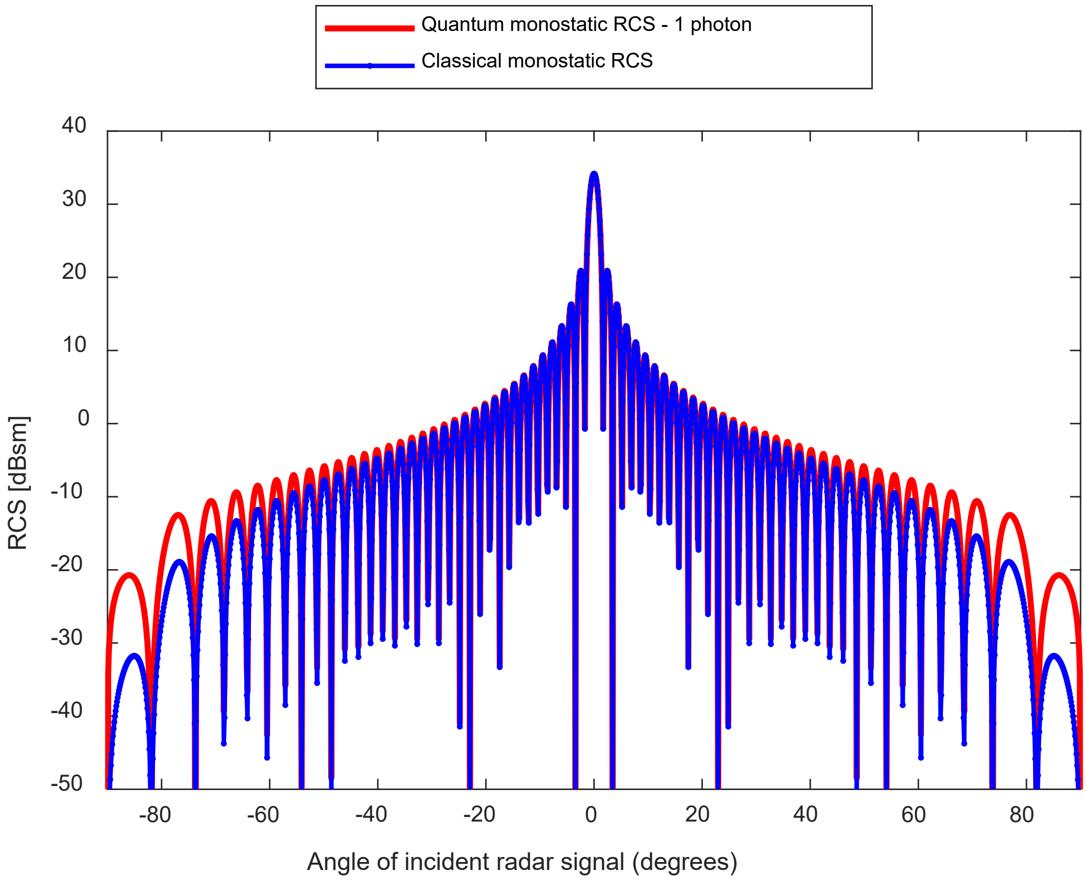
Quantum Radar

A survey of the science, technology and literature

MAGNUS HÖIJER, TOMMY HULT AND PER JONSSON



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Summary

A quantum radar is a radar based on physical phenomena described by quantum physics, and not solely by classical physics. Like in many other emerging quantum technologies, e.g. quantum computing and quantum communication, *entanglement* is the central phenomenon used in a quantum radar. Entanglement implies a strong correlation between two (or more) particles (photons, pulses). Entanglement remain even if the particles are separated by distance.

The most promising quantum radar technique today seems to be *quantum illumination*, theoretically presented by Seth Lloyd in 2008. Two entangled photons are generated, one, the idler, is kept in the radar. The other, the signal, is sent toward the target. If the signal photon is reflected back to the radar, it is likely to be detected due to its strong correlation with the idler.

Quantum illumination, in difference to many other quantum technologies, works even in a noisy environment. Therefore, the quantum illumination protocol has been proposed even for quantum communication.

The ideas behind a quantum radar is based on solid and well-accepted physics. The first experiments have been performed in the optical domain and just recently even solely in the microwave domain by use of a *Josephson Parametric Amplifier*. If the technology will develop and systems parameters interesting enough can be reached, is still an open question.

Until now, the published research on quantum radars is small compared to other quantum technology areas, probably due to radars being a niche product. However, even relatively small efforts could give substantial results.

Today's interest of a quantum radar is probably mainly military but potentially also medical.

Keywords: Quantum Radar, Quantum Illumination, Entanglement, Low Probability of Intercept (LPI), Anti-Stealth, Josephson Parametric Amplifier.

Sammanfattning

En kvantradar, är en radar som utnyttjar kvantfysikfenomen och inte enkom klassisk fysik. Analogt med andra kvantteknologier, exempelvis kvantdatorer och kvantkommunikation, kan en kvantradar utnyttja fenomenet *sammanflätning* (entanglement). Kvantmekanisk sammanflätning är en korrelation mellan två (eller flera) partiklar (fotoner, pulser) som kan bli starkare än motsvarande klassiska korrelation.

Den kvantteknologi som tycks vara mest lovande idag är *quantum illumination*. En teknik teoretiskt presenterad av Seth Lloyd år 2008. Två sammanflätade fotoner skapas. En foton, idlern, sparas i radarn, medan den andra fotonen, signalen, skickas mot målet som ska detekteras. Om signalfotonen reflekteras tillbaka mot radarn, kommer den att detekteras med hög sannolikhet, tack vare dess höga korrelation med idlern.

Quantum illumination fungerar, till skillnad från många andra kvantteknologier, även i brusiga miljöer. Således har quantum illumination även föreslagits som en teknologi för kvantkommunikation.

Idéerna bakom de föreslagna kvantteknologierna, bygger på väl påvisade och allmänt accepterade fysikaliska fenomen. Kvantradarexperiment har utförts i den optiska domänen och nyligen även i mikrovågsdomänen. En central komponent är *Josephson Parametric Amplifier*, en spinoff från övrig kvantteknologieutveckling. Om teknologiutvecklingen fortskrider så pass väl att intressanta systemprestanda uppnås, är fortfarande en öppen fråga.

Mängden forskningspublikationer om kvantradar är mindre än antalet publikationer inom liknade kvantteknologier. Troligen en följd av att radarteknologi är en nischprodukt. Efterfrågan av en kvantradar är troligen främst militär, men eventuellt finns även ett intresse inom medicinsk teknik.

Det är möjligt att en relativ liten insats inom kvantradarforskning skulle kunna ge påtagliga resultat.

Nyckelord: Kvantradar, Quantum illumination, Sammanflätning, LPI, Anti-Stealth, Josphson Parametric Amplifier.

Preface

This report is part of an internally initiated project at the Swedish Defence Research Agency FOI with the purpose of understanding and evaluating the use of quantum physics in radar systems, and the potential implications thereof. Potentially, it could perform the base for future research projects.

The report describes physics of quantum radar technology while keeping the mathematical treatment of quantum mechanics at a minimum.

Contents

1 Introduction

In 2008, Science publishes a not even three pages long article [1] by Seth Lloyd. It suggests using *entangled* light to enhance the sensitivity of photo detection. A laboratory experimental realization is published in 2013 [2]. In 2018 [3], and 2019 [4], there are early reports of using experimentally realised entangled microwave signals that could outperform the performance of classical microwave signal in a classical radar. The dawn for a potential future prototype-quantum-radar might have been seen.

A quantum radar shares many similarities with a classical radar. The distinguishing quality of a quantum radar is it benefitting from at least one physical property described by quantum physics but not by classical physics. A quantum radar may, but not necessarily must, exhibit better properties than its classical counterpart does.

Our main interest is to find out if there are quantum radar technologies that for some applications could show an increased performance relative to their classical counterparts. Examples of an increased performance are,

- Lower probability of intercept (LPI) [5]
- Decreased effectivity of electronic counter measures
- Detection of stealth vehicles
- Target characteristics (Ideally to identify the target)

A classical radar transmits an electromagnetic pulse towards a potential target. In case a target being present, a fraction of the electromagnetic energy is reflected toward a receiving antenna and the target can be detected. The reflected signal is often weak and difficult to distinguish from noise, clutter and other disturbances.

One way to enhance the detectability performance of the radar is to increase the radiated electromagnetic power of the radar pulse. Apart from the technical challenge in itself and the risk of disturbing other capabilities, the radar signal is also more easily intercepted by others.

