Journal of Physics: Conference Series **2864** (2024) 012014 doi:10.1088/1742-6596/2864/1/012014

Hybrid trap detector sensitive at visible and telecom wavelengths

Aigar Vaigu[1], Toomas Kübarsepp[1], Matt Rammo[1], and Erkki Ikonen[2,3]

[1]AS Metrosert, Tallinn, Estonia
[2]VTT MIKES, VTT Technical Research Centre of Finland Ltd, Espoo, Finland
[3]Metrology Research Institute, Aalto University, Espoo, Finland

E-mail: aigar.vaigu@metrosert.ee

Abstract. We have developed a transmission trap detector sensitive over a wide optical wavelength range. The developed device takes advantage of the smooth reflectance profile of silicon photodiodes. The detector is based on two 10 mm size photodiodes – a Si photodiode and an InGaAs photodiode. The constructed hybrid trap detector is sensitive at the wavelength range from 400 nm up to 1600 nm. The detector is designed to provide a tool for countermeasures against attacks to secure quantum communication.

1. Introduction

Quantum Key Distribution (QKD) is the generation of perfectly secure random keys between two parties that communicate by an open channel. The QKD is considered a truly secure key exchange technology and its security is made possible by the (quantum) laws of physics [1, 2, 3, 4]. Any QKD systems uses real devices, which do not have the ideal characteristics foreseen by the initial QKD concept [5]. This means that the systems used in practical applications can be vulnerable to one or more of the many quantum hacking attacks proposed or already demonstrated [6, 7, 8, 9, 10, 11].

Several countermeasures against QKD attacks have already been identified, and their effectiveness depends on rigorous characterisation of the optical devices and components [7, 12, 13]. A countermeasure against Trojan-horse attacks [14, 15, 16] requires filters and 'watchdog' detectors. It must be made sure that the properties of the components will not be altered by bright-light or special wavelength pulses. The system needs to be designed in the way that the presence of bright light can be detected.

Photodiodes, especially in the form of trap detectors, are widely used in radiometry. Combining several photodiodes reduces reflectance losses of the light detection but the spectral responsivity range remains the same, because it is a tradition to use one type of photodiodes in the trap detectors [17, 18, 19, 20, 21, 22, 23]. The advantage of using different types of photodiodes is clear because by combining photodiodes with different spectral ranges will extend the spectral responsivity of the whole detector. To achieve maximum sensitivity of the combined detector, we need to consider not only the spectral responsivity of the photodiodes but also the spectral reflectance of these photodiodes. For practical applications, it is most advantageous to employ a trap detector that is sensitive to both the visible and infrared light.

In this work, we use a combination of Si and InGaAs photodiodes. The Si photodiode typically exhibits a spectral responsivity range from 400 nm to 1000 nm, while the InGaAs photodiode's responsivity spans from 900 nm to 1600 nm. By merging optical and electrooptical performance of these two photodiodes, we can construct the most straightforward hybrid trap detector: a dual-element transmission trap detector with spectral responsivity extending from 400 nm up to 1600 nm. Our primary objective was to investigate the properties of this two-element asymmetric hybrid trap detector.

2. Use of the hybrid trap detector for QKD

The principal scheme of using the hybrid trap detector in monitoring for "side" beams in the optical system is depicted in Figure 1. By using a fibre beam-splitter, a fraction of light of the order of 10% is directed into the hybrid trap detector. If undesired light is present at any modulation frequency in addition to the weak QKD beam, then a signal can be observed by the Si or InGaAs photodiode. Depending on the properties of the signal recorded, the light beam in the quantum communication detector arm can be blocked entirely, or a fibre Bragg grating be tuned to that wavelength to reflect out the unwanted light beam.

