Rydberg RF Sensors for Spaceborne Radar Applications (RydRa 50WM2349)

James P. Shaffer, and Piotr Kozakowski

Abstract—**This report presents an overview of the results from the Rydra (50WM2349) study, prepared in support of the study's closeout. The primary objective of this study was to explore the feasibility of replacing conventional technology, currently utilized in space-borne radar systems, with quantum technology, specifically Rydberg atom-based sensors. The study was conducted in collaboration between Airbus Defence and Space GmbH, Quantum Valley Ideas Laboratories (QVIL), and the DLR**

Index Terms— **Quantum technology Rydberg sensor**

I. INTRODUCTION

In Rydra (50WM2349) study the capabilities of the quantum technology were assessed from the point of view of feasibility of replacing the conventional technology, as used in in the current space-borne radar systems, by Rydberg atom-based sensors acting as radio frequency (RF) electromagnetic signal receivers/sensors.

Rydberg atom-based receivers utilise the quantum states and energy levels of excited Rydberg atoms to sense electromagnetic signals. The study was prompted by the distinct properties of the Rydberg atoms. In particular, in alkali atoms such as caesium, light can optically excite the outer electrons into a Rydberg state that is sensitive to the external electromagnetic field. In the vapour cell filled with caesium atoms quantum interference between laser fields resonant with the atomic transitions produce an optical transmission in otherwise absorbing medium. This is known as the electro-magnetically induced transparency (EIT). The presence of an electromagnetic field alters the resonant state of the atoms and disrupts the medium’s transparency (Autler-Townes splitting). This effect is proportional to the electromagnetic field intensity. This property makes the vapour cell filled with caesium atoms a highly sensitive electromagnetic field sensor and could potentially outperform conventional receivers/sensors in terms of the detectability of the electromagnetic signals in a presence of noise. Consequently, the Rydberg atom-based receivers may offer an attractive alternative to conventional receivers utilised in the space-borne systems, in particular the systems processing signals of opportunity

II. STUDY STRUCTURE AND EXECUTION

The Rydberg study was carried out in cooperation between Airbus Defence and Space, Quantum Valley Ideas Laboratories (QVIL) and DLR Institut für Quantentechnologien with the main technical contributor being Quantum Valley Ideas Laboratories.

The study was divided into several components addressing different aspects of the research objectives. These included, among others, initial feasibility assessment, initial performance analysis, trade-off analysis, high level instrument architecture and initial space readiness analysis.

The objective of the initial feasibility assessment was to assess the capabilities of the Rydberg atom-based sensors to sense the radio frequency (RF) electromagnetic signals and in particular linear frequency modulated pulse waveforms reflected from targets. The primary focus of this assessment was to understand: achievable operational bandwidth of the Rydberg atom-based sensors, RF signal amplitude detection sensitivity, RF signal phase detection capabilities and ability of polarisation discrimination

The intention behind initial performance analysis was to assess the achievable performance of the Rydberg sensors based on

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the prior knowledge and initial experimental results carried out by Quantum Valley Ideas Laboratories. The work focused on several performance parameters such as a maximum operational bandwidth, sensitivity of the signal amplitude detection in a presence of noise, accuracy of the phase detection, and the achievable level of the cross-polarisation isolation.

The trade-off analysis. was centred around the trade-offs between Rydberg atom-based RF sensors and conventional antenna-based radar receivers with particular focus on limitations of the quantum technology and possible improvements, to surpass the performance of the receivers implemented in the current space-borne systems

In the high level instrument architecture phase of research, the objective was to propose a high-level concept of the Rydberg atom-base RF receiver architecture based on the initial performance requirements analysis and trade-offs evaluation carried out in the first phase of the research.

The objective of space readiness analysis task was to initially identify the space-ready components required to realize a spaceborne Rydberg atom-based sensor prototype, their availability and development status.