A common technique used to increase the detectability of the reflected pulse is to transmit a specific signal pulse, and to keep a copy, or idler, of the transmitted pulse. By cross-correlating the reflected signal pulse with the idler, a substantial signal processing gain can be achieved due the reflected signal and idler being strongly correlated.

An operational quantum radar would probably work in the same way as the classical radar described above. The transmitted signal and the idler (or copy) can never be completely correlated, a phenomenon coupled to the presence of noise, but quantum physics offers the concepts of entanglement[1] and squeezing.

Squeezing and entanglement of the quantum signal and idler, allow the correlation between them to be larger than the corresponding classical correlation [6]. The enhanced correlation give rise to a larger signal processing gain for the quantum radar compared to its classical counterpart.

It has also been proposed that the quantum property of the photon could be used to counteract stealth properties. A single photon, or small cluster of photons, will not scatter from the target in the same way as a high-energy radar pulses. Using this together with the quantum radars ability to detect weak echoes, offers potentially an ability to detect a target

[1] Entanglement is described in section 2.2 and squeezing is described in section 2.4.

being illuminated even at an angle of incidence where the target was designed to have as low radar cross section as possible.

2 Quantum Physics

Within quantum physics, there are properties, which have no correspondence in classical physics. The properties most relevant in understanding the idea behind a quantum radar are briefly described below. *Entanglement* is the key property in today's proposals of a quantum radar.

The electromagnetic mode theory is largely a classical theory, but given here for completeness.

2.1 Quantum Superposition

Quantum superposition means that a physical system *can* be in a superposition of two or more states.

We exemplify with the polarisation of an electromagnetic wave. Classically, the wave has one polarisation, e.g. vertical linear polarisation ($|V>$) or horizontal linear polarisation ($|H>$). In the quantum description, the wave can be in a state ($|\Psi>$) being a superposition of both vertical and horizontal polarisation,

$$|\psi> = \frac{1}{\sqrt{2}}\left(|V> + |H>\right) \ . \tag{1}$$

In contrast to the classical superposition, the quantum superposition does not add up to one new polarisation, but the state in (1) is both vertical and horizontal at the same time.

Still another property is that by performing a proper measurement of the polarization state, the quantum wave function collapse and we will measure vertical or horizontal polarisation. Thereafter the wave is no longer in superposition, but is in one of the two polarization states,

$$|\psi> = |V> \quad \text{or} \quad |\psi> = |H> \ . \tag{2}$$

We can notice two properties of quantum physics. First, the actual measurement changes the polarization state from (1) to (2). Secondly, a measurement giving one of the two states in (2) is physical. To get both vertical and horizontal polarisation from a measurement would not be physical.

2.2 Entanglement

Let us assume, we have two electromagnetic wave packets (or photons), both in superposition states according to (1),

$$|\psi_1> = \frac{1}{\sqrt{2}}\left(|V_1> + |H_1>\right) \ ,$$
$$|\psi_2> = \frac{1}{\sqrt{2}}\left(|V_2> + |H_2>\right) \ . \tag{3}$$

If the waves are independent, their total state is[2],

$$\begin{aligned} |\psi_1,\psi_2> &= \frac{1}{\sqrt{2}}\left(|V_1> + |H_1>\right) \otimes \frac{1}{\sqrt{2}}\left(|V_2> + |H_2>\right) = \\ &= \frac{1}{2}\left(|V_1>|H_2> + |H_1>|V_2> + |V_1>|V_2> + |H_1>|H_2>\right) \ . \end{aligned} \tag{4}$$

In (4) a measurement of the polarisation state of wave 1, does not affect the polarisation state of wave 2, and vice versa.

However, quantum physics allows the generation of two waves, both in superposition according to (3), that are not independent but *entangled*. In our example with the polarisation state of two waves, the total state is not the product of two independent states like in (4), but an entangled state like,

$$|\psi_1,\psi_2> = \frac{1}{\sqrt{2}}\left(|V_1>|H_2> + |H_1>|V_2>\right) \ . \tag{5}$$

If we perform a measurement of the polarisation state of wave 1 in (5) and the result is vertical (horizontal) polarisation, then we immediately know that the polarisation state of wave 2 is horizontal (vertical). That being true, even with the waves being taken miles apart after their generation, inspired Albert Einstein to describe it as "spooky action on a distance".

Today, entanglement is a well-established theory, and experimentally proven.

2.3 Heisenberg Uncertainty

According to the Heisenberg uncertainty principle, it is impossible to measure both of two non-commuting variables with infinite accuracy. A well-known example is position and momentum in the same direction. The Heisenberg uncertainty principle also quantifies the uncertainty.

Actually, it is not only impossible to measure the two non-commuting variables with infinite accuracy; it also has no meaning. A classical correspondence, well known by the

[2] The symbol $\otimes$, denotes the tensor product between the states in mode 1 and the states in mode 2. The total state in (4), spans the space of both the state of mode 1 and the state of mode 2. The independence in (4) between the state of mode 1 and the state of mode 2, implies that the total state can be written as a tensor product. In contrast, the entangled state in (5) cannot be factorized as a tensor product.

signal processing community, is that trying to specify a pulse exactly in both frequency and time has no meaning.

To the quantum mechanics community it is well known that amplitude and phase are non-commuting. Equivalently, the in-phase (I) and out-of-phase (Q) components are non-commuting. E.g. if we have a wave (state) with exactly one photon, the phase is completely unknown. If there is an uncertainty in the number of photons, they accuracy of the phase can be increased.

2.4 Squeezing

The Heisenberg uncertainty principles says that we cannot measure two non-commuting variables with infinite accuracy. However, it does not say that, the uncertainty need to be equally distributed between the two variables. In a squeezed state, the uncertainty in one of the two non-commuting variables is decreased at the expense of the uncertainty in the other variable being increased. E.g., the in section 2.3 mentioned number state of one photon is a squeezed state, as the number of photons is exactly known at the expense of the phase being completely unknown.

It is even possible to generate a two mode squeezed state, where each mode separately is not squeezed. Let us assume, we have generated two electromagnetic waves, one in each mode, both having the same minimum uncertainty in their I- and Q-components according to the Heisenberg uncertainty principles.

However, the I- and Q-components of wave 1 (I_1, Q_1), can be entangled with the I- and Q-components of wave 2 (I_2, Q_2), in such a way that certain linear combinations of (I_1, Q_1) and (I_2, Q_2) are squeezed making the uncertainty smaller, at the expense of the uncertainty being larger for a complementary linear combination [7].

Hence, each wave is not squeezed separately, but together they are squeezed. The squeezing can only be seen by the person having access to both waves.

2.5 Electromagnetic modes

It is well known that inside an empty electromagnetically well shielded cavity, the cavity can only be electromagnetically excited at a discrete number of frequencies. Every such frequency corresponds to one (or possibly a limited number of) electro-magnetic mode(s).

On contrary, in free space, there is a continuum of infinite numbers of electromagnetic modes. However, a detector, used to receive electromagnetic fields, can due to its practical and technical restrictions, only receive a finite numbers of modes. Let us assume a detector with a limited receiving bandwidth (W) and a limited temporal detection window length (T). Due to the above described Heisenberg uncertainty principle, the limited bandwidth implies that the smallest possible time accuracy is $\Delta t \sim 1/W$, and the total number of modes (d) , the detector possibly can resolve is,

$$d = \frac{T}{\Delta t} = WT \quad . \tag{6}$$

In the early description of a quantum radar by Lloyd, see [1] and section 3, the number of detector modes play a central role in giving numbers to the improved performance of a quantum radar compared to its classical counterpart.

3 What is a Quantum Radar?

A quantum radar is first of all a radar. Like a classical radar, it emits electromagnetic energy, a fraction of the energy is reflected by a target and a fraction of the reflected energy is received and measured by the radar, se Figure 1.

The quantum radar differs from the classical radar, on the use of one or more phenomena only described by quantum physics. Up until today, the quantum phenomenon proposed for a quantum radar is entanglement.

The entanglement causes an increased correlation between the signal and idler in Figure 1, especially at very weak signal levels. From a signal theory viewpoint, an improved matched filter is created, making it possible to detect weaker signals.

There are more than one proposed technique to implement a quantum radar [8]. Today quantum illumination proposed by Lloyd [1] seems to be the most promising technique. Quantum illumination describes the use of entangled state illumination to increase detection (and imaging). In this report, we will have a tendency to use quantum illumination almost as a synonym to quantum radar.