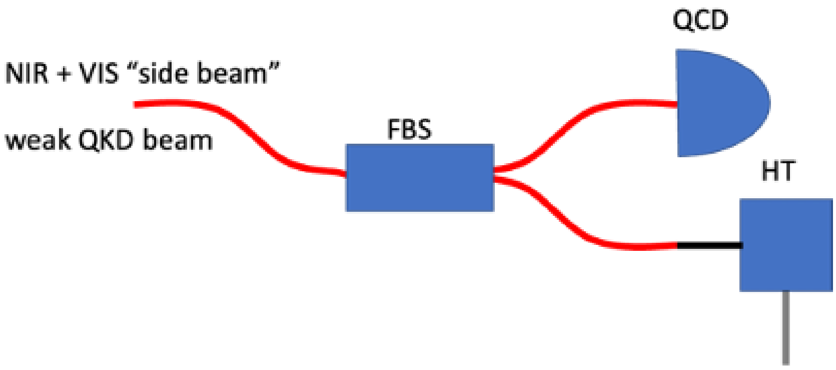

Figure 1. Principal scheme of an optical system for detecting side beams with a hybrid trap detector in a quantum key distribution (QKD) system. A combination of near-infrared and visible light (NIR+VIS) can be "side" beams launched into a telecommunication fibre by the eavesdropper. Light from the fibre network is divided into two beams with a fibre beam splitter (FBS). Most of the light is directed to the quantum communication detector (QCD), and the rest is sent to the hybrid trap detector (HT) to detect eavesdropper light. The hybrid trap detector is a free-space detector, therefore, light from the fiber output needs to be collimated before reaching the hybrid trap detector.

3. Description of the hybrid trap detector

The developed hybrid trap detector has a similar two-element transmission trap configuration as the trap detector reported in the [19]. The two large area windowless photodiodes, one 10 mm × 10 mm Hamamatsu (S1337-1010BQ) Si photodiode and one 10 mm diameter Hamamatsu (G8370-10SPL) InGaAs photodiode, were assembled at 45° of incidence angle to the incoming and reflected beam (Fig. 2). The photodiodes are arranged so that the planes of incidence are perpendicular to each other. With only one photodiode of each type, the hybrid trap detector becomes polarisation sensitive in contrast to a configuration where two photodiodes of the same kind are perpendicular to each other. The outgoing beam of the trap detector is not collinear, and it is not even at the same plane as the beam entering the trap detector.

After two reflections, the remaining light exits from the trap detector and can be used afterwards for further spectral analysis or another detector outside the sensitivity range of Si and InGaAs detectors. The electrical contacts of both photodiodes are connected directly to two BNC connectors (Fig. 3). This ensures that the photocurrents of each photodiode can be monitored separately.

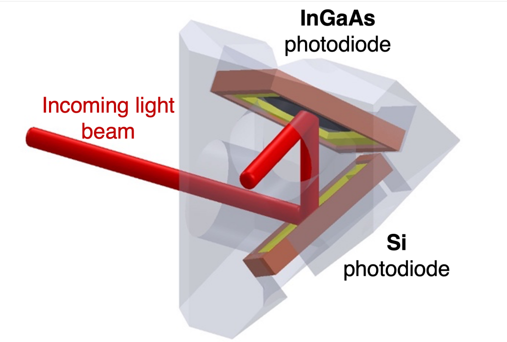

Figure 2. Open view of the hybrid trap detector in transmission mode, including one Si and one InGaAs photodiode. The light path is shown with red colour. The hybrid trap detector is asymmetric in build, and thus the operational arrangement is set so that the incoming light reflects first from the Si photodiode.

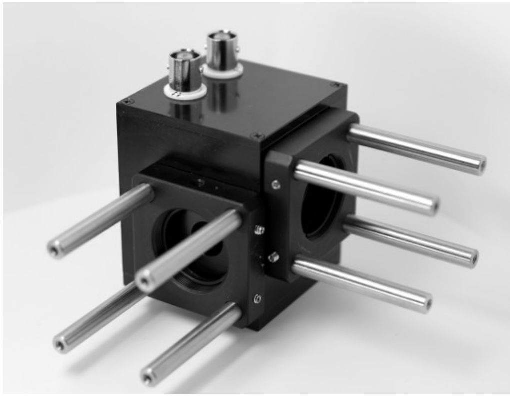

Figure 3. Outside view of the hybrid trap detector. Input and output ports are equipped with 30 mm cage system, making hybrid trap detector usable in free space and fibre-coupled applications.

