1.25-Gbit/s photon-counting optical communications using a two-element superconducting nanowire single photon detector

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ABSTRACT

The sensitivity of a high-rate photon-counting optical communications link depends on the performance of the photon counter used to detect the optical signal. In this paper, we focus on ways to reduce the effect of blocking, which is loss due to time periods in which the photon counter is inactive following a preceding detection event. This blocking loss can be reduced by using an array of photon counting detectors or by using photon counters with a shorter inactive period. Both of these techniques for reducing the blocking loss can be employed by using a multi-element superconducting nanowire single-photon detector. Two-element superconducting nanowire single-photon detectors are used to demonstrate error-free photon counting optical communication at data rates of 781 Mbit/s and 1.25 Gbit/s.

Keywords: Photon-counting, Optical communications, Superconducting nanowire single photon detector

1. INTRODUCTION

Using photon-counting detectors in an optical communication receiver can provide several advantages including excellent receiver sensitivity[1] and the ability to incoherently combine signal from multiple spatial modes.[2] However, the sensitivity and data rate of photon-counting optical communication systems can be limited by photon counting detectors with low detection efficiency, high timing jitter or long reset times. Recently, error-free photon-counting optical communication has been demonstrated at a data rate of 781 Mbit/s using a superconducting nanowire single photon detector (SNSPD).[3] The excellent timing resolution (< 35 ps), and fast reset time (~ 3 ns) provided by the SNSPD permitted a substantial increase in the data rate relative to previous photon-counting optical communication demonstrations,[4-6] which were limited to rates < 500 kbits/s. Both the data rate and sensitivity of a photon-counting optical communication system could benefit from improved photon-counting detector performance.

The sensitivity of a photon-counting optical communication system is degraded by any source of optical loss in the receiver, which includes losses in the photon counter due to both non-unity detection efficiency and blocking, which occurs when a photon arrives while the photon counter is resetting. Significant progress has been made to reduce the first source of loss, low detection efficiency, and the demonstrated SNSPD detection efficiency at 1550 nm has increased from 6.3% for the device used in the original communication demonstration[3] to 57% for a device integrated with an optical cavity.[7] The second source of loss, blocking loss, can be reduced by improving the detector performance in either of two ways: (1) by reducing the duration of the inactive period or (2) by increasing the number of detectors across which the received signal is spread so that it is less likely an incident photon will be collected by an inactive detector. This paper focuses on an approach that utilizes both of these techniques for reducing the blocking loss: a multi-element superconducting nanowire single photon detector (MESNSPD).[8]

A MESNSPD is composed of two or more independent SNSPDs that are patterned to form a continuous active area.[8] In our case, each SNSPD element is a 100-nm wide wire patterned in a ~ 4-nm thick superconducting NbN film. These

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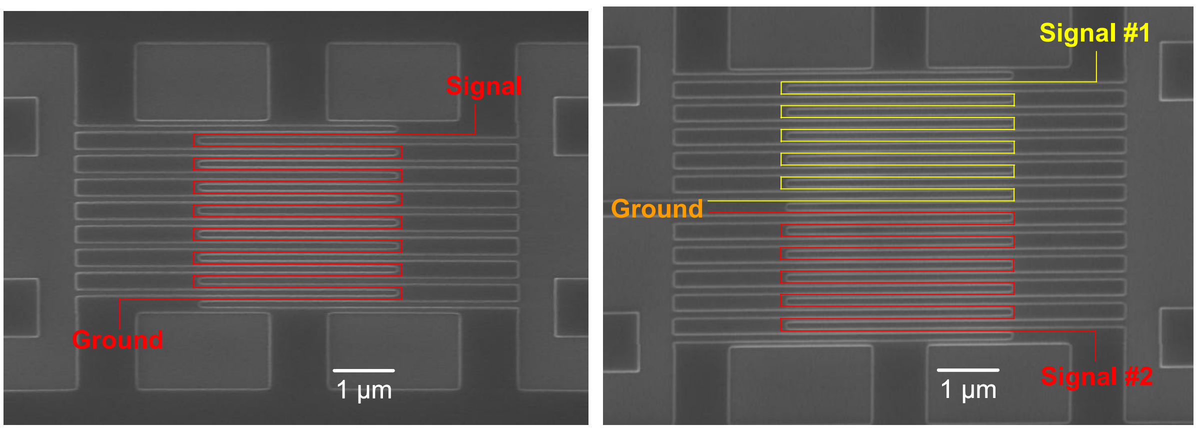
superconducting wires are cooled to 2 K, such that they are well below their ~ 10-K superconducting transition temperature, and are biased with a current slightly below their superconducting critical current. An absorbed photon can disrupt the superconductivity and cause the critical current density to be exceeded. This results in the formation of a resistive region and the diversion of current into the high-speed transmission line through which the detector is biased, which can be used to sense the absorption of a photon in the wire. The efficiency with which light can be coupled into the nanowire can be improved by designing the wire to have a meander pattern composed of many straight segments of wire with small, ~100-nm gaps between them that are connected at alternate ends to form a single continuous path (Fig. 1(a)). This continuous path can be split into multiple, independent detectors by extending some of the wires to separate contact pads, such that the current flowing between any signal lead and ground flows through only a portion of the total device (Fig. 2(b)). The straight segments composing the active area of the detector are identical in either case, and the loss due to the highly sub-wavelength gaps between them can be overcome by using an appropriately designed optical cavity.[7] In this way, an identical optical active area can be formed from one, two or potentially more independent detector elements. Furthermore, in additional to gaining multiple detector elements that count independently, the length of each device is reduced, which results in a roughly proportional decrease in its reset time.[9]