The work by Lloyd [1] is based on the signal and idler at each time instance being in single photon states. In later experimental realisations, the signal and idler are multiphoton continuous variables [3, 4, 6].

Entanglement is fragile; it is easily destroyed by loss and noise. That is a major setback for many implementations of quantum technologies [1, 9].

Surprisingly, in difference to most other quantum technologies, *a quantum radar based on quantum illumination seems to work even when the entanglement is lost* before the detection is performed [1, 3, 4, 6, 7, 10].

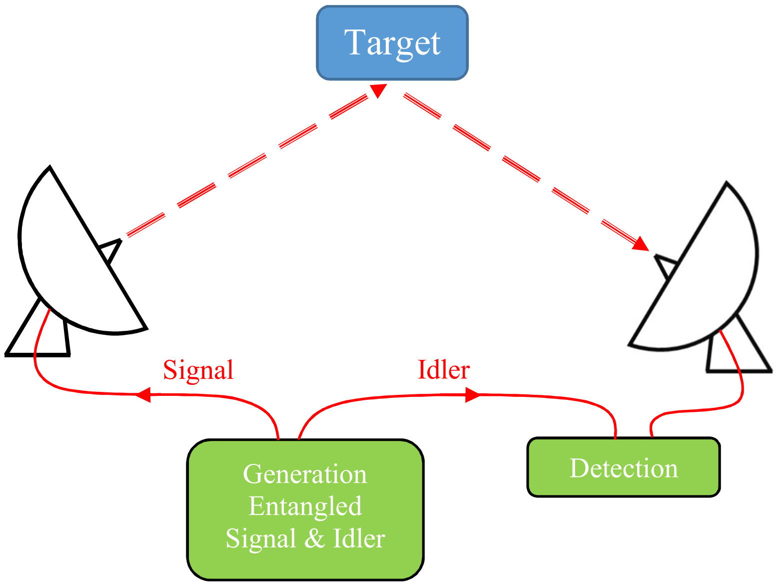

Figure 1: Principal sketch of a quantum radar. The difference to a classical radar is the signal and idler being entangled. The entanglement creates an enhanced correlation between (the part of) the signal being reflected back and the idler. Fascinatingly, the increased correlation remains even if the entanglement is destroyed by noise and losses [1, 3, 4, 6, 7, 10].

The statement is surprising. If we manage to create an entangled signal and idler pair, their seems to be some sort of remaining correlation between the signal and idler, even after the entanglement is lost due to noise and loss. Already Lloyd [1] points out this startling effect, and experiments seem to confirm the result [3, 4, 7]. Attempts to grasp the statement, have been done [6, 10], but there are probably still room for further interpretations.

We would like to add a comment about the difference between quantum illumination and many other quantum technologies. Let us, as an example, compare quantum illumination with quantum communication. Quantum communication at least claims to offer an ultra-secure communication making eavesdropping impossible. However, already small amounts of noise and loss will limit the level of security, and even a small degrading of the security of quantum communications, wipes out the use of it.

Quantum illumination, on the other hand, is typically used in a quantum radar for detection. In detection, there is always an inherent risk of false alarm and risk to miss a true target. As long as a quantum radar offers better detection properties than its classical counterparts there is a potential use of it.

4 Dawn of a Quantum Radar Concept

The ideas of quantum radar and quantum illumination to large extent emanate from the DARPA program *Quantum sensors program* [11], quoting the article by Lloyd [1], and may be seen as a starting point for the quantum radar concept.

The article by Lloyd [1] is theoretical. It uses quantum mechanical density operators[3] (ρ), but keeps mathematics at a minimum. It is not limited to any specific frequency range; actually Lloyd [1] uses words like e.g. *light*, in accordance with the optical regime, but he takes also into account cases with large noise levels more in correspondence to the microwave regime. The focus in [11] is also to a large extent the optical regime and also addresses imaging. Later in this chapter and in chapter 5, we will discuss the choice between light and microwaves for a quantum radar, or in the case of light, a quantum lidar.

The treatment by Lloyd [1] assumes single photons being sent repeatedly, but a better performance is assumed reachable by the use of multiphoton states [1].

In Figure 2, we try to graphically describe the treatment in [1]. The target in Figure 1 has been replaced by a beam splitter. The reflectivity (η) of the beam splitter does not only represent the scattering of the target, but also loss and path loss between the signal generator and the detector. The channel is assumed ideal before and after the beam splitter. The beam coming from the upper left corner represents noise photons and vacuum fields being added.

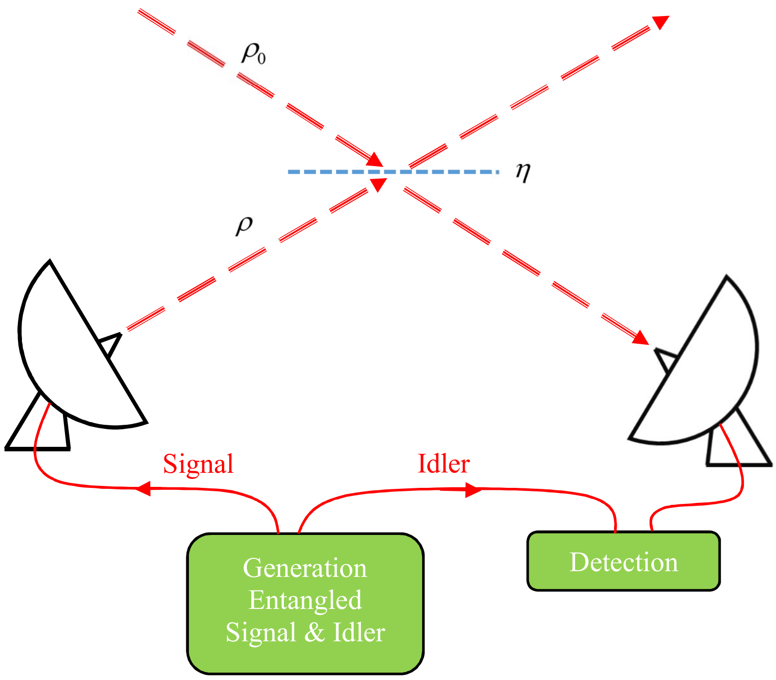

Figure 2: A mathematical treatment of the quantum radar in Figure 1.

[3] A simple interpretation of the quantum mechanical density operator for the case presented in [1] S. Lloyd, "Enhanced Sensitivity of Photodetection via Quantum Illumination," *Science,* vol. 321, no. 5895, p. 1463, 2008, doi: 10.1126/science.1160627., is the number of photons.

A key property is the number of detector modes (*d*), described in section 2.5. An average number of *b* noise photons per mode is assumed. The treatment in [1] is probabilistic with calculations of probability of detection of a target and the risk of false alarm.

A main result is that the introduction of entanglement between the signal and idler reduces the effective noise from *b* to *b/d*.

Generation of entangled signal and idler[4] pairs have been done for decades in the optical regime using nonlinear crystals, and just recently also in the microwave regime by use of the Josephson Parametric Amplifier, described in section 5.6.1.

How the detection measurement is to be performed benefitting from the entanglement between the signal and idler is a key issue. In the next section, we start by presenting a few suggestions and measurements performed.

4.1 Detection measurement in quantum illumination

The main idea of quantum illumination is that the entanglement between the signal and the idler makes it possible to distinguish signal photons from noise photons if we can perform an entangled measurements together with the idler. In such a measurement, the noise photon has a harder time masquerading as an entangled signal photon.

In the original paper of quantum illumination [1] Lloyd gives a couple of references to papers that use two-photon absorption to perform the entangled measurement [12, 13]. With this method, it is necessary to overlap the signal (or noise) photon and the idler photon at a detector. This gives rise to two complications. Since the signal is sent out to probe the environment, the idler must be stored until the signal gets back from the target. It is not always trivial to achieve experimentally, but it can e.g. be done with a low-loss delay-line where the delay is adjusted to the distance to the target. The second complication is even more troublesome for practical use of quantum illumination. Since you need to overlap the signal and idler at the detector, it is only possible to probe one distance at a time. To distinguish signal from noise photons a certain integration must be done for each distance. If the distance to target is unknown, the delay must be swept to cover all possible distance to the target. These multiple integrations will take time. This is a large difference compared to most radar and lidar systems used today where you get the response for all distances from one or a number of pulses. Lloyd conclude in this paper that this an important question that remains to be answered to make quantum illumination useful: *can the requisite entangled measurements be performed efficiently*?

