

The system efficiency increased as the wavelength, and peaked at 1310 nm, because high quantum efficiency was maintained and the absorption efficiency was increased. At wavelength higher than the cutoff, both the quantum efficiency and coupling efficiency decreased, resulting in the system efficiency decreased for the photons at the wavelength of 2000 nm, as show in Fig. 5.

According to pervious results [5], there should be a cutoff below which the photon response is produced by a hot spot, and the quantum efficiency is at high, after which it is de ceased by increasing wavelength. However, there is a increase in the sensitivity at infra-red wavelengths with the high cutoff. Thus, with hot spot theory, the superconducting nanowire with low critical current increased the cutoff for the SNTES.

The dark count rate (DCR) was measured by turning of the attenuator and the laser source. The SDE was obtained by subtracting the DCR from the output pulse rate and dividing the value by the total number of the input photons. The observed photons statistic at the 1310 nm wavelength with a  $\Delta E = 0.26$  eV at  $28 \mu\text{m} \times 28 \mu\text{m}$  is as shown in the Fig. 6.



**Fig.6.** Photon statistic at 1310 nm wavelength. The histogram of photon counting at  $\Delta E=0.26$  eV.

## 4. Conclusions

In summary, we have developed and characterized the MM fiber-coupled SNTES for the near infra-red wavelength region. The SNTES device showed a high System Detection Efficiency of 76 % for the incident photons with 1310 nm wave length and with  $\Delta E = 0.26$  eV. The proposed multimode fiber coupled SNTES device showed a high coupling efficiency of 91 % at the  $28 \mu\text{m}$  slide length with the incident light spot diameter was focused at  $20 \mu\text{m}$ , which is superior both in detection efficiency and coupling efficiency when compared with the other detectors. The proposed multimode fiber coupled SNTES presented in this paper could open a new frontier for a wide range of applications at infra-red and at optical wavelength. The ability of a SNTES detector to resolve photon number is a key feature that is still unmatched by other superconducting detector technologies. And hence it has high detection efficiency in many wavelength ranges commonly used for quantum optics applications. In the future, SNTES can also be constructed in arrays with multiplexed SQUID readouts, and more advanced versions of these multiplexing circuits may be integrated with the detectors to create even large photon – counting arrays.

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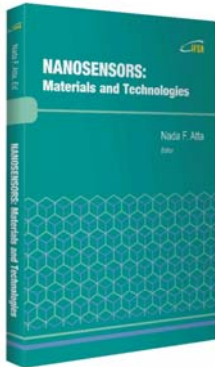
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