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COMPARISON OF 'QUANTUM RADAR' AND NOISE RADAR CONCEPTS

K.A. LUKIN

Preliminary results of the comparative analysis of quantum radar (QR) based upon quantum entanglement phenomenon and noise radar (NR) based upon classical coherence and correlation processing of random signals are presented in the paper. It has been shown that the basic idea of entangled multi-photon QR for simultaneous implementing of high penetrating ability of the entangled photons and high spatial resolution performance does not work because of decay of the entangled state of the transmitted photons. QR operation abilities are described in terms of classical physics. In addition, a two-photon QR has been modelled by means of classically phase locked two-frequency signals (regular and chaotic). A fourth type QR has been suggested.

Keyword: quantum radar, photon, noise radar, phase synchronization, coherent signal.

INTRODUCTION

Recently idea of 'Quantum Radar' (QR) has been suggested [1], which drawn a significant attention of radar engineers. Exploiting of unique properties of the entangled states of multi-photon (or multi-frequency) electromagnetic field is the basic idea of QR. There is a big hope that these properties will enable to go beyond diffraction limit in range and angular resolutions when using multi-particle radar signals [1]. Another possible schemes for QR design consist in application of a two-particle state of radar signal, and using one of them as a sounding signal, while the second one as the reference. Information on a target is to be extracted via cross-correlation between the received signal and the reference. In this case, there is one more source of target information may be used, namely: entanglement of photons in polarization states, which give a method to make conclusion on a target via detection of photon polarization changes in the reference channel due to polarization changes in the sounding signal.

The second scheme of QR is formally similar to the scheme of Noise Radar (NR) [2 – 5] where stationary wideband random signal is used as the sounding one while its copy serves as the reference signal to estimate their cross-correlation aiming extraction of the information on the range and velocity of the target.

In the paper, a brief review of published papers/patents on quantum radar and quantum imaging will be given in comparison with published papers on Noise Radar. Common and distinguishing features of these radars are briefly discussed. In addition, a method for preparation of sounding signal which may be described as entangled photons using classical notion of signals phase locking. A possibility of application of radar signals with correlations between different spectral components (signal entanglement) is considered in comparison with conventional Noise Radar scheme. A new type of QR has been suggested applicable for detection of non-stationary fluctuating/oscillating (tangage, roll, pitch, etc.) targets.

1. 'QUANTUM RADAR'

First we give below the accepted to the date description of the suggested QR concept and some related definitions. QR is a theoretical remote-sensing method based on quantum entanglement. In theory, entangled photons could be used to reveal details of objects they have never interacted with. If one particle bumped into an aircraft its twin would react in the same way, even if it never left the laboratory. Work out a way to read that behavior, and an image could be built up, even with 'no information being directly transmitted from the target' [6 – 8].

From QR block diagram [1] it may be seen that authors suggested to launch one of the entangled photons towards a target, while another one (the idle) to use for detection of a target via estimate of cross-correlation between reflected signals with the idle one. According to [1] QR intends to create a radar system which provides a better resolution and higher detail than classical radar can provide. The technology is hoped to work by using photon entanglement to allow several entangled photons to function as if a shorter wavelength was used to allow detection of small details while having an overall longer group wavelength that allows long distance transmission. The authors claimed that current radar systems become less useful as range increases, because the frequencies needed to transmit over long distances are less sensitive. According to the patent [1] this problem can be removed by entangling light at different frequencies and then sending them out together as a bundle. It says: "Entangled radar waves can combine one or more particles with a relatively high frequency for resolution, with one or more particles at a lower frequency for more effective propagation." In this way radar beam could then "propagate through different types of mediums and resolve different types of target".

However, this statement has week points. For instance, entangled state of QR signals will completely decay when QR probing signal bumps a wall and a short wavelength photon will NOT be able to penetrate through the wall and, hence, will not be able to reach a target behind the wall. In addition, there are many other factors that may destroy the entangled state of the 'radar photons'. That is why a new concept of quantum illumination has been suggested [9] to enable usage of a decoherent entangled signals enhancing detection capability compared to non-entangled radar signals [9 – 11].