Lloyd's initial paper only considered single photon states in his calculations. Tan et al. expanded the theory to also include Gaussian states and showed that with quantum illumination it is possible to improve the error-probability exponent by a factor of 4, i.e., by 6 dB, compared to a classical coherent state [6]. In a following paper, Shapiro and Lloyd elucidated that quantum illumination is unlikely to substantially improve radar performance in the low-noise regime. However, the factor of 4 improvement can be achieved with quantum illumination in a lossy, noisy and low-brightness scenario if the optimum quantum measurement is performed [14]. Usha Devi and Rajagopal

[4] A synonym to idler, used in some literature, is ancilla.

independently came to the same conclusion [15]. None of the above paper mention how to perform the optimal measurement.

Guba and Erkmen investigated two different methods to perform the quantum measurement and compared it to what is achievable with a classical transmitter and an optimal receiver [16]. One of the detectors was based on an optical parametric amplifier (OPA) with small gain and the other on a phase-conjugated (PC) receiver with a balanced difference detector. Both methods can be built with off-the-shelf optical components. They theoretically show that both detection systems perform about factor of 2, i.e. 3 dB, better than the best classical alternative based on a classical coherent state transmitter with a homodyne detection receiver in the lossy, noisy and low-brightness regime. The PC is slightly better than the OPA. Hence, it is possible to reach about half of the improvement with these known quantum measurement compared to that could be achieved with an optimum measurement according to Tan and colleagues [6].

Although theory and possible experimental implementations where presented in 2008 and 2009 it took almost five years before the first experimental realization was published by Lopaeva et al. [2, 17]. They presented a setup on an optical table where they showed that entanglement could be used to improve detection of a target in the present of a high background, see Figure 3.

The entanglement was generated in the optical regime in a spontaneous parametric down-conversion (PDC) process in a nonlinear crystal. In this experiment the photons in the signal and idler channels was not overlapped in an entanglement measurement. Instead, they used cross-correlations between photon counts in the signal and idler channels. In a clever way, they used a single array detector to measure both signal and idler photons, where about half of the pixels detected the photons from signal arm and about half of the pixels from the idler arm. Each pixel corresponds to a number of spatial modes. The target was a beam splitter and when the beam splitter was present in the signal arm, it reflected part of the signal beam onto the detector. When not present the signal does not reach the detector. Thermal noise could be added in the signal arm, produced by scattering a laser beam on an Arecchi's rotating ground glass. The right drawing in Figure 3 shows the measurement of the classical correlation. The signal output of the PDC was blocked, and the idler was divided in a beam splitter.

The test shows that the quantum illumination (QI) preforms better than the classical illumination (CI). At low background noise, the QI had stronger cross-correlations than possible by classical theory, which results in a better signal-to-noise ratio compared to CI. At higher background the QI scheme preserve the strong advantage with respect to the classical illumination based on classically correlated beams although the cross-correlations are no longer below the non-classical limit.

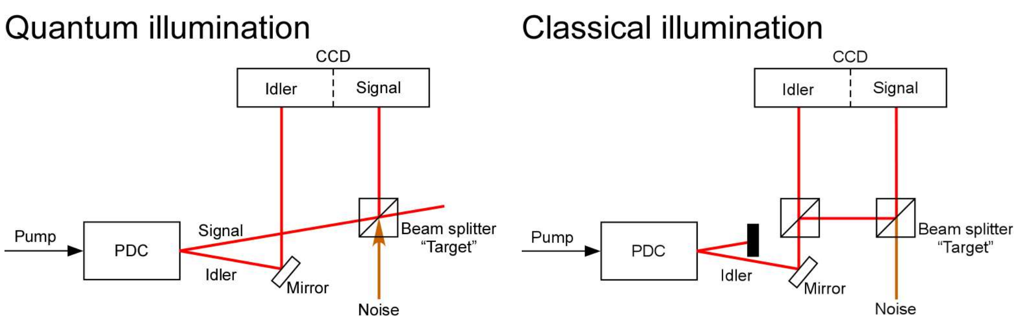

Figure 3: The schematics of the setup used by Lopaeva et al. [2]. The sketch is not to scale. The signal and idler paths are arranged so they are equally long so the photons reach the CCD detector at the same time independently which path they took. CCD – charge-coupled device, PDC – parametric down-conversion.

It is difficult to compare these results with Tan et al. [6], as explained by Ragy et al. [18], but it shows that quantum illumination can outperform its classical counter part by using entanglement. However, cross-correlation measurement does not fully exploit entanglement. Moreover, neither does their classical illumination setup represent the optimum choices for classical-illumination target detection, which are known to be a coherent-state probe and a homodyne-detection receiver. Hence, experimental proof for target-detection advantage of quantum illumination over an optimum classical detection system was not proven with this experiment. Furthermore, it is difficult to see how the setup could be used as proper quantum lidar, where the signal photons are sent to a target at an unknown distance. E.g. the signal and idler paths were set up to be equally long when the beam splitter were in place.

In 2015, Zhang et al. performed another experiment in the optical region [19] that resembles the OPA setup proposed by Guha and Erkmen [16]. In this setup, the signal and idler photons were overlapped on an OPA to perform the entanglement measurement. They compared the QI results with a classical setup using homodyne reception. Amplified spontaneous emission was added in the signal arm to simulate background noise. The QI setup was quite complex, e.g. the photon polarisation must be controlled and the path lengths must be precisely adjusted so the idler and signal photons overlap at the OPA in order for the detection to work properly. However, they manage to show that QI can outperform optimal CI. Although the experiment was simplified, e.g. the signal photons where kept in fibres and never travelled in free space to a target and back, they only achieved a 20% SNR improvement over the theoretical classical optimum, i.e. 0.8 dB instead of the 3 dB that is possible according to Guha and Erkmen [16]. The entanglement measurement used in this experiment requires an integration for every distance, which makes the method time consuming if the distance to the target is unknown and very difficult if the target is moving.

Lately, England et al. performed another QI experiment in the optical regime. In this case, they used spontaneous four-wave mixing to generate photon pairs. The signal photon was used to illuminate the target and the idler photon was measured locally to “herald” the generation of a signal photon. The setup was a lidar even though the distance to the target was 34 cm. As the source of noise, they used a laser pointing into the collection telescope. Similar to Lopaeva [2] they used cross-correlations between detections of signal and idler photons. In the quantum setup, they used cross correlations (coincidences) between the signal and idler detectors while in the classical setup they used only the detection in the signal detector and showed an advantage for the quantum setup. They did not compare their results with the optimal classical illumination as Zhang et al. [19] did in their experiment. Therefore, this experiment does not prove that quantum illumination with this setup is better than what is possible with an optimal classical illumination.

In the microwave region, there have been even fewer publications. In 2015 Barzanjeh et al. published a proposal how to reach the microwave regime that attract a lot of attention [20]. In the proposal, optical photons are converted into the microwave region and vice versa via an electro-optomechanical (EOM) converter, were photons drive a mechanical resonator. In order to work the EOM converter must be cooled down close to absolute zero temperature. The idea is to generate the entangled photons in optical regime. Signal photons are converted into microwave and are then transmitted. The reflected microwave photons are collected and converted back to the optical regime and measured together with the kept idler photons in an entanglement measurement. Despite the high interest of the publication, it is doubtful that this would be a practical solution to reach the microwave region.

Lately a couple of groups have investigated an all-microwave quantum radar [3, 4] where whey use multiphoton entangled squeezed states instead of single-photon states. In our opinion, this is the most interesting quantum radar proposal so far. These proposals and experiments are described in Chapter 6.

In the next chapter, the microwave (radar) and the optical (lidar) regions are compared. Especially in military applications, the microwave region is of more interest because it could give all-weather capability and longer ranges due to lower attenuation.

5 Quantum Radar or Quantum Lidar

A classical radar uses microwaves. The corresponding technology using light is called lidar[5]. In most communities, radar is a more known acronym than lidar, and sometimes the word radar is used independent of the electromagnetic wavelength. A similar terminology will probably be developed in the quantum case.

In this chapter, we address the question of which frequency domain is most suitable for a quantum detector system. We present results similar to the ones given in [21], but give an extra twist to it by taking conclusions in [1] into account.

To give specific number and a final judgement on the best choice of frequency domain is hard, not a least dependent on the technology development, and not within the scope of this report. Instead, we put focus on factors influencing the choice of frequency domain. Many of the outcomes are uniform to the one drawn for classical radars and lidars, and as both radars and lidars have found their fields of applications, one might guess, a similar development in the quantum case.

5.1 Directivity of transmitter

The directivity is a measure of the ability of the transmitting microwave antenna or laser to focus its energy into a specific direction.