(a) (b)

Fig. 1. (a) Scanning-electron microscope (SEM) micrograph of a 3-μm by 3.3-μm active area SNSPD with an overlayed path showing the flow of current from the signal contact to the ground contact. (b) SEM micrograph of a 2-element SNSPD with a 4-μm by 4.2-μm total active area with an overlayed path showing the flow of current in each of the detector elements.

The effect of using MESNSPDs for photon-counting optical communications and experimental demonstrations using two-element SNSPDs are described in more detail in the remainder of this paper. Experimental demonstrations were performed using two-element SNSPDs with two different active areas: 3-μm by 3.3-μm and 4-μm by 4.2-μm (Fig. 1(b)), which are, respectively, equal to and approximately 70% larger than the active area of the detector used in the original SNSPD photon-counting optical communication demonstration (Fig. 1(a)).[3] The larger active area makes it easier to efficiently couple light, but would increase the reset time for a single SNSPD, degrading the communication performance at high data rates. By using the MESNSPD approach to divide the active area into two independent detectors, however, we demonstrate communication performance that could not be achieved using a similarly-sized, single-element SNSPD.

2. PHOTON-COUNTING OPTICAL COMMUNICATIONS USING MULTIPLE DETECTORS

The temporal response characteristics of a single-photon detector must be considered in determining the optimal way to use these devices for optical communications. For instance, timing jitter in the detection process limits the minimum resolvable transmission slot duration. The SNSPDs used in this work exhibit timing jitter of ~30 ps FWHM. Thus, for transmission slot frequencies greater than ~10 GHz, it may be difficult to precisely determine in which slot a detected pulse arrived. In addition to timing jitter, most single-photon detectors require a "reset time" after each detection event. This is a period of time during which the detector is inactive and unable to detect photon arrival events. Pulses that arrive during the detector reset time will not be detected. This is referred to as detector blocking. The larger active area

SNSPDs used in the present experiments require ~3.2 ns after a detection event to recover to 75% of their peak detection efficiency.

The fact that the reset time for these devices is much longer than the timing jitter in the detection process suggests that low-duty-cycle modulation formats, where information is conveyed via short pulses that tend to be widely separated in time, would be most suitable for optical communications using single-photon detectors. Pulse-position modulation (PPM) is a low-duty-cycle modulation format that is straightforward to implement. With M-ary PPM, a symbol, representing k bits of information, is transmitted by placing a pulse in one of $M=2^k$ transmission slots. The receiver measures the time of arrival of a pulse to determine the transmitted information. PPM is ideally suited for communications with single-photon detectors as the transmission slot frequency can be made very high in order to take advantage of the good timing resolution of the detector (owing to the low timing jitter) while the PPM order (M) can be made large to increase the average time between detection events, thereby reducing the probability that a pulse arrives at the detector during the reset time from a previous detection event. Moreover, it has been shown that for large M, PPM approaches the theoretical limits of receiver sensitivity for a photon-counting channel.[1]

The use of PPM does not completely eliminate the effects of blocking. For instance, a pulse transmitted near the beginning of a symbol may be blocked by a detection event near the end of the previous symbol. The probability of this event may be reduced by increasing the PPM order, M, as illustrated in Fig. 2 (a) for a detector operating at a 10-GHz slot frequency and a 3.2-ns reset time. Note that reducing the blocking in this manner also reduces the data rate. For a ½-rate code (1 data bit for every 2 transmitted bits), the data rate is equal to $F_S * \log_2 M / (2M)$, where F_S is the slot transmission frequency.

