QUANTUM RADAR: STATE OF THE ART AND POTENTIAL OF A NEWLY-BORN REMOTE SENSING TECHNOLOGY

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***Abstract*— Quantum technology has already been introduced in many fields, like information processing and communications, and it can potentially change our approach to remote sensing in the microwave and millimeter-wave domain, leading to systems known as Quantum Radars. This new generation of systems does not leverage directly on quantum entanglement, since the latter is too "fragile" to preserve in a noisy and lossy environment, as a radar scenario, but rather on the high level of coherence derived from quantum entanglement. Quantum Illumination is a process that exploits quantum coherence of non-classical states of light for remote sensing. It allows for the generation and reception of highly correlated signals in the form of optical or microwave photons. By correlating the received signal photons with photons entangled with the transmitted ones, it is possible to clearly distinguish, among all the received photons, the echoes from background noise and interferences, boosting to an unprecedented level the sensitivity of remote sensing. Therefore, in principle, it is possible to detect very low cross-radar section objets, such as stealth targets. Nowadays, very few experiments on Quantum Radar transceivers have been reported. This work aims at summarizing the state of the art of Quantum Radar, introducing its basic working principles, though raising the possible issues of such a technology; secondly, it will point out the possibilities of photonics-assisted Quantum Radars, proposing photonics as the ideal field where quantum science and remote sensing can meet for an effective cross-fertilization.**

Keywords—Quantum Technologies, Photonics, Radar, Quantum Radar

Introduction

Although the roots of quantum mechanics can be traced back to the first half of the 19th century, it still represents a branch of physics that questions the way we observe and interpret reality since some centuries. Despite not being a very young discipline, beyond its help in understanding matter and interactions between particles, only recently it started having a technological usefulness. Indeed, in the last decades, the possibility of demonstrating many of the peculiar properties of quantum mechanics with real experiments has gradually opened the way to new technological applications. In particular, although theoretically pointed out as a paradox by Einstein, Podolsky, and Rosen in their famous paper [1], violations of locality and realism have been recently irrefutably demonstrated [2] by the Bell's inequality violations [3].

Nowadays, quantum technologies are the object of an intense research that led to the development of quantum cryptography [4], quantum computing [5] and, most recently, quantum sensing [6] - [10]. Nowadays, many different approaches have been employed to realize quantum-based systems for any of the above mentioned applications. In particular, both electronics- and photonics-based solutions have been proposed, although no winner did emerge yet. In particular, in this domain, photonics can be very attractive [9], since the generation of light beams with the needed quantum features can be easier than working only in the electrical domain [11] - [13]. Moreover, it has been demonstrated that signals with quantum features can be generated at microwave frequencies starting from light sources [8], [14], [15]. This makes quantum technologies particularly appealing for remote sensing applications, such as radars. A Quantum Radar (QR) is a remote sensing system leveraging on quantum mechanics properties of the electromagnetic fields to enhance detection capabilities with respect to classical radars. Overlooking possible military classified activities, it seems that, today, we are just at the dawn of research and development in the field of QRs. A demonstration of a complete system field trial has not been reported yet, not considering claims with no supporting evidence [16].

In this paper, we outline an updated state of the art of technology for the newly-born application of QR, considering both electronics-based and photonics-assisted technologies, particularly focusing on possible photonics solutions. Indeed, photonics already offers the possibility of enhancing radar systems capabilities with frequency and waveform agility, higher stability and resolution, and efficient signal distribution [17]. Moreover, since photonics allows for an efficient generation of quantum-entangled signals [11] - [15], it can be considered as a promising candidate to provide sources and detectors for quantum systems. The paper is structured as follows: after the Introduction, in section “Quantum entanglement and quantum radar” we briefly expose the fundamentals of quantum-based technologies, starting from the concept of *quantum entanglement* (QE); then, we focus on one of the most interesting strategies for quantum-assisted remote sensing, namely Quantum Illumination (QI), and report on the first laboratory demonstrator of a QR. In section “Photonics and quantum radar”, we show some photonics-based subsystems for the development of a QR transceiver, before outlining conclusions and perspectives a the end of the paper.

Quantum Entanglement and Quantum Radar

a) The Concept of Quantum Entanglement

In 1935, Einstein *et al*. attacked quantum mechanics [1] arguing that its description of physical reality, although correct, was “not complete”. Indeed, they raised a crucial issue consisting in quantum mechanics violation of two principles: reality and localism, that had never before been seriously questioned. Nevertheless, quantum mechanics assumptions lead to the concept of QE, which was previously unknown, and considered by Einstein some sort of inexplicable “spooky action at a distance”. Two entangled systems are deeply related, in the sense that any change (or measurement) applied to one of them, instantly affects the other, no matter how far in space they are. There are two possible explanations to this seemingly bizarre behaviour: either local realism can be violated by this category of systems, or “information” between the systems can travel even faster than light in vacuum, which is a violation of general relativity. Einstein *et al.* rejected both explanations, indirectly suggesting the presence of “hidden variables”, later analyzed by Bell [3], that should be added to quantum-based assumptions and interpretations, to give a satisfactorily complete description of the physical reality.