To specify the directivity of the transmitting laser in a lidar system is not common within the optics community. More common is to use the concept of a ray and to specify the radial beam divergence. A good laser can have a radial beam divergence of 34 µrad. If we somewhat roughly approximate the laser energy to be uniform within the beam divergence, and no energy outside the beam divergence, we can estimate the directivity to $(2/(34 \cdot 10^{-6}))^2 = 95$ dB. In a turbulent environment, the radial beam diverge may increase to 1 mrad, corresponding to a directivity of $(2/(1 \cdot 10^{-3}))^2 = 66$ dB.

A parabolic microwave antenna, as indicated in Figure 1, operating at 10 GHz (wavelength 30 mm) and having a parabolic reflector diameter of 1 meter will have a directivity of approximately $(\pi \cdot 1/0.03)^2 = 40$ dB, and a corresponding beam-width of $1.22 \cdot 0.03/1 = 37$ mrad $= 2.1^{\circ}$. A higher frequency and/or larger antenna gives a larger directivity and narrower beam-width. A parabolic reflector diameter of 10 meter operating at 94 GHz (wavelength 3.2 mm) corresponds to a directivity of $(\pi \cdot 10/0.0032)^2 =$ 80 dB, and a beam-width of $1.22 \cdot 0.0032/10 = 0.39$ mrad $= 0.022^{\circ}$.

5.2 Atmospheric losses

The losses in the atmosphere is frequency dependent. Both radar and lidar operate at frequency domains corresponding to low opacity-windows. The attenuation and scattering

[5] The term ladar is also used.

in the microwave frequency range is lower than in the optical frequency range. In the case of rain and/or fog, the difference becomes substantial.

5.3 Radar Cross Section

The radar cross section is a measure of the reflection from the target in a specific direction. The reflection toward the receiver of the radar and lidar systems is of most importance.

In the optical case, the reflection is often diffuse and Lambertian, due to the optical wavelength being much smaller than typical sizes of the object.

In the microwave case, the reflection is often much more specular, making the radar cross section potentially much higher than in the optical case.

5.4 Effective Area

The effective area of the receiver is a measure of how much of the reflected planar electromagnetic wave, from the target toward the receiver, can be collected by the receiver. Making the receiver large enough, the effective area equals the physical area. Hence, the potential effective area is the same for both radar and lidar. However, today’s technology provides higher effective areas for radar systems, mainly because of easier manufacturing due to the longer wavelength and thus less strict tolerances.

5.5 Noise

The photon energy ($h\nu$) is for an optical photon of 500 THz, $3.3 \cdot 10^{-19}$J, and for a microwave photon of 5 GHz, $3.3 \cdot 10^{-24}$J. The thermal energy ($k_B T$) is $4.1 \cdot 10^{-21}$J at room temperature (300 K). Photons are bosons and follow the Bose-Einstein distribution. For the optical photon, the thermal energy is much smaller than the photon energy, making thermal noise a minor problem. For the microwave photon, the situation is the opposite and the influence from thermal noise is substantial. That is not favourable for the creation of entangled photon state.

However, by use of cryogenic system lowering the temperature to 7 mK, the thermal energy is lowered down to $9.7 \cdot 10^{-26}$, making the thermal energy even smaller than the microwave photon energy. That explains the need for cryogenics in the microwave domain, whereas many experiments in the optical domain can be performed at room temperature.

5.6 Quantum Technology

Due to the lower noise levels in the optical domain compared to the microwave domain, it is no surprise noticing that quantum optics is a much more developed technology area than quantum microwaves. The recent interest into quantum computers may change that. The invention of the Josephson parametric amplifier (JPA), generating quantum entangled microwave photons, seems today essential in the development of a quantum radar system based solely on microwave technology.

5.6.1 Josephson Parametric Amplifier (JPA)

A parametric amplifier is a device that will transfer energy from a pump-signal to an input signal so that the output signal is an amplified copy of the input signal. This is done by letting the pump-signal control a physical parameter of a non-linear component. In the early days of microwave electronics it was common to use e.g. a varactor diode, and control its capacitance by a ‘pump’ signal that would through a mixing process amplify an input signal [22].

The microwave component in this case is a Josephson junction, which is two metal plates, isolated from each other by a very thin layer of insulating material [23-25]. This allows for electrons on both sides of the insulating layer to interact. By applying a pump signal, see Figure 4a, at twice the operating frequency f_0, results in parametric amplification where a mixing signal at $(f_0 - f_{in})$ with the amplitude A, see Figure 4b, on the input signal port is gaining energy from the pump signal and is amplified by the signal gain G and reflected back out through the output port, see Figure 4c. Also, an idler signal at $(f_0 + f_{in})$ is created in the mixing process with an amplitude that is determined by the intermodulation gain M and the input signal amplitude. If the input signal is vacuum noise, this process is the same as the parametric down conversion [25, 26] in optics where a single pump photon is split into a signal and an idler photon.

A strong quantum correlation exists between the signal and idler, because they originate from the same pump photon, which will result in a squeezing of the conjugated I and Q signals. For this process to work it is necessary to cool the JPA to temperatures of mK. This temperature is also needed, so that the entanglement between the photons is not destroyed immediately by the thermal noise.

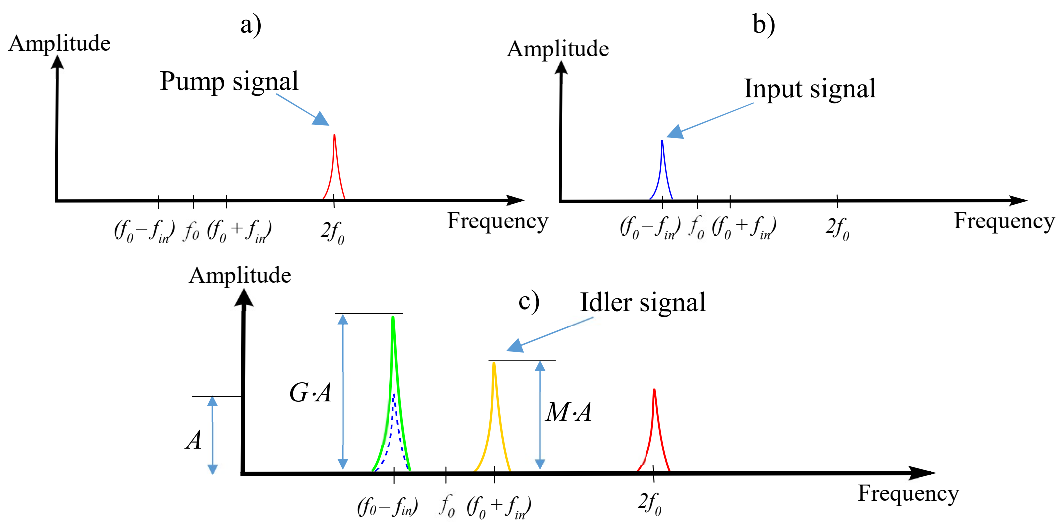

Figure 4. a) A pump signal is controlling the parameter of the JPA and is the source of energy supply of the system. b) An input signal is applied to the input port of the JPA non-linearity and is mixed with the pump signal. c) From this mixing process, two frequency components are created. At $(f_0 - f_{in})$ there is an amplified version of the input signal and at $(f_0 + f_{in})$ is created a mixing component amplified by the intermodulation between the input signal and the pump signal.

5.7 Quantum Illumination Radar in a Noisy Environment

In [21] it is discussed that the full system, including the environment, needs to be at cryogenic temperatures for a microwave system. However, the experimental results presented in chapter 6, seems to confirm that it is sufficient that the microwave-entangled state is generated at cryogenic temperatures. The thereafter-added noise deteriorate the quantum illumination radar, but there is still a resilience making the detection performance of a quantum illumination radar better than its classical counterparts [3, 6, 10].

Actually, Lloyd [1] points out that the advantage of a quantum illumination radar relative to its classical counterpart, is increased in a noise environment. Hence, if the environment (due to thermal noise) in the microwave domain is noisier than its optical counterpart, the advantage of a quantum radar relative to its classical counterpart may be larger than the advantage of a quantum lidar relative to its classical counterpart.

6 The First All-Microwave Experiments

In 2018 and 2019 a couple of articles are presented by Defence Research and Development Canada together with University of Waterloo [3, 7, 25, 27] and a multinational article by Institute of Science and Technology Austria, University of York, Massachusetts Institute of Technology, University of Camerino, INFN and CNR-INO [4]. The articles are interesting from an experimental point of a view, but also triggers a few theoretical issues.