These multiple phases of research were spread over a period of 14 months accompanied by periodic progress reviews and interim reporting. All planned components of the research were successfully completed and are summarised in this report.

III. Prior Research And Theoretical Underpinnings

Rydberg atoms form a basis for several quantum technologies due to their uniformity, stability, and unique properties as described extensively in [1]. While Rydberg sensors were predominantly studied for sensing the amplitude of continuous wave RF signal, dynamic temporal response could occur at sub-microsecond time [4,5] rendering Rydberg sensors suitable for detecting pulse modulated signals [5–9]. Furthermore, it was previously shown [3,10,11] that Rydberg sensors could detect phase and discriminate polarisation of the RF signals.

The Rydra study built upon prior research work conducted by Quantum Valley Ideas Laboratories, the results of which were published in [2]. In [2], the atomic response to pulse-modulated RF signals was studied to demonstrate capabilities of Rydberg sensors to sense individual RF pulses, and to evaluate limitations related to signal-to-noise ratio and timing accuracy. The Rydra study advanced previous work by exploring the technology's capability to detect linear frequency modulated pulse waveforms with parameters typical for the space borne radar systems and to outline a high-level concept of the Rydberg atom-based RF receiver architecture based on the initial performance and trade-offs analyses.

The study was designed as an exploratory study aimed at gaining understanding of the various aspects of the technology, and in particular, to explore feasibility of the Rydberg atom-based receivers to replace the conventional space-borne radar sub-systems. It should be stressed that the primary objective was to enhance understanding of the technology, identify existing research gaps, and examine the interplay between quantum and conventional technologies, thereby ensuring that that the future studies are grounded in robust evidence and clear understanding of the technology and its benefits.

IV. Prior Research And Theoretical Underpinnings

A. Introduction

Rydberg atom-based sensors can be viewed as a novel approach to measure RF electromagnetic fields and a potential alternative to conventional methods of RF field sensing. Rydberg atom-based sensors offer several advantages over more traditional methods of RF field detection and measurements, namely, the Rydberg atom-based sensors are entirely dielectric, and hence nearly transparent to the target RF filed. They can be manufactured in almost any shape and/or size. The unique property of the Rydberg atom-based sensors, namely self-calibration i.e., ability to measure the value of the absolute electric field intensity, presents an advantage over conventional radar receive subsystems, which usually require same form of calibration.

The Rydberg-atom based sensors are photonic devices that are read out optically, hence they are more immune to electromagnetic interference. They can operate in very wide frequency range and provide a response directly in base-band (optical read-out) without a need for down-conversion

Rydberg states are highly excited states of atoms, characterised by the large principal quantum number. In gas-phase atomic medium, such as a vapour cell filled with Cecum atoms, for instance, light can optically excite the outer electrons into a Rydberg state, which increases atoms sensitivity to the external RF field. In other words, because Rydberg electrons are relatively weakly bounded to the nuclei compared to a valance states they have stronger response to the RF field.

In the Rydberg vapour cell, quantum interference creates optical transmission in otherwise an absorbing cell - this is called electromagnetically induced transparency (EIT). In the presence of the RF field/signal the EIT window splits (Autler-Townes splitting) and this splitting is proportional to Rabi frequency and, hence, to the amplitude of the RF field. The sensitivity of the Rydberg sensors is relatively large due to the large transition dipole moments. There are, however, several limiting factors affecting the sensitivity of the Rydberg sensors. In principle the sensitivity of the sensors is limited by the atomic shot noise, however, more often the sensitivity is limited by the probe laser shot noise.