Alternatively, one may reduce the effects of blocking by imaging the received signal on an array of several single-photon detectors, such as a MESNSPD. Each photon detection event will disable a single detector for a reset time, leaving the others available for subsequent detection events. The detection statistics for an array of Geiger-mode avalanche photodiodes have been previously reported.[10] Similar techniques may be used to calculate the blocking probabilities for a MESNSPD. Fig. 2 (b) shows the calculated blocking probabilities for a MESNPD operating with a 10-GHz transmission slot rate and 3.2-ns reset time. Significant reductions in the blocking probability may be obtained with relatively small numbers of detectors.

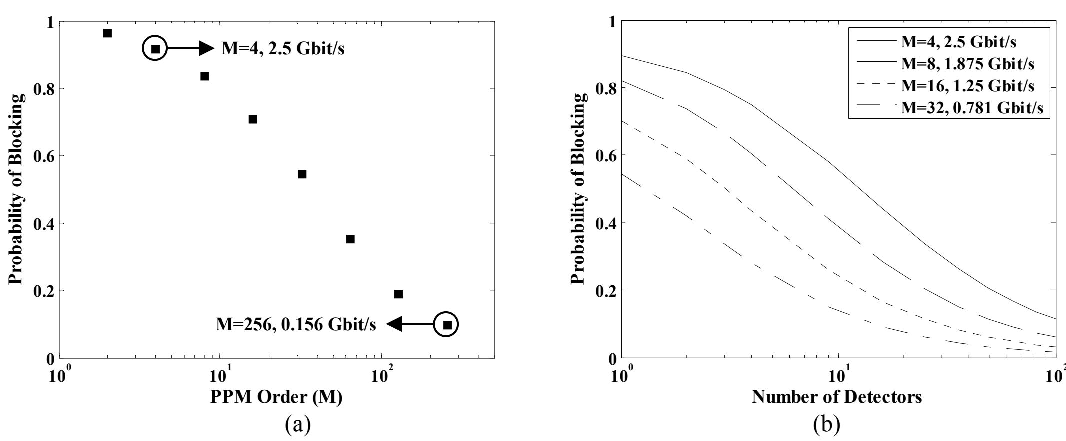


Fig. 2. Calculated blocking probabilities for SNSPDs with a 3.2-ns reset time for an incident 10-GHz PPM signal with 1.5 photons per pulse: (a) as a function of the PPM order and (b) as a function of the number of detectors in a MESNSPD

3. EXPERIMENTAL SETUP

The performance of a two-element SNSPD in an optical communication system was tested in the experimental setup shown in Fig. 3 (a). This setup is identical to the one used in reference 3, except for the addition of a second SNSPD, a second 20-Gsample/s analog-to-digital converter (ADC) and a second threshold detector. A 32-ary PPM waveform was used at a 10-GHz slot rate, corresponding to an uncoded data rate of 1562 Mbit/s and a coded data rate of 781 Mbit/s. The optical coupling of this signal into the two adjacent detectors and the electrical readout from these detectors is described in reference 8. Prior to analog to digital conversion of the output electrical signal, the amplified electrical signal from one detector was sent through an RF delay line. This RF delay line was used along with an optical delay line, inserted before the light is coupled into the detectors, to optimize the timing of the two output signals with respect to the sampling in each of the ADCs. The threshold detector levels for each channel were optimized independently and the resulting photon arrival times were decoded and used to measure the error-rate.