First, they give the first experimental results from a quantum radar solely working in the microwave domain. A key component, is the Josephson Parametric Amplifier[6], used to produce quantum entangled photons, or actually multiphoton entangled pulses.

It should be pointed out that the experiments are in their infancy. The total distance from the transmitting antenna to the receiving antenna is in the order of a meter. The Canadian group does not even include a target, but transmits directly from the transmitting antenna to the receiving antenna, see figure 3 in [7].

However, they compare their results with a corresponding classical set-up not using entanglement and get substantial better results in the quantum entanglement case. Figure 10-13 in [7] shows measurement receiver operating characteristic (ROC) curves. The detection probability is higher in the quantum case. As a figure of merit they claim [7], "the quantum radar achieves the same performance as the classical radar while reducing the number of samples integrated (hence the integration time) by a factor of eight".

In section 4.1, and [1], it is pointed out that the signal and idler need to overlap in time and as we à priori do not know the distance to the target, we have to probe for many potential different distances, which is time consuming. In [3, 7, 25, 27] this is addressed in another way, which we now briefly retell.

Figure 5 shows a simplified block diagram of the quantum measurements in [7]. In the Josephson parametric amplifier (JPA), two mode squeezed[7] entangled signal and idler are generated. The JPA is cooled down to 7 mK, due to its superconductive parts and to make noise not an issue in the generation of entangled pairs. The signal and idler are generated at different discrete frequencies so they can be separated as indicated in Figure 5.

The signal and idler are amplified in steps. The purpose is to reach such high signal levels that the I- and Q-components of the signal and idler can be measured using standard classical measurement instruments. The amplification adds a lot of noise and the entanglement is lost, but a quantum enhancement in the form of a higher correlation between the signal and idler persist, not reachable in the classical case [7]. As we mentioned already in chapter 3, there is still ongoing work trying to understand this increased persisting correlation.

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[6] It is actually not used in the amplifying mode, and also the expression Josephson parametric converter (JPC) is used, but to our knowledge, it is basically the same component.

[7] Two-mode squeezing is described in section 2.5.

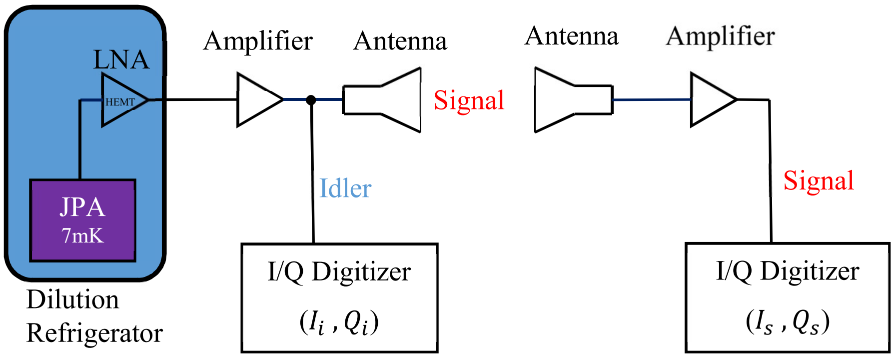

Figure 5: Block diagram of the quantum radar setup in [7]. The figure is a simplification of Figure 5 in [7].

In [7], they measure the I- and Q-components from the idler (I_i, Q_i), and equally for the signal (I_s, Q_s), as indicated in Figure 5. They calculate the correlation[8] between the idler and signal, and conclude that it is 2.5 times stronger compared to when they perform a similar experiment but without the idler and signal being generated in two-mode squeezed entanglement. The measurements are repeated up to 100 000 times, to be able to present the above-mentioned receiver operating characteristic (ROC) curves.

A point to notice, the signal and idler are measured separately in Figure 5. There is no need for overlap of signal and idler at the detector, and hence also no need for the above, and in section 4.1, and [1] mentioned, time consuming probing of different distances.

The question arises, is this quantum any longer? Two signals are measured; they can be convoluted to find maximum overlap, just as in classical signal processing. Quantum entanglement exist inside the refrigerator on the left side of Figure 5, but not outside.

In [28], Balaji answers the question by saying, they have performed measurements using quantum entanglement with better results than the corresponding solely classical case. Balaji does not claim to have built the optimal quantum sensor, but claims to have built an experimental prototype, and leaves the question of “how quantum” to the purist.

A deeper look into [3, 7, 25, 27] unmasks; separately, the signal and idler are thermal noise signals, and very hard, no to say impossible, to distinguish from another thermal noise source. It is logic that in [3, 7], the quantum (noise) radar has been compared to a classical noise radar. In [4] they claim, performing a comparison with the coherent state being a much stronger benchmark. Still, they claim an up to three times improved signal-to-noise ratio for the quantum illumination compared to the coherent state illumination.

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[8] For the explicit detector functions used to calculate the correlation, see [7] D. Luong, C. Chang, A. Vadiraj, A. Damini, C. Wilson, and B. Balaji, "Receiver Operating Characteristics for a Prototype Quantum Two-Mode Squeezing Radar," *arXiv preprint arXiv:1903.00101,* 28 Feb 2019 2019. [Online]. Available: https://arxiv.org/abs/1903.00101..

7 Microwave Quantum Radar Cross Section

According to several authors [8, 29-32], the quantum radar cross section (QRCS) area of a signal transmitted by a quantum radar will be perceived as a larger reflected signal than in the classical case. This effect is attributed to the quantum properties that are obtained when transmitting only a few photons at a time. A comparison of this effect, with respect to the classical RCS, will be analysed in this section.

7.1 Classical Radar Cross Section

The classical radar cross section (CRCS) area is a performance measure of how well the radar target is perceived by the radar. CRCS is defined as the projected cross section area in meter squared of a sphere that reflects the same amount of power as the radar target. This measure will then give a performance metric of how good or bad a specific radar is at detecting an object.

The CRCS depends on the geometry of the target and its capability to absorb electromagnetic energy. This means that the reflected power, and therefore the CRCS will vary greatly depending on the angle of incidence and the angle of reflection of the radar signal.

The CRCS of a radar target can therefore be calculated according to [8, 29, 33],

$$\sigma_C = \lim_{r\to\infty} 4\pi r^2 \left|\frac{\mathbf{E}_s}{\mathbf{E}_i}\right|^2 = \lim_{r\to\infty} 4\pi r^2 \left|\frac{\mathbf{H}_s}{\mathbf{H}_i}\right|^2 , \qquad (7)$$

where σ_C is the classical RCS measured in square meters, $\mathbf{E}_s$ and $\mathbf{H}_s$ are the scattered electric and magnetic fields, $\mathbf{E}_i$ and $\mathbf{H}_i$ are the incident electric and magnetic fields. The distance between the radar and the target is denoted by r. This definition of RCS is going to be important when the quantum radar cross section (QRCS) is defined.

The incident magnetic field will induce a surface current on the target, using the *physical optics approximation* it can be simplified accordingly,

$$\mathbf{J}_S \approx 2\hat{\mathbf{n}} \times \mathbf{H}_i , \qquad (8)$$

where $\hat{\boldsymbol{n}}$ is the normal vector to the surface of the target. This surface current will in turn generate a scattered *far-field approximation* [33],

$$\mathbf{E}_s = -j\frac{k\eta}{4\pi r} e^{-jkr} \iint_S \mathbf{J}_S(\mathbf{r}') e^{jk\mathbf{r}'\cdot\mathbf{r}} dS , \qquad (9)$$

where k is the wavenumber and η is the intrinsic impedance.

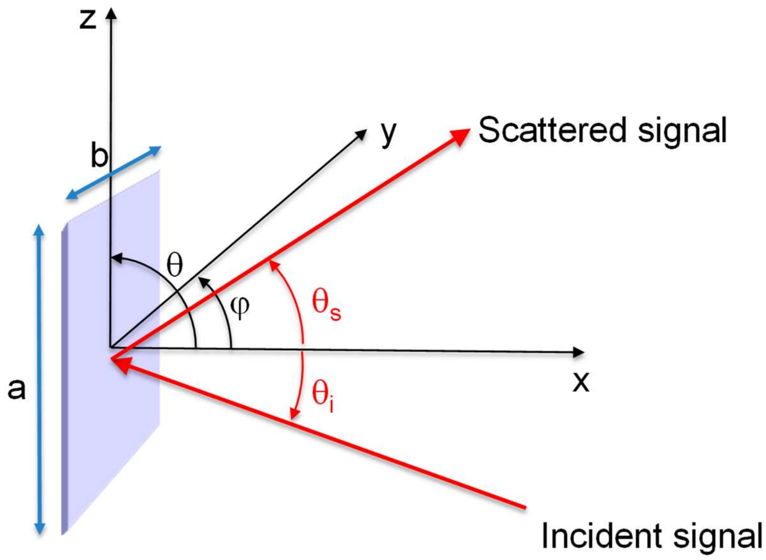

Figure 6: A flat metal plate (a x b) as a simulated radar target. In the monostatic case, a radar signal is transmitted in all angles sequentially and the return signal is measured. In the bistatic case, a signal is transmitted from fixed direction θ_i and the return signal is measured in all angles θ_s sequentially.