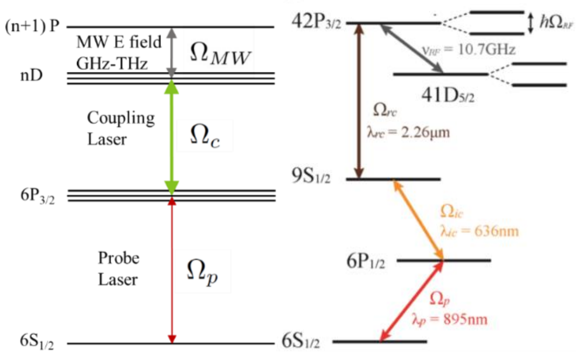

Fig. 1 Two-photon approach to Rydberg atom-based sensing for Cs atoms (left figure) and three-photon approach to Rydberg atom-based sensing for Cs atoms. The wavelengths of the lasers are shown in the figure (right figure)

In relation to the sensitivity, it is worth noting that there are two different preparation and read-out schemes, which can be considered, and which have an impact on a sensitivity, namely, a two-photon approach and a three-photon approach. Figure 1 (left) shows the scheme which was used, in the Study, for the first Rydberg atom-based sensor experiment. The method requires two lasers, namely, a probe laser and a coupling laser. The advantage of the method is that it only requires two lasers, but suffers from residual Doppler shifts of the atoms. The residual Doppler shift broadens the spectral line of the probe laser transmission (broadening the EIT window), reducing sensitivity and the ability to detect phase effects. Figure 1 (right) shows a second scheme that QVIL introduced, where three lasers are used in a configuration where Doppler shifts almost completely cancel out. The method in Figure. 2 can increase the sensitivity by around an order of magnitude as well as increase sensitivity to phase effects. The disadvantage of the method is that it requires an additional laser and the two coupling lasers may require amplification.

B. Approach to Achieving Objectives

As a part of the Study a set of initial requirements was defined to verify suitability of the Rydberg atom-based seniors to receive liner frequency modulated pulse waveforms with parameters typically used in conventional space borne radar systems. These included the centre frequency, pulse length, frequency slope, and pulse repetition rate. In addition, the expected sensitivity of the Rydberg atom-base sensors to receive the return signal from the target i.e., the minimum energy that the receiver can detect and discriminate was defined. Here the challenges and trade-offs with regard to the two-photon preparation and readout method vs. three-photon preparation and readout method were analysed. The deep dive into the relation between the quantum sensors and the conventional antenna receivers was taken and this relation was explored. Finally, the initial system concept was proposed following the sensitivity analysis and trade-offs

C. Basic Requirements Validation

The requirements were assessed base on a 2-photon and 3-photon preparation and readout methods as well as unaided i.e., bare vapor cell and assisted vapour cell i.e., developed by QVIL Rydberg all dielectric glass on silicon monolithic receiver. A constructed receiver consists of vapour cell inside a hollow-core photonic crystal structure which slows RF field and increases its intensity The structure is able to improve the RF field/signal detection by approximately 30 dB and it is shown schematically in Figure 2.

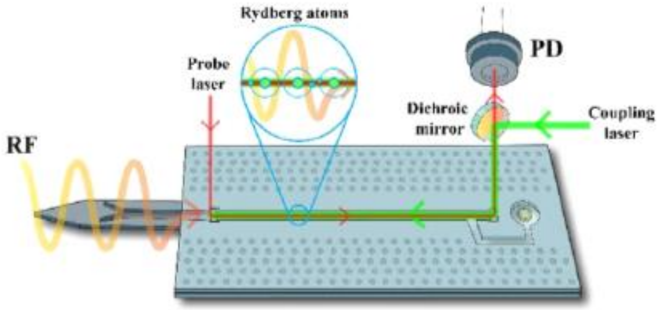

Fig. 2. Receiver consisting of vapour cell inside a hollow-core photonic crystal structure

D. Rydberg Receiver Centre Frequency

In terms of the centre frequency the right Rydberg transitions could be selected to satisfy the requirement of 5.52GHz using a standard two-photon preparation and detection scheme. Usually there are several different Rydberg transitions that could be considered to satisfy the centre frequency requirement. All of the transitions have large transition dipole moments and the coupling light is straightforward with electro-optic modulation. With the centre frequency requirement set at 5.52GHz the 89S1/2-88P3/2 transition at 508.6740 nm was the suggested. Hence satisfying the centre frequency requirement doesn't present a challenge.

