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SUMMARY REPORT

Kvanttimekaaninen takaisinsironta/Quantum mechanical back-scattering

Prof Ilkka Tittonen, ilkka.tittonen@aalto.fi, Aalto-yliopisto, Tietotie 3, 02015 Espoo
Vladimir Kornienko, Cynthia Vidal

Abstract

The European flagship initiative is expected to turn Europe's excellent research results in areas like quantum secure communication, quantum sensing and quantum simulation and computing into concrete technological opportunities that can be taken up by industry. This project was focused on quantum back-scattering and its applications to covert target detection. We studied the means of generating optical entangled fields and their propagation through lossy, entanglement-breaking communication channels. Our research objective was to study the influence of passive jamming on optical target detection protocol.

In analytical treatment we have considered different sources of noise such as thermal background and partially reflective jamming targets. We used the formalism of density matrix and of the quantum Chernoff bound to characterize quantitatively the influence of these noise sources on the target detection protocol in terms of minimal number of trials required to ascertain the target presence or absence. In experiment, we have compared different sources of entangled photons – bulk bismuth borate (BiBO) crystal and a waveguide in periodically-poled potassium titanyl phosphate (KTP). Photon pairs were generated by frequency-degenerate spontaneous parametric down-conversion with a continuous-wave laser diode pump. The set-up allowed us to probe both non-jammed and jammed target detection protocols. We used time-correlated single-photon counting (TCSPC) system for photon detection and timing. Data processing scripts have been created.

We have demonstrated quantum back-scattering based optical target detection protocol based on entangled photons at distances of up to 4 m with target reflectance down to 6%. Jamming, passive reflectance in the target path were shown to make high-power solutions with sensitive detection systems unapplicable due to the saturation of the detector by the probing beam reflected from the jammer. We have shown that bulk nonlinear crystals are advantageous for high flux applications, while fiber and waveguide-based commercial solutions are ideal for communication applications such as quantum key distribution. In data processing, we have demonstrated the use of a ring buffer algorithm for correcting the shape of the coincidence counts histogram.

The results of the project can be used in the design of target detection protocols and quantum communication. Our results on the boundary between the low-noise and high-noise regimes can arguably lead to an advanced microscale imaging technique combining the data from both single-beam and double-beam protocols.

1. Introduction

The European flagship initiative is expected to turn Europe's excellent research results in areas like quantum secure communication, quantum sensing and quantum simulation and computing into concrete technological opportunities that can be taken up by industry. Quantum information processing (QIP) exploits fundamental quantum-mechanical properties to realize capabilities beyond classical physics. Nonclassical states are essential for optics-based QIP, providing the bases for quantum teleportation device-independent quantum key distribution (QKD), quantum computing and quantum metrology. Nonclassical states can increase the signal-to-noise ratios (SNRs).

The so called squeezed states have been employed to beat the classical-state limits in optical-phase tracking, biological sensing and gravitational wave detection. The basic generation of these optical states with non-classical noise properties has been standard in optics laboratories since 1990's, but the usability in practice is still challenging due to mixing of optical phases at beam splitters, mirrors and detectors leading to loosing of the original benefit of lower noise. Another interesting outcome of nonlinear optics is that in addition to affecting noise properties of light one can also create pairs of photons that are generated in a way that they carry a mutual quantum-mechanical correlation even when they are physically far apart. This so called entangled pair creates a quantum state that leads to a situation that by detecting one of the photons, also the state of the other photon is known. This well-known effect can also be used for quantum metrology, quantum illumination and even for secret communication.

Our motivation in studying the quantum back-scattering-based target detection protocols is that such a radar has been proven to be advantageous over any conceivable radar built on classical technologies in the regime of very low signal-to-noise ratio.

2. Research objectives and accomplishment plan

The research was focused on quantum back-scattering and its applications to covert target detection. We studied the means of generating optical entangled fields, and their propagation through lossy, entanglement-breaking communication channels.

In particular, we were investigating what is the impact of a partially reflecting jamming object on the target detection protocol with entangled photons. In contrast to thermal background, the state at the detector is exactly the one sent to the remote target. Thus, all the benefits of expanded phase space of the entangled state are virtually ignored, unless the information is available to the observer on how to differentiate between the jammer return and target return signal. One way of introducing this information is with temporal resolution, and that is the approach that has been investigated in the current project.

Our research objective was to study the influence of passive jamming on optical target detection protocol.