To get a basic comparison between the classical radar cross section (CRCS) and the, in section 7.2 defined, quantum radar cross section (QRCS), a uniform and isotropic flat plate is used as a target, see Figure 6.

By inserting the incident field and the geometry of the target (flat plate) into (7), an expression for bistatic CRCS σ_C , at the azimuth angle φ=0, can be formulated as [29, 32],

$$\sigma_C = \frac{4\pi A^2}{\lambda^2}\cos^2\left(\theta_s\right)\cdot \mathrm{sinc}^2\left(\frac{1}{2}ka\left(\sin\left(\theta_s\right)-\sin\left(\theta_i\right)\right)\right) , \tag{10}$$

where A is the area of the plate with *a* and *b* as its width and height, λ is the wavelength. From (10) it is obvious that the RCS has the form of a sinc-function weighted by a cosine-squared function. For the monostatic QRCS the scatter angle is set to $\theta_s = \pi - \theta_i$,

$$\sigma_C = \frac{4\pi A_\perp^2}{\lambda^2}\cos^2\left(\theta_s\right)\cdot \mathrm{sinc}^2\left(ka\sin\left(\theta_s\right)\right) . \tag{11}$$

7.2 Quantum Radar Cross Section

To understand how the quantum radar cross section (QRCS) works, it is necessary to first have some understanding of the photon, so first we need a definition of a photon. Because of the wave - particle duality, it is impossible to determine a probability function for the position of the photon. Only at the moment of detection we can say with some certainty were the photon was and this detection (measurement) of the photon will annihilate it. So a wave function can be defined as going from one photon, γ = 1, to no photon at the moment of detection, according to,

$$\psi(\mathbf{r},t) = \langle 0 | \hat{\mathbf{E}}^{(+)}(\mathbf{r},t) | \gamma \rangle \ , \tag{12}$$

where $\hat{\mathbf{E}}^{(+)}$ is the part of the quantum electric field operator contributing to the annihilation of a photon. This means that before measuring the photon, it is assumed to be everywhere with a probability depending on antenna pattern, attenuation, scattering, diffraction and other radar channel impairment (classical and quantum mechanical).

7.2.1 Specular reflection

In this investigation, it is assumed that the interaction between the incident photon and the atom in the target is energy conserving, which means that the target geometry is assumed to consist of a perfect mirroring material having no loss. By using the *rotating wave approximation* [8, 29], the Hamiltonian for the photon-atom interaction can be written as,

$$\hat{H} = \sum_{\mathbf{k}} \hbar\omega_{\mathbf{k}} \hat{a}_{\mathbf{k}}^{\dagger} \hat{a}_{\mathbf{k}} + \frac{1}{2}\hbar\omega_{\mathbf{k}}\hat{\sigma}_z + \hbar\sum_{\mathbf{k}} g_{\mathbf{k}} \left(\hat{a}_{\mathbf{k}} \hat{\sigma}_+ e^{-i\omega_k t + i\mathbf{k}\cdot\mathbf{r}} + \hat{a}_{\mathbf{k}}^{\dagger} \hat{\sigma}_- e^{i\omega_k t + i\mathbf{k}\cdot\mathbf{r}} \right) \ , \tag{13}$$

where the first summation on the right side is the photon state for mode k and the middle term on the right side is the state of the atom $\hat{\sigma}_z$. The third term describes the interaction between the photon and the atom where $\hat{\sigma}_+$ represents the atom going from a lower state to a higher and $\hat{\sigma}_-$ represents the atom going from a higher state to a lower. The dipole moment of the atom is denoted by $g_{\mathbf{k}}$. In this photon-atom interaction there is no measurement of the photon, so it will retain its quantum state, including the entanglement [29].

Since every atom in the target is impinged by the incident photon, with some probability, they will also retransmit the energy of that photon. This will give a classical superposition of all the photon probability functions from every atom in the target [8, 29, 30]. This superposition of probability waves can be expressed as,

$$\sigma_Q = 4\pi A_\perp(\varphi,\theta) \frac{\left| \sum_{n=1}^{N} e^{j(\mathbf{k}_i - \mathbf{k}_s)\cdot\mathbf{x}_n} \right|^2}{\int_0^{2\pi}\int_0^{\pi/2} \left| \sum_{n=1}^{N} e^{j(\mathbf{k}_i - \mathbf{k}_s)\cdot\mathbf{x}_n} \right|^2 \sin(\theta_s)\, d\theta_s d\varphi_s} \ , \tag{14}$$

where $A_\perp$ is the projected area towards the radar receiver and N is the number of atoms in the target surface placed at coordinates $\mathbf{x}_n$. This will result in a bistatic QRCS expression for the flat plate in Figure 6, at the azimuth angle φ=0,

$$\sigma_Q = \frac{4\pi A_\perp^2}{\lambda^2} \left|\cos(\theta_s)\right| \cdot \text{sinc}^2\left(\frac{1}{2} ka\left(\sin(\theta_s) - \sin(\theta_i)\right)\right) , \tag{15}$$

where $A_\perp$ is the projected area of the plate with *a* and *b* as its width and height. From (15) it is clear that the RCS has the form of a sinc-function weighted by an absolute-cosine function. For the monostatic QRCS the scatter angle is set to $\theta_s = \pi - \theta_i$,

$$\sigma_Q = \frac{4\pi A_\perp^2}{\lambda^2} \left|\cos(\theta_s)\right| \cdot \text{sinc}^2\left(ka \sin(\theta_s)\right) . \tag{16}$$

By comparing (11) and (16), a difference is noticed, the cosine-squared against the absolute cosine. This difference is shown with the simulation in Figure 7. It can be observed that the QRCS has approximately 10 dB stronger reflected sidelobes, furthest from the mainlobe, than in the classical CRCS.

Figure 7 also shows the bistatic RCS for the same target and frequency as in the monostatic case. The right figure in Figure 7 suggests the difference in the outermost side lobes being as high for the bistatic case, approximately 10 dB. Both these comparisons would suggest that the quantum RCS is much larger than the classical RCS when the targets projected area towards the receiver is small. When the projected area towards the receiver is large, both methods give the same result, as the broadside of the target shows in the main lobe.

The reason for this difference is that the classical RCS is formed by currents on the surface of the target, while the quantum RCS is formed by superpositioning the probability waves of all the atoms on the surface of the target.

In the left figure of Figure 8, it is obvious that a bistatic quantum RCS give a considerably stronger radar return than a monostatic classical RCS, even at a small difference between incident and scatter angles. In the opposite case, shown in the right figure of Figure 8, it can be seen that a bistatic classical RCS give a stronger radar return than a monostatic quantum RCS except in the furthermost sidelobes.

7.2.2 Reflection of entangled photons

According to [29] the entanglement of the photon is retained from the reflection of the target because no measurement of the photon is involved in the reflective process. This means that every atom in the target surface will interact with the photon with a certain probability, whether it is entangled or not. Hence, this is a quantum phenomenon, decoupled from entanglement, which can be used for quantum radar technology.