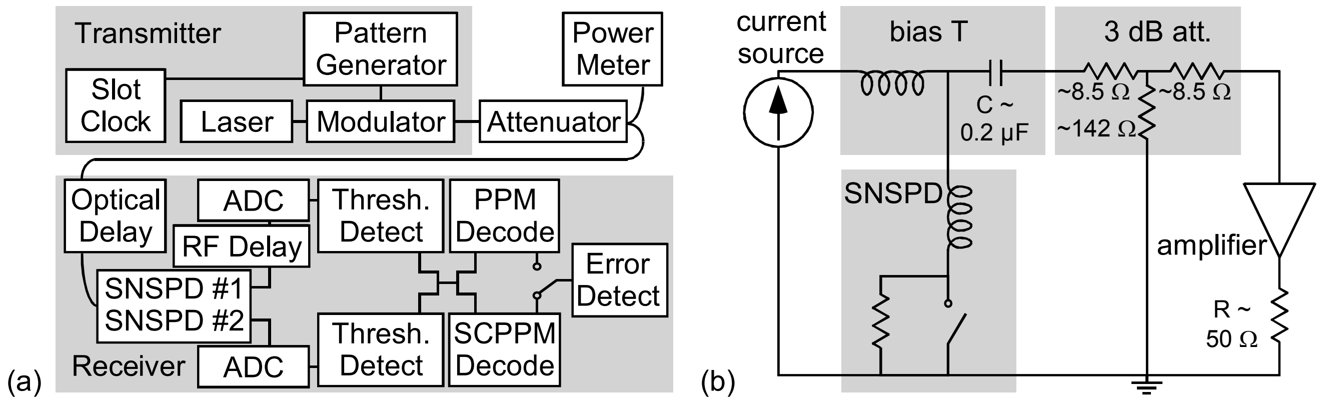
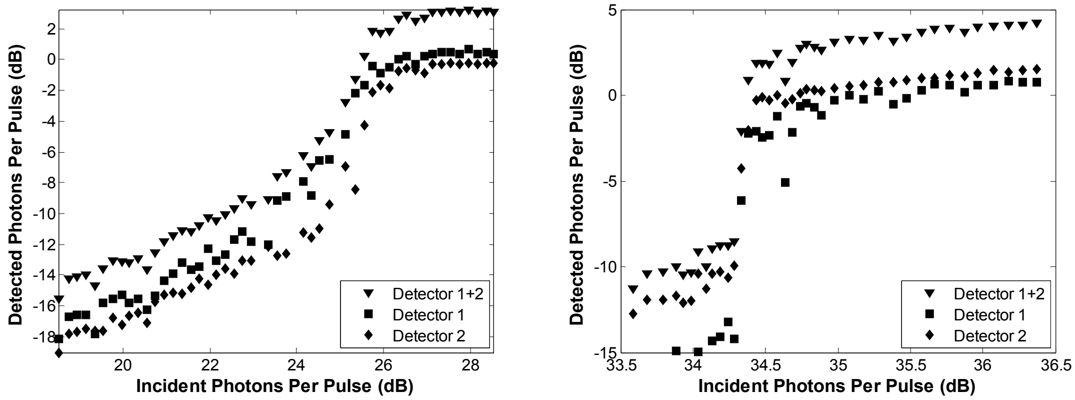


Fig. 3. (a) Schematic of the experimental setup and (b) the portion of the electrical circuit used to bias and readout the SNSPD that results in a change in device performance as a function of the detector count rate

The performance characteristics of the SNSPD vary at high optical intensities, as was previously noted.[3] Fig. 4 (a) and (b) show the measured detection performance for a two-element SNSPD, as well as the performance of each of the individual detector elements. Each of the curves displays the same basic features. At low incident powers, the detected power increases linearly with the incident power. Because the probability of detecting each pulse in this regime is very low, the blocking probability is low. Thus, the ratio of the incident number of photons per pulse to the detected number of photons per pulse in this power regime provides a measure of the total coupling loss and detection efficiency of the detectors. For example, in Fig. 4 (a), the total loss includes ~9-dB coupling loss per detector element, primarily due to the focused optical spot being larger than the active area of the devices, and detection efficiency losses of ~25.6 dB and ~27 dB for each of the two detector elements. The total loss for the combined two-element SNSPD was ~32.2 dB. Note that the individual detectors exhibit ~3 dB more coupling loss than the combined detectors in this measurement due to the fact the same coupling optics were used for all measurements. So, only half of the total power was incident on the individual detector elements as compared to the two-element SNSPD. At an incident power level of ~24-dB photons per pulse, the detection efficiency of the elements increases, as can be seen by the sharp increase in the slope of the measured detector performance. This change in detector performance will be discussed shortly. Finally, for very high incident flux levels, the SNSPD detection probability saturates due to the effect of detector blocking. The saturation level for the 2-element SNSPD is nearly two times that of the individual detectors. The ~0.5-dB difference observed in the saturation levels for the individual detector elements, and the difference in the saturation level observed for the single-element SNSPD used previously[3], may be due to small differences in the reset performance of the detectors.[11]