Many years later, however, the former of the two possible above-mentioned explanations has been demonstrated to be true [2], [3]. Bell’s theorem proves that no hidden variable-based model can complete quantum mechanics without violating local realism anyway, and experiments supported this theoretical result [2]. Thus, entanglement between particles has become a common phenomenon, even in small macroscopic systems [18], and its features have been demonstrated to be useful in many applications. If a pair, or a group, of entangled photons is generated, the perturbations experienced by one or more of them is instantly transferred to all the others, even though they did not undergo the same perturbations, no matter where they are located. These unique features of entangled particles can be employed in remote sensing, as exposed in the following.

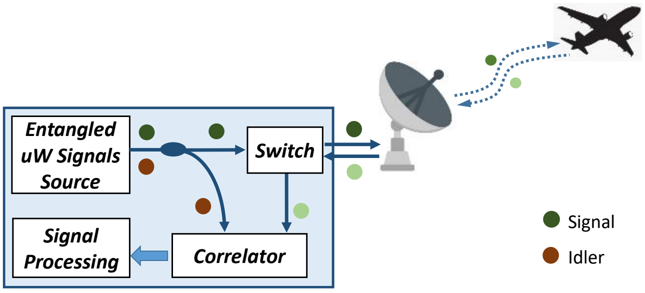

Fig. 1. Basic scheme of a Quantum Radar.

b) The Technique of Quantum Illumination and the Quantum Radar.

Any electromagnetic field, regardless its frequency, is “carried” by photons. As a fact, any pair or group of photons, at any wavelength (or frequency), from radiofrequency (RF) to light, can be generated as entangled. Throughout this paper, we will commonly refer to RF photons or optical photons, depending whether we are talking about an electrical or an optical signal. Let’s consider a system generating entangled photons, and assume a part of them is launched toward a target, whereas the remaining ones are stored in the system. Ideally, when the launched photons interact with the target, somehow changing their properties, the remaining local ones, due to QE, would show the same changes, even though they did not hit the target. This does not really happen, and it is not QE itself being directly employed for sensing. Indeed, QE is very “fragile”, and it does not survive to losses and noise typical of the radar environment: when the sensing photons reach the target, QE with the local photons is already lost and the above-described approach does not apply. However, even though in this scenario the QE is broken, all the photons still maintain an extremely strong coherence, that can be exploited in QRs similarly as in classical radars. The technique relying on this non-classical coherence for remote sensing is Quantum Illumination.

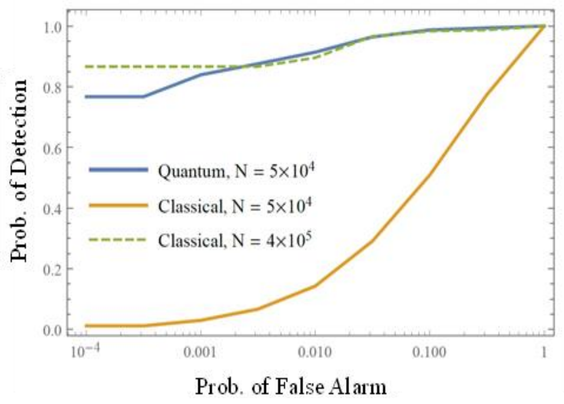

Fig. 2. Comparison between the ROC curves of the QR (blue line) and of an equivalent classical radar (orange and dashed green lines) [10].

The scheme of principle of a QR exploiting QI is depicted in Fig. 1. The entangled photons generated by a source at microwave frequency are separated as signal (deep green circles in Fig.1) and idler (deep red circles). The signal photons are sent to an antenna, whereas the idler photons remain in the system. Once the signal hits a target, it is backscattered to the antenna (light green circles), being received and fed back into the system, where it is correlated with the idler. This way, the preserved coherence deriving from QE allows distinguishing the photons composing the backscattered echoes from any other photon that is part of noise or other transmissions.