Expected outcomes of the project were as follows:

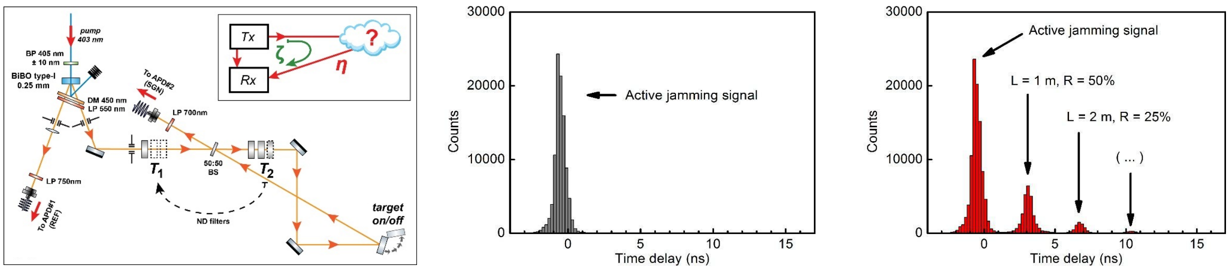
1) To provide a review of current results on covert target detection;

2) To elaborate analytical description of target detection protocols based on entangled photons in the optical range;

3) To demonstrate experimental target detection with correlated photons at distances > 1 m.

3. Aineisto ja menetelmät / Materials and methods

Back-scattering target detection protocol is based (inset in Figure 1a) on creating an entangled state of light, storing one part ("reference", "idler") and sending the other ("signal") to the remote target. Target return signal is combined during the detection stage with the stored reference beam. Similar to noise radars, correlation measurements increase signal-to-noise ratio of the detection and help to suppress the noise. In this project for the matter of simplicity we correlate the electronic pulses only, and not the optical beams themselves. This is justified by the fact that the target return signal under normal conditions has a random phase of the state [R. Nair, M. Gu // *Optica* 7, 771-774 (2020)]. Also, our results hold also for the case of more sophisticated implementations.



(a) (b) (c)

Figure 1. (a): Sketch of the experimental set-up. "BS" – beam-splitter, "APD" – avalanche photodiode, "BiBO" – nonlinear crystal (bismuth borate, $Bi(BO_2)_3$), "BP" – band-pass filter, "LP" – long-pass filter, "T_1","T_2" – neutral density filters. (Inset:) operating principle of target detection protocol. η – effective reflectance of the target, ζ – jamming reflectance. (b),(c): Photocurrent coincidence events for the cases of (b) target absent and (c) target present. Effective distances to target are provided in panel (c).

Our analytical approach starts from calculating the conditional probabilities of detecting a photon at the detector in the signal channel. We have taken into account background radiation ("b"), target return signal (reflectance "η"), and jamming reflectance ("ζ"). Using these probabilities, we constructed density matrices describing the field at the detector for two cases: (i) target present and (ii) target absent. This allowed us to use the quantum Chernoff bound [K.M. Audenaert // *Phys. Rev. Lett.* **98**, 160501 (2007)] to estimate the minimum number of trials N_{min} required to ascertain the presence or absence of the target. Finally, we derived the connection between N_{min} and experimental parameters – observation time.

There are two types of measurements that can be performed with such a system. Single-beam interrogation, being in a significant way similar to classical radars, involves only the signal beam and measuring the target return beam; information in the reference channel is completely ignored. Under double-beam interrogation, the correlation measurements are performed on both the channels.

Depending on the ratio between b, η, and ζ, there are two limit cases of low noise ($\eta >> \zeta, b$) and high noise ($\eta << \zeta$ or $\eta << b$). In the low noise regime, it is only required to detect a single photon in the signal channel to claim that the target is there. In the high noise regime, the additional signal due to the target presence is modest, and it is necessary to differentiate between two broad narrow-spaced distributions of photocounts as illustrated in Figure 2.

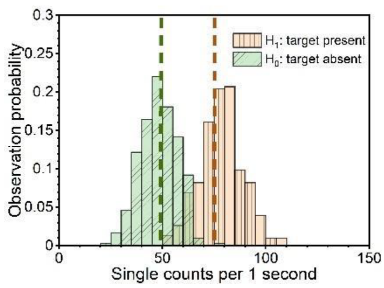


Figure 2. Histograms of photocounts in the high noise regime for the cases

of target absent (left distribution, H_0) and target present (right distribution, H_1).

Experimental realization of the project was based on a bulk nonlinear crystal, which was pumped with a continuous-wave blue laser diode to generate pairs of entangled photons. We used type-I frequency-degenerate spontaneous parametric down-conversion (SPDC) in a bismuth borate ($Bi(BO_2)_3$) crystal. Pump source was a continuous-wave laser diode (403 nm) with 10 mW of power at the crystal. Beam diameter was 2 mm. After the crystal, pump radiation was removed with a dichroic mirror and a long-pass filter. In the reference (idler) arm, the radiation was coupled into a 105 μm multimode fiber. In the signal arm, the metal mirror as a target was introduced in a Sagnac-interferometer-type arrangement, allowing simultaneous detection of target return signals corresponding to different delay times and effective reflectance values. A beam-splitter in this configuration acts both as the source of a jamming signal, and as a partially reflective interferometer mirror in the target return path. For photon detection, timing, and correlation measurements a time-correlated single-photon counting (TCSPC) system (Aurea Lynxea) was used, based on silicon avalanche photodiodes operating in the photon-counting regime.