(a) (b)

Fig. 4. Measured two-element SNSPD detected photons versus incident photons. Lines (not drawn) of slope one represent curves of constant detection efficiency. The detection characteristics were measured for a fixed external bias current for a two-element SNSPD with (a) a 4-μm by 4.2-μm total optical active area illuminated by a 32-ary PPM optical signal at 10 Gslot/s and (b) a 3-μm by 3.3-μm total optical active area illuminated with a 16-ary PPM optical signal at 10 Gslot/s.

Although the saturation of the detection probability at high optical intensities due to blocking is not surprising, the source of the increased detection efficiency just below this intensity level is less obvious. In addition to the increased detection efficiency, the detector dark count rate increases and the maximum current that may be sourced before exceeding the superconducting critical current decreases at these high optical intensities. We believe this effect is due primarily to the AC coupling of the signal line used to read out the SNSPD (Fig. 3(b)). During a detection event, the nanowire becomes resistive and current is diverted through the capacitor in the bias T into the AC-coupled amplifiers and the 50-Ω-terminated transmission line. Each current pulse from a detection event adds a small amount of charge to the capacitors in the bias T and the amplifiers, which results in current being sent back into the detector when the nanowire is superconducting. At high counting rates, a significant amount of extra current is forced through the nanowire while it is superconducting in order to cancel the DC component of the output signal. The small capacitors in the amplifiers will discharge quickly, partially discharging the large capacitor in the bias T and resulting in a small, temporary rise in the current through the device. The large capacitor in the bias T will fully discharge over a much longer, ~20-μs time-scale, which is determined by its capacitance and the resistance to ground in the attenuator. The current sent through the SNSPD due to the AC-coupling of the readout increases the total current in the device and consequently increases the detection efficiency at high count rates.

These AC-coupling effects not only change the performance of the SNSPD at high optical intensities, but can actually prevent stable operation at certain combinations of bias current, optical intensity and detection efficiency. The detection efficiency can change abruptly with increasing bias current or optical intensity because the SNSPD switches from counting at a low rate, with low detection efficiency, to counting at a high rate with much higher detection efficiency (Fig. 4(b)). In some cases, the detector cannot be operated in a stable fashion with intermediate detection efficiency. Near these unstable points, large variations in the detected optical power can result from small changes in the incident optical power or detector operating conditions. Correlated variations in the detected optical power from both elements in the two-element SNSPDs and variations in the detected optical power from one element due to the biasing of the adjacent element have been observed.[12]

4. COMMUNICATIONS RESULTS

Fig. 5 shows the measured bit-error-rate performance for the two-element SNSPD with 4-μm by 4.2-μm total active area. Using a slot rate of 10 Gslot/s, a ½-rate turbo code and a PPM modulation format, the maximum data rate at which error-free performance could be achieved was 781 Mbit/s (32-ary PPM). For the two-element SNSPD, error-free performance was obtained at an incident power level of ~26.3-dB photons per pulse (2.7-dB detected photons per pulse). This result is similar to that achieved previously for a single-element SNSPD, but the optical active area was ~70%

larger for the two-element SNSPD as compared to the single-element SNSPD.[3] Thus, multi-element SNSPDs are one approach for increasing the detector optical active area without sacrificing the speed of the receiver.

