Rebirth of InGaAs avalanche photodiodes for high bit rate single photon applications

Z. L. Yuan, B. E. Kardynal, J. F. Dynes, A. R. Dixon,[1] A. W. Sharpe, A. J. Shields
Toshiba Research Europe Ltd, 208 Cambridge Science Park, Cambridge CB4 0GZ, UK
zhiliang.yuan@crl.toshiba.co.uk

Abstract

We show here gigahertz operation of InGaAs avalanche phtooididoes for high count rate single photon detection in the near infrared, and attribute such success to the self-differencing circuit developed recently. The self-differencing InGaAs detectors are applied to high speed quatnum key distribution, photon number detection, and random number generation.

Introduction

InGaAs avalanche photodiodes (APDs) have been used in the quantum information community as a convenient single photon detector in the near infrared for more than a decade. Particularly for quantum key distribution (QKD), they are the natural choice, due to their compactness and cryogenic-free operation. For this reason, all the single photon implementations in the SECOQC fibre network[2] utilise InGaAs APDs. Until now afterpulse noise in these devices has severely limited the bit rate in practical QKD systems to a few kbps. Recently, however, a simple and low cost self-differencing (SD) circuit has given a new life to InGaAs APDs for high bit rate application.[3] Here, we show SD-APDs single photon detection at gigahertz clocked rate, and their subsequent applications in QKD,[4] photon number detection,[5] and high bit rate generation of random numbers of the highest quality.[6]

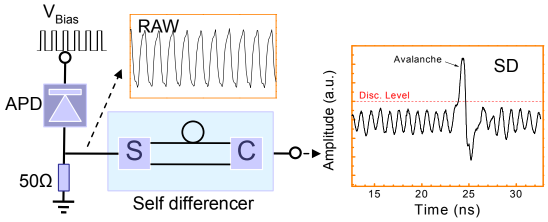

Figure 1: The self-differencing circuit. Avalanche signals, buried in the capacitive response before the SD, become clearly visible after the SD.

Self-differencing mode operation

As shown in Fig. 1, the SD circuit consists a signal splitter and a signal differencer connected by two co-axial cables with a length difference corresponding to a period of the APD gating bias. The periodic capacitive response of the APD gating can be near perfectly cancelled in the output, leaving non-periodic avalanche signals clearly identifiable. Using the SD, we can detect avalanches that are 10 times weaker than previously possible. As a result of the reduced avalanche charge, the afterpulse noise is sufficiently suppressed so that InGaAs APDs can operate at frequencies in excess of 1GHz with a detection efficiency of 10% at 1550nm. We have also measured a continuous count rate of 100MHz. Moreover, the detectors feature high temporal resolution (50ps) and only need mild cooling to -30ºC, making them highly practical.

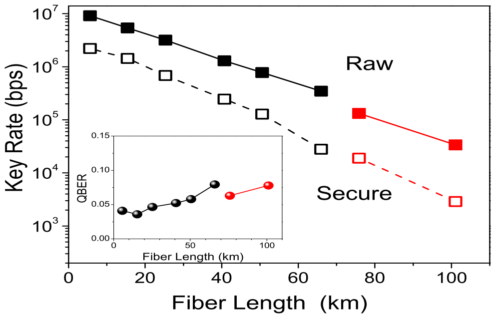

Figure 2: Results for 1GHz QKD with InGaAs APDs across SMF-28 fibre links of various lengths. Raw (solid squares) and secure (open squares) bit rates as a function of fibre length. The inset shows the quantum bit error rate (QBER).

Gigahertz quantum key distribution

Gigahertz QKD has been successfully demonstrated using phase encoding. Using μ=0.2 and a clock frequency of 1.036GHz, we have recorded the highest bit rates achieved so far. Fig. 2 shows the dependencies of the raw and secure bit rates a function of fibre distances. The raw bit rate is 9.16Mbps at 5.6km fibre, falling to 348kbps at 65.5km. The measured QBER is also shown in the inset of Fig. 1. It remains fairly constant for short fibres below 25km, but increases with fibre length for longer lengths due to a combination of attenuation and pulse dispersion in the fibre. Even without fibre dispersion compensation, the QBER at 65.5km is sufficiently low to allow secure keys to be formed. The secure bit rate follows the raw bit rate, decreasing exponentially with fibre distance. The secure bit rate is determined to be 2.20Mbps, 129 and 27.9kbps for 5.6, 50.5 and 65.5km respectively. Secure key exchange over distances much longer than 65km requires compensation of dispersion of the fibre. We employ a fibre Bragg grating device at Alice's side to pre-compensate the fibre dispersion so as to reduce the deleterious dispersive broadening. The QBERs at 75.8 and 101.1km are then measured to be 6.30% and 7.80%, respectively, sufficiently low to allow secure key exchange. The secure key rate is determined to be 19.0 and 2.88kbps for 75.8 and 101.1km respectively, as shown in Fig.2.