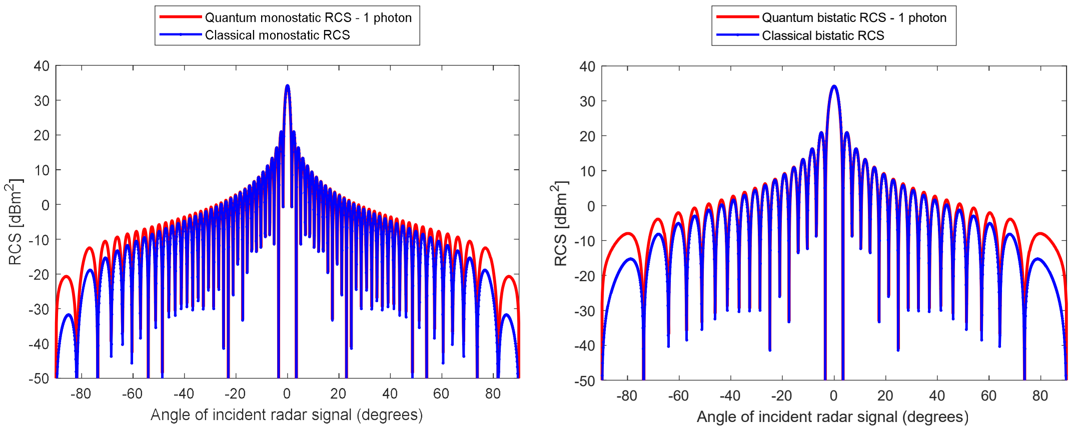

Figure 7: A simulated comparison of a monostatic RCS measurement (left figure) using a 1 m^2 flat quadratic metal plate irradiated with a 5 GHz plane wave for the classical case, and a single 5 GHz photon in the quantum case. A simulated comparison of a bistatic RCS measurement (right figure) using a 1 m^2 flat quadratic metal plate irradiated with a 5 GHz plane wave for the classical case, and a single 5 GHz photon in the quantum case.

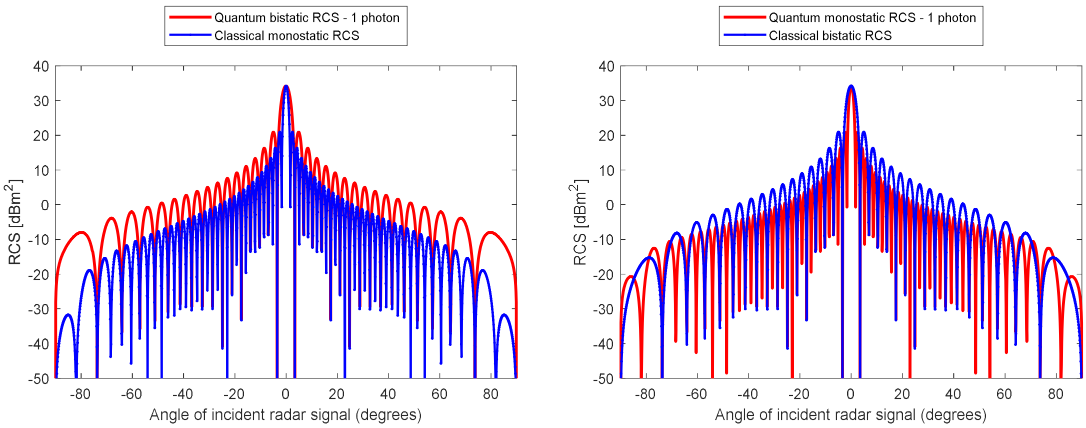

Figure 8: A simulated comparison of a bistatic quantum RCS measurement and a monostatic classical RCS measurement (left figure) using a 1 m^2 flat quadratic metal plate irradiated with a 5 GHz plane wave for the classical case, and a single 5 GHz photon in the quantum case. The opposite case where a simulated comparison of a monostatic quantum RCS measurement and a bistatic classical RCS measurement (right figure).

8 Possibility of Countermeasures against a Quantum Radar

To counteract a traditional radar an *electronic countermeasure* (ECM) signal is transmitted towards the radar receiver, either to create false targets or to hide the true target. To achieve this, the ECM use three basic jamming modes [34]:

- *Repeater*; receive the radar signal, modulate it and retransmit the modified signal.
- *Transponder*; create a replica of the radar signal, modulate it and retransmit the modified signal at peak power.
- *Noise*; transmitting a noise signal to cover the true target.

In all the jamming modes, it is not necessary to know the design of the radar signal. This jamming could be done blindly, but without any information about the radar, it would be an almost impossible task. Therefore, to efficiently jam a radar, it is beneficial to have information from *electronic support measures*/*electronic intelligence* ESM/ELINT.

If the quantum radar signal consists of squeezed vacuum photons, it would be impossible to detect the radar signal with a traditional ESM/ELINT-system, since the quantum radar transmits only a very small number of photons which would be an extremely low powered noise signal that will be exactly the same as thermal noise and would have 0 dB in photonenergy-to-noisedensity ratio (E_{ph} /N_0) per photon. This means that for someone who is listening it would be impossible to separate the radar photons from ordinary noise photons. The radar on the other hand has the half of the photon-pairs that is entangled with the photons that were transmitted. This will give the radar a signal processing gain from the inherent correlation between the entangled photon-pairs. If the entanglement is created through a parametric down-conversion, the amount of correlation depends on the achieved squeezing factor, which will then increase the signal processing gain. This make the quantum radar the ultimate *low probability of intercept* (LPI) radar with respect to the probability of intercept (POI), which will be zero when using traditional ESM/ELINT-receivers.

For jamming a quantum radar, it would be necessary to have a *jam-to-signal ratio* (JSR) of more than the squeezing factor of the entangled signals. If we had a perfect entanglement between the transmitted and the stored photons, i.e. an infinitely high squeezing factor, it would be impossible to jam the quantum radar. That, since it would have infinite correlation with the stored photons, but this is not realistic scenario that means that it is in fact possible to jam a quantum radar. To jam a quantum radar you will have to know which frequency it is transmitting on and the direction it is transmitting from, then the jamming signal would have to have a JSR larger than the squeezing factor to be successful.

So jamming of a quantum radar is possible, but it is going to be difficult since there is no way of determining the transmitted frequency or even know if the radar is active or not. By keeping updated about the research on parametric downconverters and quantum radar it might be possible to guess what signal processing gain that can be achieved and thereby what JSR is needed.

9 Discussion & Conclusion

Quantum radar is a new subject, for the radar community as well as the quantum physics community. Despite its infancy, a few experiments have been performed in the all-optical domain and recently even in the all-microwave domain. They are simplified laboratory experiments, but they show proof of principles.

Authors advocate that with same effort put into quantum radar research and engineering, as into many other quantum technologies, we would see substantial results, potentially even working quantum radar systems.

A quantum radar has the possibility of being more robust than other quantum technologies like quantum computing, quantum communication and quantum sensing. The quantum technologies of today are largely based on quantum entanglement. Quantum entanglement is often a fragile property, easily destroyed by attenuation and noise.

However, the quantum illumination protocol, being proposed for the quantum radar, seems to have its supremacy, relative to classical counterparts, in a noisy environment. A rethink is here necessary, as quantum technologies are generally seen as being vulnerable. That is not necessary the case for a quantum radar based on quantum illumination.

A quantum radar where the quantum properties are no longer there, might still work as a radar, in contrast to e.g. quantum communication where the actual purpose of it is no longer fulfilled once the quantum properties are lost.

As of today, a quantum radar supremacy is not in generating strong signals, but its ability to recognize a reflected signal at weak signal to noise ratios. One implication thereof is the quantum radar being a candidate for a low-probability-of-intercept (LPI) radar.

There is also a quantum effect on the radar cross section area suggesting a target might be more visible using a quantum radar than a classical radar. This effect is most visible when very few photons are transmitted simultaneously, and would make it more difficult to hide the target using stealth technology. Noticeably, this effect does not depend on the presence of entanglement.

To counteract a quantum radar seems to be very hard, due to a very low transmitted power from the radar. This would make it impossible to detect using traditional methods for finding radar signals. Jamming the radar signal is still possible if the jamming power is high enough. This is similar to jamming a traditional LPI radar were it is necessary to jam with more power than the signal processing gain of the radar to be successful.

A short reflection on the international interest of quantum radar, implementations and publications so far. During the first decade of quantum illumination, only a few experiments have been published and only a couple of them have shown with clarity that their system is better than the optimal classical illumination. It is surprising that not more experiment has been published especially in the optical regime where many of the necessary components have exist for many years, e.g. single-photon detectors and sources of entangled photons.

We suspect that there are efforts in this area that never reach the scientific community. For example China claims already having a quantum radar [35]. Although most scientists doubt these claims [36], articles in magazines and on the web show that there are activities that never reach the scientific journals, both in China and the western world. It seems like some research in the area has already become secret. Remarkably few traces of quantum radar activities can be found in Russian sources.

We assess it as possible to see a creation of a quantum radar. The physical and technological barriers do not seem to be invincible, and we cannot completely exclude, a quantum radar already been created.

The success in the creation of a quantum radar depends on the ability of bringing together knowledge from different communities like radar, microwaves, optics, and quantum physics.

Experience tell us that scientific and engineering work manage what first seemed to be impossible. The robustness of quantum illumination may make it also a candidate for quantum communication [11].

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