4. Measurements of the performance

Before assembling the hybrid trap detector, the Si and InGaAs photodiode reflections in the visible and in IR were characterised with the Agilent Cary 5000 spectrophotometer. The reflection measurement was carried out for both s and p polarisations, and to reduce the single photodiode alignment errors, the reflection was measured for positive and negative angles of incidence. As shown in Figure 4, the reflectance for the Si photodiode for s and p polarisations is higher and smoother than for the InGaAs photodiode. Therefore, in the hybrid trap detector, the more reflective Si photodiode was placed in front to maximise light reaching the second - the InGaAs photodiode. For instance, in the case of reverse photodiode order, the combined detector would be insensitive to the input light at the wavelength of 500 nm. Combining the typical responsivity data of the Hamamatsu Si and InGaAs photodiodes with the reflectance data, it is concluded that the hybrid trap detector sensitivity reaches up to 1600 nm.

The spatial nonuniformity of the hybrid trap detector responsivity is affected by the spatial nonuniformities of individual photodiodes. Based on the individual photodiode spatial uniformity measurements, the spatial nonuniformities of the hybrid trap detector are estimated to be less than 0.5%.

The absolute responsivity of the hybrid trap detector was determined by comparison with a calibrated transmission trap detector consisting of six silicon-based photodiodes (calibrated at Czech Metrology Insitute) at laser wavelengths of 639 nm and 852 nm and with a calibrated InGaAs photodiode (calibrated at Aalto University, Finland) at laser wavelengths of 1309 nm and 1545 nm. A laser beam of diameter 2 mm was used. The incident power of all all wavelengths and for both polarisations were chosen small enough to guarantee the linear response of the

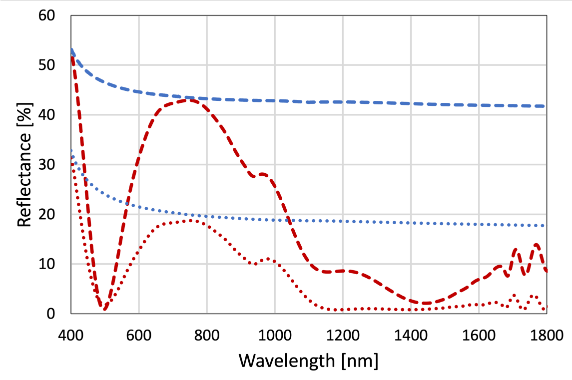

Figure 4. Reflectance of Si (blue lines) and InGaAs (red lines) photodiodes at 45° degrees of incidence and at s (dashed lines) and p (dotted lines) polarisations.

photodiodes. The spectral responsivity, $R_{ht}(\lambda)$, of the hybrid trap detector was calculated as

$$R_{ht}(\lambda) = \frac{i_{ht}(\lambda)}{i_c(\lambda)} R_c(\lambda),$$

where $i_{ht}(\lambda)$ is the photocurrent of the hybrid trap detector, $i_c(\lambda)$ is the photocurrent of the calibrated detector, and $R_c(\lambda)$ is the spectral responsivity of the calibrated reference detector. The transmittance of the hybrid trap detector was determined by comparing the measured photocurrents $i_c(\lambda)$ of the reference detector before and after the hybrid trap detector. All photocurrents were corrected for dark signal, and all measurements were done at room temperature.

The responsivity and transmittance results are presented in Table 1. The estimated relative standard uncertainties ($k = 1$) for the measured results were less than 1%. As expected, the responsivity and transmittance of the hybrid trap detector are polarisation dependent.

In the spectral range up to 1000 nm, the responsivity contribution is mainly due to the photocurrent produced by the Si photodiode at both polarisation states. This facilitates the detection of “side” beam attacks in the visible wavelength range with high probability. On the other hand, at the wavelengths of 1309 nm and 1545 nm, the dominating responsivity contribution is from the InGaAs photodiode because silicon is transparent at those wavelengths. The variation in the transmittance due to the polarisation state of the incoming light is less pronounced than that of the responsivity of the hybrid trap detector (Table 1). This can be explained by the reflectance of both Si and InGaAs photodiodes (Fig. 4). Nevertheless, the fraction of optical power in the transmitted beam is still high enough in the visible spectral range, approximately 6%-7%, to be reliably detected and used for further analyses of possible ”side” beam attacks.

5. Conclusions

We propose a technical solution for a hybrid trap detector taking advantage of the reflection and absorption properties of Si and InGaAs photodiodes. Such a solution extends the responsivity of a single photodiode, which we have demonstrated by conducting measurements in the visible and near infrared spectral ranges of interest to quantum communication. The responsivity and the transmittance of the hybrid trap detector are sensitive to polarisation state of incoming beam. This is due to polarisation dependence of reflectance of photodiodes in the detector. A possible further development of that hybrid trap detector is combining three photodiodes in a three-element reflection trap detector to achieve a polarisation insensitive responsivity.