With the set-up, we were able to study both low noise regime without the jamming, and the high noise regime with jamming signal. In the former case, the target is at T_1 position, interferometer path is blocked, and a beam-splitter is only used as a mirror (R = 50%) re-directing the target return photons to the detection. In the latter case, the beam-splitter produces a jamming signal controlled by the attenuators T_1, and the target effective reflectance is given by the product T_1T_2. Also, we can switch before the single-beam interrogation when the data in the reference channel is completely ignored, and the double-beam interrogation, when the coincidence measurements are performed.

For processing TCSPC data, we have created a set of data processing tools available on GitHub [https://github.com/VladimirVKornienko/Time-tagged-data--Aurea-file-conversion], and we were also using the data processing package from [https://github.com/QuantumPhotonicsLab/readPTU]. Our goal was to optimize the data processing so as to enhance the performance of the target detection protocol. We have investigated the use of a ring buffer algorithm which allows correcting the shape of the histogram of the coincidence detection events.

3. Results and discussion

Literature review revealed the most efficient approaches to covert target detection. At radio frequencies, it can be achieved by means of a noise radar [K. Lukin, A. Stove, C. Wasserzier // *IEEE AaE Syst. Mag.* **35** (9), 6-7 (2020)], where a pseudo-random waveform is used to modulate the transmitted signal, and the target return signal is correlated at the detector with the modulating waveform. A noise radar must be a broadband device with large duration of the transmitted pulse. Detection of the transmitted signal by an external observer is obstructed by the pseudo-random nature of the transmitted signal, while the stored information on the modulation waveform allows for sensitive correlation-based detection. In the optical range, the most promising results are obtained with infrared lasers invisible to a human eye. Optical target detection at distances of up to 1 km has been demonstrated with a femtosecond fiber laser (1.56 *μ*m wavelength) and a cryogenically-cooled single-photon detector [A. McCarthy *et al*. // *Optics Express* **21**, 8904 (2013)], with a spatial resolution of down to 1 mm, but the total distance to target being an unknown multiple of a 6 m interval corresponding to pulse-to-pulse distance. Both of these approaches were used in the experimental parts of the project.

In experiment, with the set-up shown in Figure 1 we demonstrate the detection of target with 4% effective reflectance at the distance of 4 m. We have tested 2 different sources of entangled optical beams. The first one was a commercial system (Aurea Technology) based on a periodically-poled potassium titanyl phosphate ($KTiOPO_4$, KTP) crystal with a waveguide structure. The waveguide is phase matched for parametric down-conversion in the degenerate type-II mode (frequencies of the output photons are equal, polarizations of the entangled photons are orthogonal) for continuous-wave (CW) 405 nm pump radiation. The wavelengths of the generated radiation can be tuned with temperature of the crystal. System delivers biphotons at 20 Hz rate with 0.2 mW optical pump power. The second one was a custom-built source based on a 0.25 mm thick bismuth borate ($Bi(BO_2)_3$, BiBO) crystal pumped with a CW 403 nm laser diode. Due to higher optical damage threshold of a bulk structure as compared to a waveguide one, we were able to reach the coincidence counting rate of 500 Hz for the pump power of 10 mW, albeit at the cost of lowering the conversion efficiency. Histograms of arrival time difference between the two photons are shown in Figure 3.

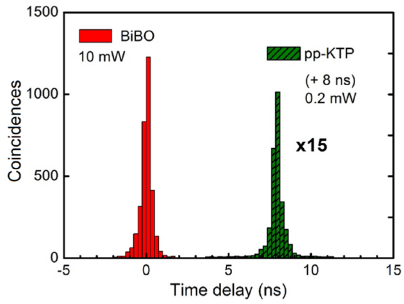
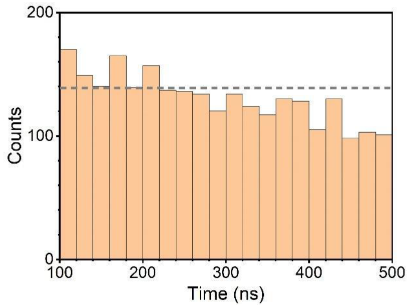
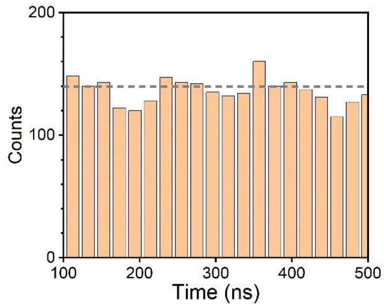


Figure 3. Number of coincidence detection events per 5 seconds time interval for two types of biphoton sources.