There are several transitions that can be used for the three-photon preparation and readout scheme as well. The transition dipole moments are similar to those identified for the two-photon approach. The 88P3/2-89S1/2 at 2231.9362 nm and the

90P1/2-91S1/2 at 2231.5911 nm transitions were suggested for the system. As in the case of the two-photon preparation and readout, the three-photon system can use electro-optic modulation to generate coupling light for all the desired channels (see Bandwidth Section)

E. Operational Bandwidth

The Rydberg atom-based sensors assisted by the photonic crystal, as described above, are limited to 10MHz bandwidth. This is due to the fact that the designed Rydberg vapour cell is imbedded into the photonic crystal structure which enhances the atom-RF interaction but limits the operational bandwidth. However, larger bandwidths can be realised by utilizing multiple independent photonic crystal receivers each having 10 MHz bandwidth. All different sub-bands can be active at the same time, so that all the channels can be simultaneously read out. The coupling laser for each channel can be detuned from resonance to maximize the signal at each detuned RF target frequency. A single laser system can provide the light to each element, since the frequency shifts can be generated by electro-optic modulation. It was estimated that 11 Rydberg vapour cell imbedded into the photonic crystal structures would be needed to satisfy requirement of 100 MHz system bandwidth with margin.

F. System Directivity

In order to satisfy the specified directivity of 53 dBi a focusing element(s) is/are required. The acceptance angles of the Rydberg receivers consisting of vapour cells inside a hollow-core photonic crystal structures without any focusing elements give the estimate directivity of D_{θ}=22, or 13.5 dBi. There isn't a difference between the three photon and two photon readout and preparation schemes with respect to the directivity. The simplest solution would be to use an approximately 63 x 63 array of 11 photonic crystal cells operating at different sub-bands of 100MHz system bandwidth. Each of the 11 cells could be fitted into a 11 cm x 11 cm square or hexagonal tiling pattern. Such an array would have a size of approximately 7 m x 7 m. With a panel to panel spacing of approximately 11 cm, the directivity would be $D = \varepsilon\, N\, \Delta x\, \Delta y\;\; 4\pi/\lambda^2$, where ε is the efficiency and Δx and Δy are the panel spacings in the two dimensions. The estimated directly of such array would be approximal 53 dBi, assuming ε close to 1. In this basic solution the number of elements needed for a 63 x 63 array is relatively large leading to increase power consumption and size and mass of the supporting system. One laser could roughly drive 100 sensors, so the power consumption and size and mass scaling for such an array is not advantageous. Other options can be considered, such as parabolic dishes configured in a close packed array each with a receiver panel (11 cells). The system directivity is then the sum of sub-system directivities. With an array of five 3m parabolic dishes each having acceptance angle of 1.3 give a directivity of approximately 51dBi. The concept of such system is shown in Figure 3.