Table 1. Measured responsivity and transmittance values of the hybrid trap detector as a function of polarisation state ($\updownarrow \leftrightarrow$ state) of incoming beam and wavelength (λ). The fractions of measured photocurrents are presented for both Si photodiode (Si PD) and InGaAs photodiode (InGaAs PD) of the hybrid trap detector at each polarisation state. The responsivity of hybrid trap detector incorporates summed up photocurrents from Si photodiode and InGaAs photodiode.

	Si PD		**InGaAs PD**		**Hybrid trap detector**	
λ nm	$\updownarrow \leftrightarrow$ state	Fraction of total photocurrent	$\updownarrow \leftrightarrow$ state	Fraction of total photocurrent	Responsivity A/W	Transmittance
639	s	84%	p	16%	0.3362	7.40×10^{-2}
	p	96%	s	4%	0.4293	7.64×10^{-2}
852	s	74%	p	26%	0.5191	6.11×10^{-2}
	p	93%	s	7%	0.6025	6.16×10^{-2}
1309	s	0	p	100%	0.4322	5.90×10^{-3}
	p	0	s	100%	0.1799	9.48×10^{-3}
1545	s	0	p	100%	0.5020	8.42×10^{-3}
	p	0	s	100%	0.2104	6.43×10^{-3}

Acknowledgments
The work leading to this study was funded by the European Metrology Programme for Innovation and Research (EMPIR) projects 14IND05 Optical metrology for quantum-enhanced secure telecommunication (MIQC2) and 19NRM06 Metrology for Testing the Implementation Security of Quantum Key Distribution Hardware (MeTISQ). The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States. The work is part of the Research Council of Finland Flagship Programme, Photonics Research and Innovation (PREIN), decision number 346529, Aalto University.

References
[1] Bennett C H and Brassard G 2014 *Theoretical Computer Science* **560**(P1) 7–11 ISSN 0304-3975
[2] Gisin N, Ribordy G, Tittel W and Zbinden H 2002 *Reviews of Modern Physics* **74**(1) 145–195 ISSN 0034-6861 URL `https://link.aps.org/doi/10.1103/RevModPhys.74.145`
[3] Scarani V, Bechmann-Pasquinucci H, Cerf N J, Dušek M, Lütkenhaus N and Peev M 2009 *Reviews of Modern Physics* **81**(3) 1301–1350 ISSN 0034-6861 URL `https://link.aps.org/doi/10.1103/RevModPhys.81.1301`
[4] Pirandola S, Andersen U L, Banchi L, Berta M, Bunandar D, Colbeck R, Englund D, Gehring T, Lupo C, Ottaviani C, Pereira J L, Razavi M, Shaari J S, Tomamichel M, Usenko V C, Vallone G, Villoresi P, Wallden P, Vallone G, Villoresi P and Wallden P 2020 *Advances in Optics and Photonics* **12**(4) 1012 ISSN 1943-8206 URL `https://opg.optica.org/abstract.cfm?URI=aop-12-4-1012`
[5] Gottesman D, Lo H K, Lütkenhaus N and Preskill J 2004 *Quantum Information and Computation* **4** 325–360 ISSN 1533-7146
[6] Lydersen L, Wiechers C, Wittmann C, Elser D, Skaar J and Makarov V 2010 *Nature Photonics* **4**(10) 686–689 ISSN 1749-4893 URL `https://doi.org/10.1038/nphoton.2010.214`
[7] Jain N, Wittmann C, Lydersen L, Wiechers C, Elser D, Marquardt C, Makarov V and Leuchs G 2011 *Physical Review Letters* **107**(11) 110501 ISSN 0031-9007 URL `https://link.aps.org/doi/10.1103/PhysRevLett.107.110501`
[8] Gerhardt I, Liu Q, Lamas-Linares A, Skaar J, Kurtsiefer C and Makarov V 2011 *Nature Communications* **2**(1) 349–354 ISSN 2041-1723 URL `https://doi.org/10.1038/ncomms1348`
[9] Weier H, Krauss H, Rau M, Fürst M, Nauerth S and Weinfurter H 2011 *New Journal of Physics* **13**(7) 073024 ISSN 1367-2630 URL `https://iopscience.iop.org/article/10.1088/1367-2630/13/7/073024`