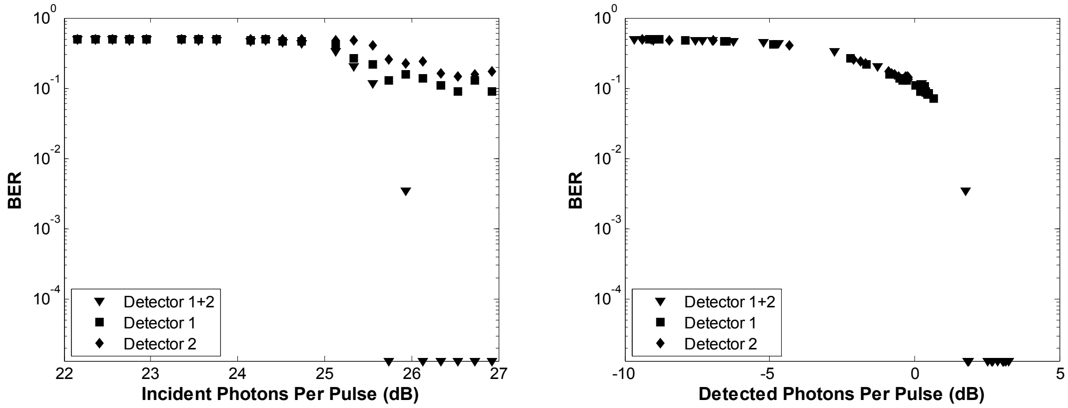


Fig. 5. Measured communications performance using 32-ary PPM at 10 Gslot/s with a ½-rate turbo code (781 Mbit/s) and a 4-μm by 4.2-μm two-element SNSPD. Bit-error-rate performance plotted versus (a) incident photons per pulse and (b) detected photons per pulse.

Similarly, Fig. 6 shows the measured bit-error-rate performance for the two-element SNSPD with 3-μm by 3.3-μm total active area. The measured bit-error-rate plotted as a function of detected photons per pulse clearly removes much of the noise that appears when the bit-error-rate is plotted as a function of incident photons per pulse, suggesting that the noise is due to fluctuations in the detected power as a function of incident power. As discussed previously, the fluctuations in the detection probability are large near the point where the detector performance is unstable (Fig. 4(b)), which is likely the reason the noise in Fig. 6(a) is significantly worse than in Fig. 5(a). Using this 3-μm by 3.3-μm total active area detector and the same constraints on the waveform, the maximum data rate at which error-free performance could be achieved was 1.25 Gbit/s (16-ary PPM). For the two-element SNSPD, error-free performance was obtained at an incident power level of ~ 35.5-dB photons per pulse (2.9-dB detected photons per pulse). This data rate is faster than can be achieved with a single-element SNSPD with this total active area, indicating that multi-element SNSPDs are also useful for achieving higher data rates with a fixed detector active area.

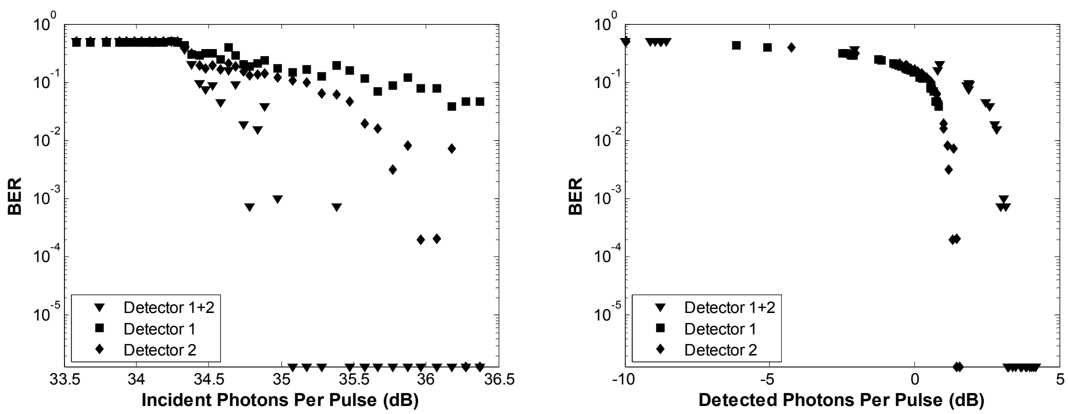


Fig. 6. Measured communications performance using 16-ary PPM at 10 Gslot/s with a ½-rate turbo code (1.25 Gbit/s) and a 3-μm by 3.3-μm two-element SNSPD. Bit-error-rate performance plotted versus (a) incident photons per pulse and (b) detected photons per pulse.

Finally, it is interesting to note that the performance of the two-element SNSPD is significantly worse relative to the individual elements than would be predicted from a simple model of blocking loss. Specifically, the blocking loss for the two-element SNSPD should be lower than for an individual detector element due to the presence of two elements, as discussed in section 2. Therefore, compared to the individual elements, the two-element SNSPD should require a lower incident power level to achieve error-free performance due to both the lower coupling loss and due to the lower blocking loss. However, the number of incident photons per pulse required for error-free performance by the two-element SNSPD is only ~ 1.2 dB lower than for one of the individual detectors (detector 2), despite a ~ 1.8 dB difference in their total coupling loss calculated at low incident intensity. Similarly, the plot of bit-error-rate versus detected photons per pulse (Fig. 6(b)) also suggests a penalty for the two-element detector relative to its individual elements.