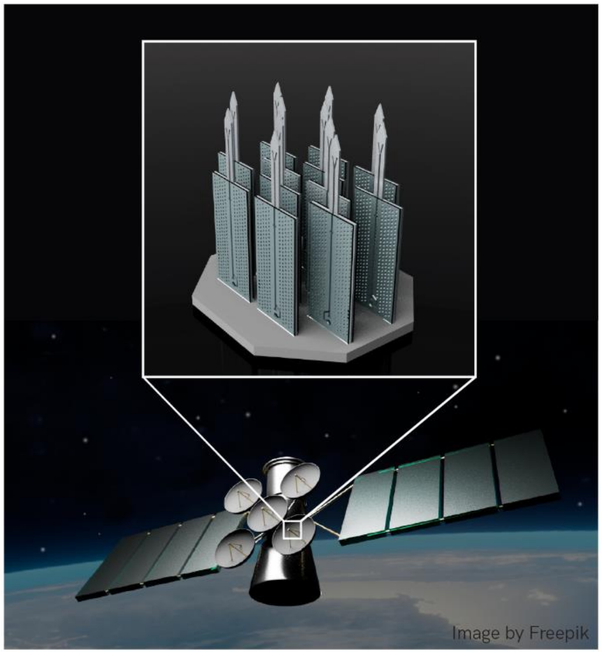

Fig. 3. Illustration showing the concept of the proposed system

G. Phase modulated Signals

The three-photon approach is advantageous for phase modulated signal detection because there is less of an effect due to the atomic velocities. The example of the phase response of the three-photon preparation od readout approach is shown in Figure 4.

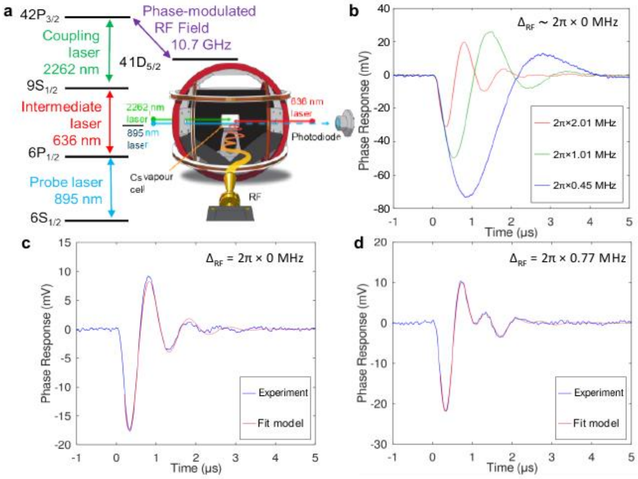

Fig. 4. Example of the phase response

H. Signal Polarisation Detection

The Rydberg atom-based photonic crystal receivers can detect a single polarisation Since the sensitivity can be much higher in a single polarisation, the number of receivers can be doubled to detect both polarisations at the same time if needed. This is the trade-off between the high sensitivity and flexibility in polarisation detection

I. Signal Polarisation Detection

The specified sensitivity of the Rydberg atom-based sensor has been set to -80 dBm in 10 MHz bandwidth, giving a sensitivity of -150 dBm/Hz. The sensitivity requirement can be satisfied by using mm-sized laser beam and a photonic crystal receiver for each channel. In a bare vapour cell, using 100 µm diameter laser beams (2-photon preparation and readout method) the sensitivity is limited to approximately -124 dBm/Hz. The signal is proportional to the number of atoms and the shot noise is inversely proportional to the square root of the laser power. In a case of the 3-photon preparation and readout method the sensitivity increases to approximate -139 dBm/Hz. If one adds the engineered photonic crystal receiver then approximate 30 dB of additional amplification can be achieved.

The Rydberg sensors measuring an electric field intensity via Rabi oscillations of the atoms do not dissipate power on the radio frequency transition. The power is dissipated on the probe laser transition via photon scattering. The performance of the convectional antenna systems is typically evaluated with respect to the RF power dissipated across the antenna's load. In order to make a connection between the electric field received by an antenna and the power dissipated across the antenna's load the Antenna Factor (AF) was used. The Antenna Factor, reflects the use of an antenna as a field measurement device or probe and is most widely used antenna's descriptor in the EMC area. The Antenna Factor allows one to compare the quantum (Rydberg atom) and conventional technologies, i.e., the Rydberg sensor electric field sensitivity can be, to large extent, compared to an equivalent antenna.

Antenna factor is the factor when multiplied by the voltage across the receiving antenna's load gives the incident electric or magnetic field. Thus, the electric filed antenna factor is given by $AF = E_{incident}/V_{received}$ where $E_{incident}$ is the electric filed incident on the antenna and $V_{received}$ is the voltage induced across the terminals of the receiver (antenna's load).