Later on a theory of Quantum Radar has been elaborated in the book [12], where all the radar related issues have been considered from the view-point of Quantum Physics, namely: QR standoff sensors, target radar cross-section for QR, QR jamming, Interferometric QR, etc. In particular, three different types of future QR have been considered in [12]: 1) QR based upon Entangled Photons generating, radiation and processing; 2) Single photon QR that exploits possible advantages of Quantum scattering of a separated photons by a target; 3) QR which transmits a signal formed by coherent photons (actually classical fields) and received with the help of QM detector. In addition, the entangled photons have been used to perform so called ghost imaging [6 – 8], where authors think that they are able to generate image of an object without scanning, but just illuminating it and detecting scattered signal as a bucket [7]. However, they perform scanning over CCD matrix in idle channel of the imager with further estimation of cross-correlation of the detected both bucket and the idle signals for every CCD matrix pixel. In other words, in these experiments the algorithms for the detected signals processing are the same as in case of Synthetic Aperture Radar (SAR) imaging, and, in particular, in case of coherent imaging with the Ground based Noise Waveform SAR [5].

In the next section we briefly describe NR concept and Noise SAR imaging technique and make their comparisons with QR and ghost imaging, respectively, where entanglement photons are in use.

2. NOISE RADAR

Noise Radar is a radar that uses the classical noise/random/chaotic continuous or pulsed waveform as a radar signal and *coherent* reception of radar returns via estimation of cross-correlation $R(\tau)$ between the reference signal (properly delayed copy $u(t-\tau)$ of the transmitted random signal) with the radar return $v(t)$ [2 – 5]

$$R(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} v(t)\, u(t-\tau)\, dt \qquad (1)$$

In this way, Noise Radar uses the illumination of a target by random signal and coherent detection (both amplitude and phase) of the scattered wave. Noise waveform with a variable power spectrum width enables controlling the radar range resolution, since it is defined by the signal power spectrum bandwidth B, as follows: $\Delta r = c/2B$, where c is the velocity of light.

Usage of random waveform gives such benefits as absence of range ambiguity and improving immunity against external electromagnetic interferences and jamming [2 – 5]. The latter property is common for any coherent radar, but noise radar has a unique anti-jamming property: robustness with respect to coherent single frequency interference.

Usually, radar returns and reference signals are down converted to intermediate frequency band and digitized with a fast ADC having two channels with 1-1.5 GHz instant pass-band width and 1-3 GS/s sampling rate with 8–12 bit depth resolution. The sampled radar returns and reference signals are processed in a PC using standard algorithms for their cross-correlation (1) estimation. Nowadays FPGA based signal processing is also in wide use [13]. Applying maximum likely-hood method we may estimate the target range, while estimation of the Doppler frequency in the cross-correlation function gives us information on a target velocity. In this way, we may see a similarity between NR and QR concepts: in the latter case a comparison of the reflected signal and the idle (or reference) signal is also required if one has to retrieve the information on the target, as it is described in more detail in [1, 7 – 8]. Similar comparison with so called ancilla state is to be done in case of quantum illumination technique [9 – 11].

For microwave imaging of an object, one should implement motion of a noise radar antenna in cross-range plain and apply a standard 2D SAR imaging technique via range and azimuth compressions to the radar returns and construct image of a distributed object [13 – 14]. As it may be seen in [13 – 14] the procedure of taking images with ground based noise waveform SAR is very similar to that suggested in the ghost imaging concept based upon entangled photon concept. In addition, 3D tomographic imaging may be implemented via range compression and 2D aperture synthesis via MIMO operational mode for each range bin [14].

The related measurements were carried out inside a laboratory room with concrete walls, ceiling and floor. A polyethylene sphere covered with aluminum foil was placed in the middle of the room and was used as the standard target. Inside the room there were several desks and laboratory tables with electronic devices and equipment on their tops, PCs, metal chairs and multiple metal objects. Similar experiments have been done for outdoor scenario. In the Noise waveform SAR the random/noise sounding signal was transmitted towards the scene, while its copy was stored in the onboard memory and used as a reference (ancella state) for retrieving information on the range, intensity and phase of every pixel, in the way similar to that in which is similar to QR and Quantum Illumination operational mode. We may conclude that operational Noise Radar technique provides similar benefits as the thought QR and Quantum Illumination ones.