c) The First Laboratory Demonstrator of a Quantum Radar

Very recently, Luong *et al*. reported the first example of a complete prototype of a lab-operated QR [10]. The presented system is completely based on electronic technology and is inspired by, but does not directly leverage on QI, since it does not need joint measurements on signal and idler, but it needs just independent measurements. The entangled employed signals are generated by a Josephson Parametric Amplifier (JPA), amplifying vacuum quantum fluctuations, producing a double sideband RF signal. The two sidebands, at 6.1445 and 7.5376 GHz, are entangled. The former is employed as the idler, whereas the latter is the signal transmitted by an antenna. In [10], the signal is received directly by another nearby antenna, thus performing a sort of back-to-back measurement of the system characteristics. The transmitted power is -82dBm, and the correlation between the idler and the received signals are exploited to extract the transmitted signal from the background noise, without any particular effort to attenuate multipath effects and clutter. To better assess the performance of the proposed QR, it is compared with a similar classical radar. The receiver operating characteristic (ROC) curves of both systems have been measured, as reported in Fig. 2. Apparently, the classical system, to have comparable performance, needs a much higher number of integrated echoes, corresponding to an eight-time longer integration time. It is also proven that the correlation between the QE-generated signal and idler is up to 2.5 times stronger than in the case of the classical coherent radar.

However, a big limitation of this proposed QR is that the JPA is a microwave resonator based on superconductivity, meaning that it requires cryogenic temperatures to operate. In [10], a bulky dilution refrigerator is necessary, to make the JPA operate at a temperature as low as 7 mK. This feature does not really meet the needs for a future cheap, small-size, and low-power hungry solution.

Photonics and Quantum Radar

d) The Photonics-Assisted Quantum Radar

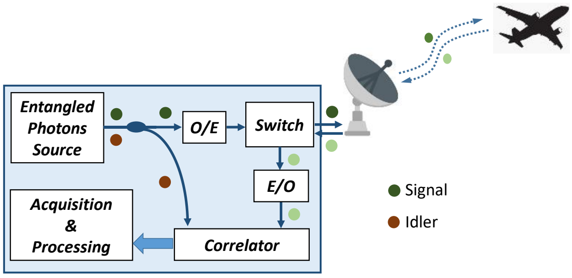

Fig. 3. Basic scheme of a photonics-assisted Quantum Radar. The Entangled photons source produces photons with QE starting from low-frequency electrical domain signals.

At first, QI for remote sensing has been proposed in the optical domain [6], [7], applied to photodetection. By exploiting the strong correlation persisting between formerly entangled particles or fields, it showed a remarkable enhancement of the signal-to-noise ratio (SNR), thus improving the detection of low-reflectivity targets. Later, it has been demonstrated that QI can be operated also in the microwave domain, but the signal generation is still performed optically [8], showing that photonics sources and detectors can greatly be of help in developing a QR.

The scheme of a photonics-assisted QR is depicted in Fig. 3. It is very similar to the scheme in Fig. 1, with the fundamental difference that the generation and the acquisition of signals is operated in the optical domain, exploiting the advantages offered to microwave systems by photonics. The generation can consist in the photonic up-conversion to RF frequency of one, or more, low-frequency electrical signals composed by entangled photons, operated by an electro-optical (E/O) conversion stage. Conversely, reception may exploit photonic down-conversion in an opto-electronic (O/E) conversion stage. E/O and O/E operations can be performed with techniques described in [17], provided that photonics-assisted up- and down-conversions do not alter the quantum features of the original signal.

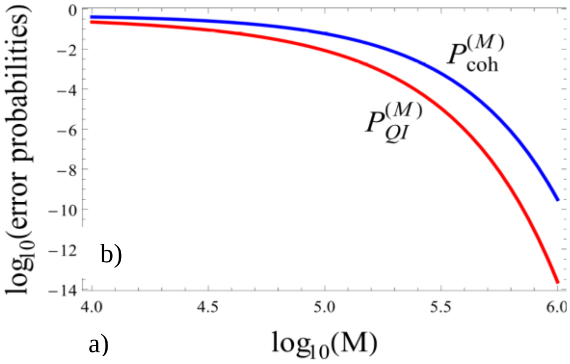

Fig. 4. Performance comparison between the error probability of a QI receiver (red curve) and a classical coherent receiver (blue line) [8].

Fig. 4 shows the performance comparison between a microwave QI system (red line) and an equivalent classical coherent radar (blue line), as reported in [8]. The plot traces the detection error probability as a function of parameter *M*, equivalent to the system time-bandwidth product, for *M* >>1, witnessing the better performance achieved by QI. This is possible because the error probability depends on the SNR, and QI guarantees a much higher SNR for faint returning echoes. The main drawback of QI, as it has been proposed, is that it needs joint measurements of the signal and idler, meaning that the backscattered signal should be correlated with its idler, that should be stored in the system by quantum memories or optical fiber loops [8].