For the collected 2-channel TCSPC data, we have developed a data processing algorithm with a ring buffer, where photon arrival events are written in the buffer and arrival time differences are calculated between all pairs of events stored in buffer. As compared to conventional technique when the start-stop mechanism is implemented between nearest events only, ring buffer algorithm allows one to get rid of the systematic error in the number of coincidences decreasing with increasing the delay time, as shown in Figure 4.



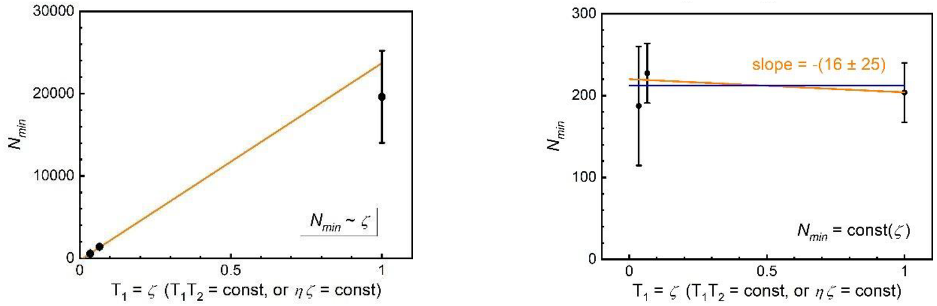
(a)



(b)

Figure 4. Distribution of coincidences in background photodetection events with different data processing algorithms: (a) closest events only; (b) ring-buffer algorithm.

In the low noise regime, we observed linear scaling of the minimal number of trials (N_{min}) with inverse target reflectance ($1/\eta$) for both single-beam and double-beam interrogation. In the high noise regime (Figure 5), N_{min} scales linearly with jamming reflectance for single-beam interrogation technique. Double-beam interrogation with time-resolved detection allows one to ignore the jamming coincidences – that is to skip all the counts from the first, jamming peak in Figure 1b,c. We thus demonstrate that back-scattering-based double-beam interrogation target detection (1) is more robust to background noise, and (2) temporal resolution is required in order to compensate for the influence of jamming targets.



(a) (b)

Figure 5. In the high-noise regime, the minimal number of trials (N_{min}) as a function of the jamming target reflectance (in this case, T_1): (a) scales linearly with T_1 for single-beam interrogation, and (b) remains constant for double-beam interrogation.

4. Conclusions

In the project, we have demonstrated quantum back-scattering based optical target detection protocol based on entangled photons. Target detection is demonstrated at distances of up to 4 m with target reflectance down to 6%. We have found that a partially reflecting jamming target can introduce noise to the detection protocol, eliminating the benefit of expanded phase space of an entangled state. We have established a link between the minimal number of trials (N_{min}) and the minimal experimental time. Results on N_{min} asymptotic behavior under correlation-enhanced target detection demonstrate that the double beam detection protocol can be tailored by choosing the detection modes. Introducing time resolution can enhance the performance of the double beam detection by a factor of $\zeta/b >> 1$ (ζ – jamming reflectance; b – background noise level in photons per radiation mode). We have shown that a partially reflecting changes the detection from low noise regime to high noise regime for single beam detection, and the asymptotic behavior of N_{min} is changed. Jamming, passive reflectance in the target path were shown to make high-power solutions with sensitive detection systems unapplicable due to the saturation of the detector by the probing beam reflected from the jammer.

Literature review has shown that correlated-photon-based imaging is ideal for covert operation due to low transmitted power and efficient background suppression. At the same time, for time-of-flight depth measurements in the field operation conditions, LIDAR-based technologies are the best match.

We have also demonstrated that for high flux applications bulk nonlinear crystals are advantageous over fiber and waveguide-based sources of correlated photons, due to low-gain regime of operation. Fiber-based commercial solutions are ideal for communication applications such as quantum key distribution due to intrinsic stability and high level of control.

The results of the project can be used in the design of target detection protocols and quantum communication. Difference in asymptotic behavior of N_{min} can arguably lead to a modified imaging technique combining the data from both single-beam and double-beam protocols.

5. Scientific publishing and other reports produced by the research project

The results of this project have been disseminated to the broad scientific audience on the following conference:

“Physics Days 2022” (Espoo, Finland): V. V. Kornienko, A. Pönni, M. Raasakka, and I. Tittonen, "The impact of backscattering on classical and quantum optical target detection" (oral presentation).

Results were also presented on the annual MATINE seminar on 25.11.2021.

The manuscript of the article is now also in preparation, to be submitted to a high-impact scientific journal:

V.V. Kornienko, C. Vidal, A. Pönni, M. Raasakka, I. Tittonen, "Partially Reflecting Jamming Targets in Correlation-Enhanced Target Detection" (*to be submitted*).