3 Classical modelling of 'quantum radar' signals

In quantum optics, entangled photons are normally generated via *spontaneous* parametric down conversion, provided proper equalizing the phases of the generated photons propagating through two different channels in the optical nonlinear crystal. Spontaneous radiation of an atom means radiation induced by *quantum fluctuations of vacuum* [15] which provides phase locking of the down converted photons of different frequencies, which are called as entangled photons.

In classical physics we may simulate quantum entanglement with the help of generating of two (or more) signals having the same or different frequencies, provided their phase locking, i.e. preserving their mutual phase shift (in other words, position along the time axes). Generally, entangled signals may have frequencies with either (1) resonant ratio: $N\omega_1 = M\omega_2$ or (2) non-resonant, or ergodic, ratio: $N\omega_1 \neq M\omega_2$, where N and M are integer numbers. Some results of computer simulation of the correlation reception of entangled signals $S_1 = \sin(\omega_1 t + \sigma_1\psi_1)$ and $S_2 = \sin(\omega_2 t + \sigma_2\psi_2)$ with different rates σ_1 and σ_2 of their de-phasing (decoherence) for the case of M=6 and N=7 are presented in Fig.1-4.

However, instead of validation or disproval of the QR concept via computer simulation, we suggest and briefly describe another application of the entangled photons (or their classical analogue) in radar, which may be considered as a Fourth type of QR. We suggest to apply entangled photons as an entire radar signal for sounding of a nonstationary target making an oscillatory motion with the frequency close to the difference frequency of the entangled photons frequencies.

Fig.1 through Fig.4 show entangled signals and their performance for two different cases: (1) perfectly phase locked signals and (2) signals with rather strong dephasing. We have estimated and showed in Fig.1 and Fig.3 the following performance of the signals

$$S_1 + S_2; \quad (S_1 + S_2)^2 \ and \quad S_1 \bullet S_2$$

Their autocorrelation and cross-correlations estimated with the help of Eq.(1) are shown in Fig. 2 and Fig. 4.

In spite of significant dephasing (entanglement destroying) of two entangled signals, one may observe residual autocorrelations for a single frequency signal $R_{S_1S_1}(\tau)$ and that for entangled signals $R_{S_1+S_2}(\tau)$, while it is not the case for their cross-correlation $R_{S_1S_2}(\tau)$. The latter means, in particular, that there is no chance to extract information on a target when trying to exploit entanglement phenomenon in QR in case of strong decoherence of the entangled signals. At the same time, the target's information may be retrieved when using entangled waves after their summation, which corresponds to the case of quantum illumination [9 – 11]. This is the main difference from the consideration of entangled photons applications in [1], [6 – 7].

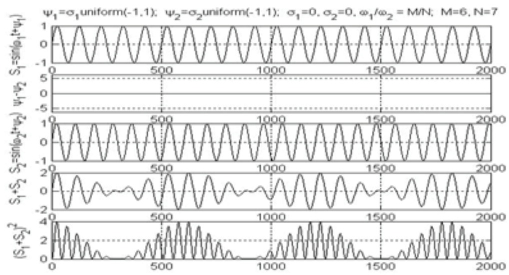

Fig. 1. Two signals and their "entangled' composition

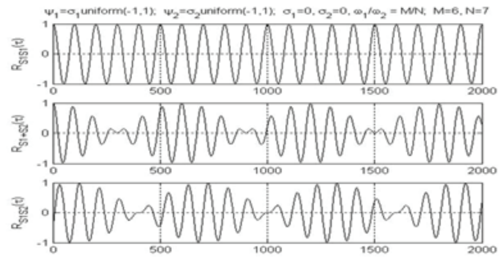

Fig. 2. Autocorrelation (top) and cross-correlation (bottom) of two signals along with autocorrelation of the 'entangled' waves (middle)