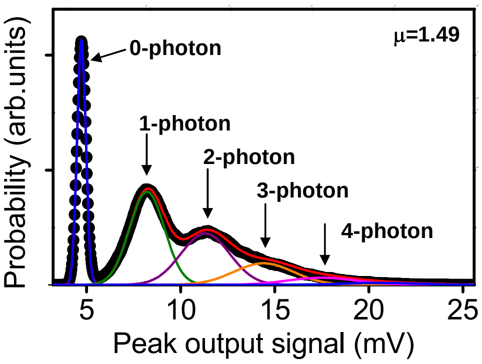

Figure 3: Photon number resolving. Distribution of the peak output signal generated by the SD-APD under illumination by a 1550nm pulsed laser with an average detected intensity of μ=1.49 photons/pulse. The lines show a fit to the data.

Resolving photon numbers

The second application for the SD-APD is to resolve photon number. As we measure extremely weak avalanches, the photon-induced signal amplitude is dependent on the number of photons that stimulated the avalanche, and therefore the SD-APD can resolve photon numbers. Figure 2 plots the distribution in the peak output signal voltages from the self-differencing APD for an average detected flux of μ=1.49 photons/pulse from a 1550nm pulsed laser. The trace shows a series of maxima and shoulders which are centred around 4.7, 8.4, 11.5, 14.6 and 17.6mV, which we ascribe to the avalanche current induced by 0, 1, 2, 3 or 4 photons. By measuring the avalanche current before it saturates in the device, we can distinguish avalanches stimulated by different numbers of photo-excited holes. Notice that for this particular incident flux (1.49 photons/pulse), the output is dominated by 1- and 2-photon signals, as expected. The assignment of the features to detection of different photon number states is confirmed by the dependence of the output signal distribution on the incident laser pulse intensity, where the multi-photon peaks become progressively stronger as the laser intensity increases.

High speed random number generation

The third application for SD-APD is for high speed random number generation (RNG). We devise a simple RNG setup: illuminating a SD-APD with a faint CW 1550nm laser source with coherence time (~1μs) much longer than the APD gating period (1ns). Random collapse of its wave-function into a detection gate, in combination with random emission time, provides perfect randomness. Time-tagging electronics were used to record a stream of photons for a duration of 2 minutes with a photon flux of ~20pW. We acquired a large binary file of around 500MBit recorded at a rate of 4.01MBps. The large binary file was then subjected to two important statistical test routines (1) the NIST statistical test suite (Fig.4) and (2) the Diehard test suite, and has passed all tests in both routines. To our knowledge, this is the first time for a physical RNG to produce a raw output that is sufficiently random to pass these tests. Previously, raw output of all physical RNGs, typically quantum RNGs, suffer from bit bias or correlation caused by impairment in physical implementations.

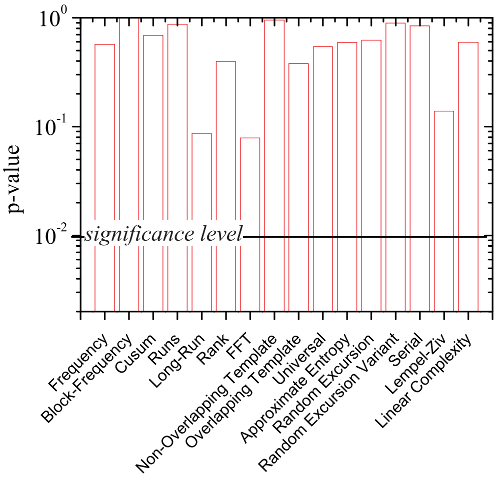

Figure 4: Results of the NIST statistical tests on 500M of binary bits from the RNG. All tests are passed at the α=0.01 significance level.

Summary

In summary, InGaAs SD-APDs are now a viable option for gigahertz single photon detection with photon number resolution. We believe it will be useful for many applications in the quantum information community. Particularly, as an application to the present SECOQC network it will boost the existing bit rate by orders of magnitude.

References

1. A R Dixon is also at Cavendish Laboratory, University of Cambridge, CB3 0HE, UK
2. EU Integrated Project SECOQC; www.secoqc.net.
3. Z.L.Yuan *et al.*, Appl.Phys.Lett. **91** (2007), 041114
4. Z.L.Yuan *et al.*, Appl.Phys.Lett. **92** (2008), 201104
5. B. E. Kardynal *et al*., Nature Photonics **2** (2008).
6. J. F. Dynes *et al.*, to be published.