Although the source of this penalty requires further investigation, it may be related to the fact the error-rate is limited by the detection probability of pulses that have a high blocking probability. Error-free performance can only be obtained when there is a relatively high probability of detecting a photon from each pulse. Even with two photon counting detector elements, the probability that each element will detect a photon from a given pulse is high enough that significant correlations exist between the detection events in the two detectors: both detectors are likely to detect photons from pulses that do not follow preceding pulses too closely in time and both detectors are likely to miss photons from the second pulse of two that are closely spaced in time. If the detector recovery process were digital, the probability of detecting photons from a pulse separated from the preceding pulse by less than the detector reset time would decrease as the optical intensity increased and it became more likely that the detector fired on the first pulse. However, the SNSPD detector recovery is not digital and the probability of blocking varies continuously with time following the previous detection event.[9] As the optical intensity is increased, the probability of blocking can decrease. Therefore, the small slope of the detection probability at high optical intensities shown in Fig. 4 (a) and (b), is due in part to progressively more photons being detected from pulses that have some probability of being blocked. In order to achieve error-free performance, the probability of detecting photons from some of these pulses with finite blocking loss must be made sufficiently high. Given the correlation between the pulses detected/blocked by each detector and the fact the detection efficiency changes with the count rate in this intensity regime, it is clear that the coupling loss at low optical intensity may not be used to accurately predict the difference in optical power required to achieve error-free performance for the two-element detector versus its individual elements. Therefore, the fact the incident photons can be split across two detectors in the two-element SNSPD appears to provide little reduction in the total blocking loss, but the faster reset time of the detector elements does allow higher data rates to be achieved.

5. CONCLUSION

The effects of detector blocking on a photon-counting optical communication system using a SNSPD and a 10-Gslot/s PPM signal were investigated. A MESNSPD was proposed as an approach that could reduce the reset time and provide multiple independent elements while maintaining the required active area. An experimental demonstration was performed in which the bit-error-rate was measured for two different area two-element SNSPDs and for each of the elements independently. Compared to the 781-Mbit/s data rate achieved previously with a single-element SNSPD,[3] a data rate of 781 Mbit/s was achieved using a two-element SNSPD with 70% larger active area, and a data rate of 1.25 Gbit/s was achieved using a two-element SNSPD with the same active area. The increase in maximum achievable data rate using a two-element SNSPD was found to be due primarily to the faster reset time of the individual elements relative to a single-element SNSPD with the same active area. The smaller than expected benefit provided by the two-element SNSPD relative to the individual elements may be attributed to the fact the detectors were operated under conditions where pulses with an appreciable blocking probability needed to be detected for error-free performance.

This research suggests several areas for future work. First, the variation in the detector performance at high counting rates was attributed to the AC-coupling of the readout electronics, which limited the stability of the detector performance in some situations. Modifications to the electrical circuit which mitigate this affect will be investigated. Additionally, the benefits predicted by a model in which the detector recovery is a digital process cannot accurately capture the behavior observed at the high counting rates investigated here. Further investigating the source of this penalty and refining this model to reflect the continuous nature of the recovery process in the detectors would allow the benefits of multiple elements to be better predicted. Finally, larger arrays of detectors with integrated readout electronics would allow the number of detected photons per element to be much less than one per pulse. Such MESNSPDs, with many high-efficiency elements, would allow the 1.25-Gbit/s data rate demonstrated here to be achieved with better sensitivity would allow higher data rates to be achieved and would simplify optical coupling to the detector.

6. ACKNOWLEDGMENT

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11. The reset performance of an SNSPD depends on the nanowire length, its inductivity and the detection efficiency of the SNSPD as a function of current (see reference 8). These measured reset performance of the two SNSPD elements used in this work is consistent with the ~ 0.5 dB difference in the saturated level of detected photons.
12. The correlated variations in the detected optical power were likely due to mechanical vibrations of the optical probe used to couple light onto the detector. The observed variation in the detected optical power in one detector due to the biasing and counting of the adjacent detector may be due to heating. This effect was only observed at high count rates.