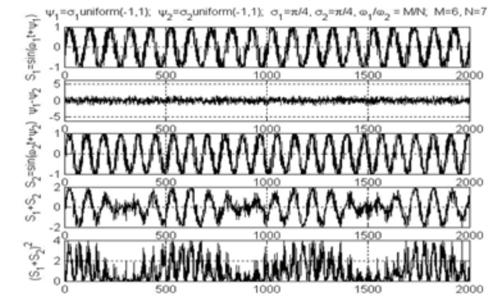

Fig. 3. Two waves, mutual randomized phases and their 'entangled' compositions in case of strong dephasing (decoherence)

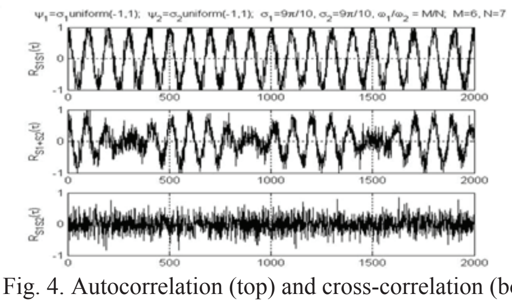

Fig. 4. Autocorrelation (top) and cross-correlation (bottom) of the entangled signals along with autocorrelation of the 'entangled' signals (middle) in case of strong dephasing

Thus, we may assume that idea of entangled photon in radar might be used in different way, namely as composition of two (or more) different photons with locked phases, which compose a nonstationary waveform with mutually phase locked spectral components. Such a waveform may provide a possibility to get more information on the illuminated target, which might be additionally studied. In particular, we may expect kind of resonant reflection in case of difference frequencies period is close to characteristic time of target oscillatory motion, such as aircraft and ship pitching and other motions.

The waveforms of that type may be generated either Quantum mechanically, via entanglement, or classically, via phase locking (synchronizing) of classical waves. In this way, we have suggested "Quantum Radar" of fourth type.

CONCLUSIONS

Noise Radar was a "crystal dream" of radar engineers during several decades. Nowadays it works. Today Quantum Radar looks nonrealistic for the claimed long range applications, but it could be a promising approach in extremely near field applications. At the same time, since entanglement of two (or more) photons may be considered as a phase locked waves the same functions of Quantum Radar may be implemented with the help of classically synchronized (phase locked) signals of different frequencies. In this case a fourth type of QR may be introduced which exploits nonstationary nature of the entangled signals and may provide efficient detection of oscillating targets and in nonlinear radar implementations.

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Представлены предварительные результаты сравнительного анализа квантового радара (КР), основанного на явлении квантовой запутанности и шумового радара (ШР), использующего классическую когерентность и корреляционную обработку случайных сигналов. Показано, что основная идея КР, использующая запутанные многофотонные состояния для одновременной реализации высокой проникающей способности запутанных фотонов и высокого пространственного разрешения не работает из-за распада запутанного состояния передаваемых фотонов под действием окружающей среды. Показана возможность описания КР в терминах классической физики. Кроме того, проведено моделирование двухфотонного КР с помощью методов классически фазовой синхронизации двух сигналов (регулярных или хаотичных) и предложен КР четвертого типа.

Ключевые слова: квантовый радар, фотон, шумовой радар, фазовая синхронизация, когерентный сигнал.

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Наведено попередні результати порівняльного аналізу квантового радара (КР), заснованого на явищі квантової заплутаності і шумового радара (ШР), що використовує класичну когерентність і кореляційну обробку випадкових сигналів. Показано, що основна ідея КР, яка використовує заплутані багатофотонні стани для одночасної реалізації високої проникаючої здатності заплутаних фотонів і високого просторового розділу, що не працює, через розпад заплутаного стану переданих фотонів під дією навколишнього середовища. Показана можливість опису КР у термінах класичної фізики. Крім того, проведено моделювання двохфотонного КР за допомогою методів класичної фазової синхронізації двох сигналів (регулярних або хаотичних) і запропоновано КР четвертого типу.

Ключові слова: квантовий радар, фотон, шумовий радар, фазова синхронізація, когерентний сигнал.

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