Assuming $R = 50\ \Omega$ load and $P = P_A A_E = V^2/R$, where P is the power dissipated across antenna's load, P_A is the power density at the antenna aperture and $A_E = \lambda^2 G/4\pi$ is the effective antenna aperture the Antenna Factor can be written as $AF = E_{incident}/V_{received} = \surd(120\pi/(R \cdot A_E)) = 9.73/(\lambda \cdot \sqrt{G})$. Substituting $V_{received} = \sqrt{P \cdot R}$ one gets $E_{incident} = 9.73/\lambda \cdot \sqrt{(P/G) \cdot R})$.

If the goal is to detect a -150 dBm signal in a 1Hz bandwidth at 5.52 GHz one gets $E_{incident} = 1.15\ \mu V/m$

In a case of the Rydberg atom-based sensor, the estimates/calculations were based on the achieved by QVIL results of the measurements in the laboratory conditions. The gain of the photonic crystal receiver was calibrated against a bare vapor cell. The bare vapor cell was calibrated using the Autler-Townes splitting to calibrate the attenuators in the signal source. The calibration values were then compared to the RF measurements of the antenna gain taking into account cable losses. The results obtained using the two-photon method were$2.40\ nV/(m\sqrt{Hz})$, which in 1Hz bandwidth gives $2.40\ nV/m$, while the three-photon method yielded sensitivity of $0.50 nV/(m\sqrt{Hz})$, which in 1Hz bandwidth gives $0.5\ nV/m$ With the measured gain of 100, of the photonic crystal receiver, the Rydberg atom-based sensor would have a minimum detectable electric field, with a 1s integration time of, $0.024\ nV/m$ for the two-photon optical readout and $0.005\ nV/m$ for the three-photon optical readout. One can back calculate the equivalent minimum detectable power/gain product (P/G) for a 1s integration time using above mentioned RF electromagnetic fields and the Antenna Factor. For the two-photon optical readout $P/G = 4.37 \times 10^{-20} \approx -164\ dBm$, while for the three-photon readout $P/G = 1.90 \times 10^{-21} \approx -177\ dBm$. With the constructed photonic crystal receiver, the initial requirement of sensitivity can be satisfied, and every more can be pushed close to the background noise

J. System Concept

Following the initial feasibility assessment and the performance analysis based on a set of defined requirements and technology capabilities and detailed sensitivity analysis, as presented above, the rudimental system architecture has been proposed utilizing the photonic crystal vapor cells (Figure 5).

The proposed conceptual solution is a five-dish array shown in Figure 3. Each dish has a sensor panel that can simultaneously sense all 11 channels, each with a 10 MHz bandwidth. The centre frequency is 5.519 GHz. The directivity is 51 dBi. The sensitivity aspect, as extensively described above is close to the requite value. The initial estimate of the system weigh was < 75 kg and the volume < 300 liters, not counting the dishes. The power consumption is estimated to be ~750 W. The system parameters are summarised in Table 1.