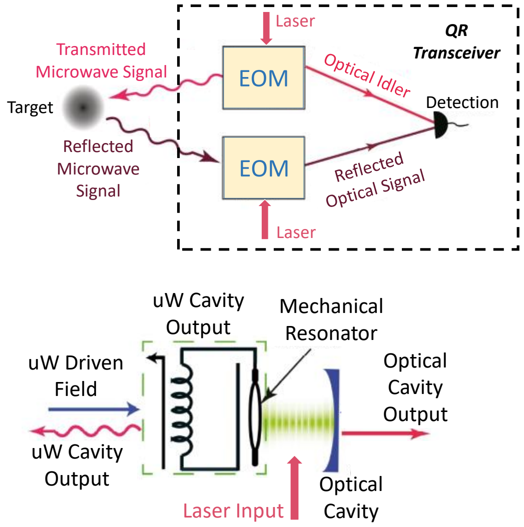

Fig. 5. a) Scheme of a photonics-assisted QR transceiver; b) Scheme of the electro-optical modulators (EOMs) performing E/O or O/E conversions for quantum radar applications [8].

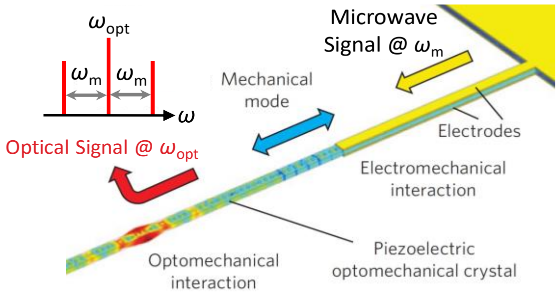

Fig. 6. Scheme of the photonics-integrated modulator for coupling microwave quantum-entangled signals with optical signals [14].

The translation of the quantum properties of an entangled microwave signal to the optical domain (O/E) and viceversa (E/O) is possible thanks to E/O modulators (EOM) as reported in Fig. 5. Fig. 5 a) schematically shows how they can be employed to operate sensing in the microwave domain but generate and acquire the signals with photonic techniques. These EOMs can exploit, for instance, opto-mechanical effects by coupling, thanks to a mechanical resonator, an optical cavity fed by a laser input, with a microwave cavity driven by a RF signal, as depicted in Fig. 5 b).

A very interesting solution to modulate optical signals with entangled RF signals is reported in [14]. This EOM has been realized in Aluminum Nitride, monolithically integrated on a single photonic chip. An optical waveguide, contacted with metal electrodes, is injected with a continuous wave laser at an optical telecom frequency $\omega_{opt} = 2\pi\times196$ THz, by means of a Bragg grating (BG). As sketched in Fig. 6, a microwave signal made by entangled RF photons, oscillating at frequency $\omega_m = 2\pi\times4.2$ GHz, is applied to the electrodes, thus exciting a mechanical mode inside the waveguide crystal. This mechanical mode is carried by phonons, that can oscillate at the frequency of the applied electrical signal. This way, they modulate the injected laser, creating two entangled sidebands at $\omega_{opt} \pm \omega_m$. Therefore, this device acts as a quantum transducer, allowing the transfer of the quantum state of a microwave signal to the optical domain. Such an EOM can be employed to exploit the advantages brought about by microwave photonics in the radar domain, as extensively explained in [17].

Conclusions and Perspectives

Quantum properties of electromagnetic fields disclose the possibility of breaking classical limits in many domains, in particular in that of remote sensing. It gives, in principle, an impressive enhancement of sensitivity, especially when detecting targets with very small radar cross-sections and weak returning echoes. This can be achieved because, among all the photons received by a QR, it is possible to extract only the photons related to the transmitted signal, thanks to the strong correlations created by QE. This is true, in principle, no matter how faint is the received echo. Therefore, quantum technologies can boost the sensitivity of remote sensing to an unprecedented level, potentially excluding the possibility of having stealth targets and overcoming jamming techniques.

Recently, it has been demonstrated that QR is feasible, albeit a lot of research is still to be carried on to take this kind of systems to an acceptable technological readiness level. On the other hand, in the last decade, microwave photonics has shown its capabilities of enhancing the performance of RF systems leveraging on the unique features of optical and electro-optical technology. Nowadays, photonics can be a key enabling technology also for QRs, considering that it already allows efficiently generating and detecting quantum entangled photons, and quantum transducers between optical and RF domain are already available. Photonic sources of optical entangled photons have been reported in [11] - [13], but research has still to be brought on to ascertain if it is possible to exploit these sources to obtain RF entangled signals and idlers, e.g. thanks to classical direct or external modulation by non-entangled electrical signals.

Finally, it is important for EU to foster research activities to fill the technological gap between actually existing photonic technology and the requirements of QR systems. Indeed, some non-EU countries are massively investing in quantum technologies, including QR, and EU should keep the pace of these developments.

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