[10] Jain N, Anisimova E, Khan I, Makarov V, Marquardt C and Leuchs G 2014 *New Journal of Physics* **16**(12) 123030 ISSN 1367-2630 URL https://iopscience.iop.org/article/10.1088/1367-2630/16/12/123030
[11] Makarov V, Bourgoin J P, Chaiwongkhot P, Gagné M, Jennewein T, Kaiser S, Kashyap R, Legré M, Minshull C and Sajeed S 2016 *Physical Review A* **94**(3) 030302 ISSN 2469-9926 URL https://link.aps.org/doi/10.1103/PhysRevA.94.030302
[12] Meda A, Degiovanni I P, Tosi A, Yuan Z, Brida G and Genovese M 2017 *Light: Science Applications* **6**(6) e16261 ISSN 2047-7538 URL https://doi.org/10.1038/lsa.2016.261
[13] Tamaki K, Curty M and Lucamarini M 2016 *New Journal of Physics* **18**(6) 065008 ISSN 1367-2630 URL https://iopscience.iop.org/article/10.1088/1367-2630/18/6/065008
[14] Gisin N, Fasel S, Kraus B, Zbinden H and Ribordy G 2006 *Physical Review A* **73**(2) 022320 ISSN 1050-2947 URL https://link.aps.org/doi/10.1103/PhysRevA.73.022320
[15] Jain N, Stiller B, Khan I, Makarov V, Marquardt C and Leuchs G 2015 *IEEE Journal of Selected Topics in Quantum Electronics* **21**(3) 168–177 ISSN 1558-4542
[16] Lucamarini M, Choi I, Ward M, Dynes J, Yuan Z and Shields A 2015 *Physical Review X* **5**(3) 031030 ISSN 2160-3308 URL https://link.aps.org/doi/10.1103/PhysRevX.5.031030
[17] Zalewski E F and Duda C R 1983 *Applied Optics* **22**(18) 2867–2873 ISSN 0003-6935 URL http://www.opticsinfobase.org/viewmedia.cfm?uri=ao-22-18-2867seq=0html=true
[18] Fox N P 1991 *Metrologia* **28**(3) 197–202 ISSN 0026-1394 URL http://iopscience.iop.org/0026-1394/28/3/018 http://stacks.iop.org/0026-1394/28/i=3/a=018?key=crossref.61371b20300a09e9b2a88628615939d2
[19] Vaigu A, Kübarsepp T, Manoocheri F, Merimaa M and Ikonen E 2015 *Measurement Science and Technology* **26**(5) 055901 ISSN 0957-0233 URL http://stacks.iop.org/0957-0233/26/i=5/a=055901?key=crossref.bf3bfbad1741a05072b2df9e7c55e457 http://iopscience.iop.org/0957-0233/26/5/055901/article/
[20] Kübarsepp T and White M 2010 *Applied optics* **49**(19) 3774–9 ISSN 1539-4522 URL http://www.opticsinfobase.org/viewmedia.cfm?uri=ao-49-19-3774seq=0html=true
[21] Gardner J L 1994 *Applied optics* **33**(25) 5914–8 ISSN 0003-6935 URL http://www.opticsinfobase.org/viewmedia.cfm?uri=ao-33-25-5914seq=0html=true
[22] Sildoja M, Manoocheri F, Merimaa M, Ikonen E, Müller I, Werner L, Gran J, Kübarsepp T, Smid M and Rastello M L 2013 *Metrologia* **50**(4) 385–394 ISSN 0026-1394 URL http://iopscience.iop.org/0026-1394/50/4/385/article/
[23] Müller I, Johannsen U, Linke U, Socaciu-Siebert L, Smid M, Porrovecchio G, Sildoja M, Manoocheri F, Ikonen E, Gran J, Kübarsepp T, Brida G and Werner L 2013 *Metrologia* **50**(4) 395–401 ISSN 0026-1394 URL http://iopscience.iop.org/0026-1394/50/4/395/article/ http://stacks.iop.org/0026-1394/50/i=4/a=395?key=crossref.71bc8bfaf76e203ccbc1955de25af841