THE QUANTUM ILLUMINATION STORY

Superposition and entanglement, the quintessential characteristics of quantum physics, have been shown to provide communication, computation, and sensing capabilities that go beyond what classical physics will permit. It is natural, therefore, to explore their application to radar, despite the fact that decoherence—caused by the loss and noise encountered in radar sensing—destroys these fragile quantum properties. This article tells the story of “quantum illumination,” an entanglement-based approach to quantum radar, from its inception to its current understanding. Remarkably, despite loss and noise that destroy its initial entanglement, quantum illumination does offer a target-detection performance improvement over a classical radar of the same transmitted energy. A realistic assessment of that improvement’s utility, however, shows that its value is severely limited. Nevertheless, the fact that entanglement can be of value on an entanglement-breaking channel—the meta-lesson of the quantum illumination story—should spur continued research on quantum radar.

ENTANGLEMENT-BASED QUANTUM RADAR: FROM MYTH TO REALITY

Many quantum radars currently studied in the literature use a phenomenon called entanglement to address the problem of distinguishing signal from noise, which is one of the most important problems faced by any radar. Until recently, entanglement-based quantum radars at radio frequencies existed only in theory; their practicality was very much in doubt. The situation has changed with a recent experimental implementation of all the necessary components of a quantum two-mode squeezing (QTMS) radar, which operates at microwave frequencies and can be described as a quantum range finder. In this article, we lay out the exact problem solved by this prototype, namely quantum noise, and explain how entanglement can overcome the existence of this noise. By analyzing the QTMS radar prototype, we point out a technological route to an entanglement-based quantum radar that can, in principle, perform all tasks that radars can and must do, such as array processing, clutter suppression, and image processing (including synthetic aperture radar and inverse synthetic aperture radar).

ENHANCING CLASSICAL TARGET DETECTION PERFORMANCE USING NONCLASSICAL LIGHT

In this article, we demonstrate theoretically and experimentally how one can exploit correlations generated in monolithic semiconductor quantum light sources to enhance the performance of optical target detection. A prototype target detection protocol, the quantum time-correlation (QTC) detection protocol, with spontaneous parametric down-converted photon-pair sources, is discussed. The QTC protocol only requires time-resolved photon-counting detection, which is phase-insensitive and therefore suitable for optical target detection. As a comparison to the QTC detection protocol, we also consider a classical phase-insensitive target detection protocol based on intensity detection. We formulated the target detection problem as a probe light transmission estimation problem, and we quantify the target detection performance with the Fisher information criterion and the receiver operation characteristic analysis. Unlike classical target detection and ranging protocols, the probe photons in our QTC detection protocol are completely indistinguishable from the background noise and therefore useful for covert ranging applications. Finally, our technological platform is highly scalable and tunable and thus amenable to large scale integration necessary for practical applications.
RYDBERG ATOMS FOR RADIO-FREQUENCY COMMUNICATIONS AND SENSING: ATOMIC RECEIVERS FOR PULSED RF FIELD AND PHASE DETECTION

We report on the development of detection methods for amplitude and phase of pulsed radio-frequency (RF) electromagnetic fields with Rydberg atoms. We begin with an overview of the basic principles of Rydberg-atom-based sensing and measurement of RF electromagnetic fields. An overview of the underlying atomic physics and the method for amplitude as well as phase sensing of electromagnetic radiation with Rydberg atoms is provided. Atomic RF receivers using Rydberg atoms for analog and digital communications and sensing of modulated RF fields are discussed. Detection of pulse-modulated RF and time-domain RF pulse waveform imaging with a Rydberg-atom receiver are demonstrated. The transient response of the Rydberg-atom vapor to a modulated RF field is observed at the 10-nanosecond level, from which a new lower limit to the achievable instantaneous signal bandwidth of atomic RF receivers is established. Finally, we present and describe a new method to measure the phase of an RF field implemented to not require an RF reference wave. The method employs phase-coherent excitation pathways involving the optical fields in the atomic sensing medium with the signal RF field. The optical RF phase-sensing approach lends itself to the realization of atomic RF sensors, measurement and imaging devices that are relevant to applications in RF communications and sensing.

EQUIVALENCE OF CLASSICAL AND QUANTUM ELECTROMAGNETIC SCATTERING IN THE FAR-FIELD REGIME

Quantum remote sensing, also known as quantum detection and ranging (QUDAR), is the use of entangled photon states to detect targets at a stand-off distance. It inherently relies on sending many single photons through free space, bouncing off of a target and returning to the sensor. It is therefore necessary to understand how single photons interact and scatter from targets of macroscopic size. This article relates quantum and classical scattering in the far-field regime. Specifically, we show that due to the photon’s position uncertainty, the path over which the photon traverses is not well defined, and this causes quantum interference. The result of this interference exactly replicates classical scattering behavior of electromagnetic waves. We will show that one can exactly derive the classical electric field scattering integral using a purely quantum construction. Although this article focuses on the context of QUDAR, it is very general to any application involving far-field electromagnetic scattering. Finally, we delve into the QUDAR multiphoton quantum scattering advantage shown in previous literature and further develop the theory. Specifically, we provide explanations as to why this advantage has not been observed in the classical regime, as well as provide insight as to the experimental requirements necessary to achieve this cross-section enhancement.