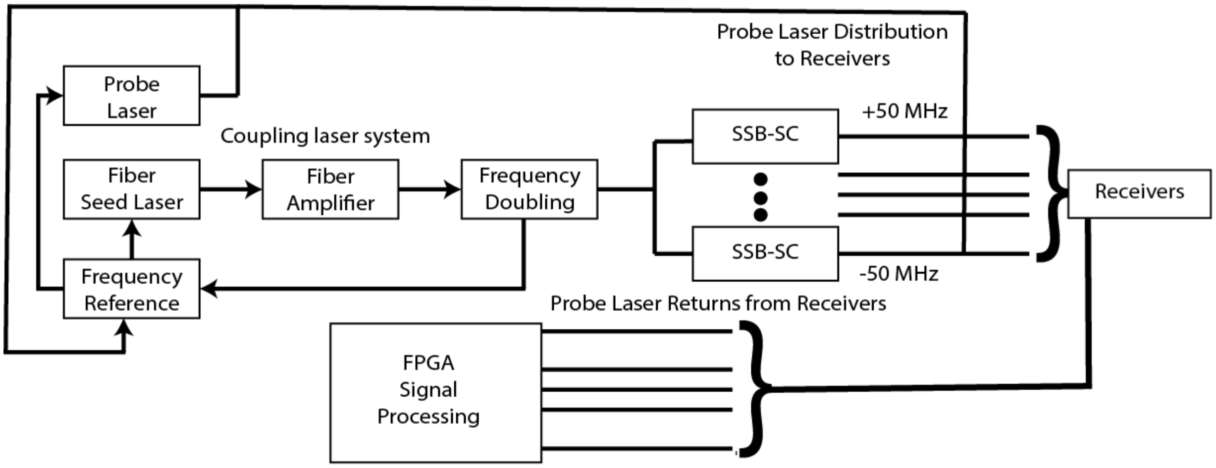

Fig. 5. Proposed architecture for the laser and signal processing system. The system is constructed around the two-photon preparation and readout scheme, and can serve as a bases for a three-photon scheme

TABLE I
SUMMARY OF SPECIFICATIONS FOR THE PROPOSED SYSTEM (HIGH LEVEL) IN COMPARISON TO THE MISSION REQUIREMENTS

Parameter	**Requirement**	**Proposed High Level Design**
Centre frequency	5520 MHz	5519 MHz
System bandwidth	100 MHz	11 Simultaneous channels, ±50 MHz from centre frequency
Channel bandwidth	10 MHz	10 MHz
Directivity	53 dBi	51 dBi with the proposed solution
Sensitivity	-150 dBm/Hz	<-170 dBm/Hz with three-photon preparation and readout scheme
Duty Cycle	50%	50%
Polarisation	Circular	Linear Rx, but large sensitivity margin
Size	1323 liters	< 300 liters + parabolic dishes
Weight	<400 kg	< 75 kg + parabolic dishes
Power	1.5-3 kW	< 750 W

V. SUMMARY

In this study the feasibility of using Rydberg atom-based sensors in radar applications was explored. The concept of the space-borne system comprising Rydberg receivers was proposed and its performance assessed against a set of requirements. The defined requirements were typical for the space-borne radar system that uses conventional technologies. The proposed system successfully met most of the requirements with several advantages over conventional systems. The system based on Rydberg atom-based receivers offered high sensitivity. This high sensitivity was achieved, in particular, when the receivers were using a three-photon preparation and readout schemes and their performance was assisted by the photonic crystal structure developed by QVIL. It is understood that, at this stage, the packaging of the three-photon system is not as matured as the two-photon systems but because of its advantages it was identified as main focus of the future work. In the course the study it was demonstrated and the quantum technology has large potential to be used in the space-borne radar receive systems

VI. FINAL REMARKS AND FUTURE WORK

It worth stressing that Rydra study being exploratory in nature and not intended to provide immediate practical application revealed several scientific and technical avenues worth exploring to further deepen insight into relation between quantum and conventional technologies. The study significantly contributed to basic understanding of the above-mentioned relation and showed the pathway for specifying the key parameters of the space-borne radar receivers in the language of quantum technology. This can be illustrated taking one of the key parameters of the conventional RF receivers, namely, a noise figure, which cannot be directly defined in the language of the quantum receivers (Rydberg atom-based receivers). Instead, the term, sensitivity needs to be introduced and define for the receivers based on conventional technologies. The study also laid the groundwork for advancing the technology readiness level by validating the concept and proving a high-level Rydberg atom-base RF receiver architecture based on the initial performance requirements and trade-off analyses. With the foundational work the study provided a strong bases for new potential proposals aiming at conducting more targeted investigations, research and development as well as scaling up the technology. It could also serve as bases for a future collaboration between research and commercial entities

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