Quantum Monopulse Radar

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Abstract **─** We evaluate the feasibility of a quantum monopulse radar, focusing on quantum illumination (QI) radars and quantum two-mode squeezing (QTMS) radars. Based on their similarity with noise radar, for which monopulse operation is known to be possible, we find that QTMS radars can be adapted into monopulse radars, but QI radars cannot. We conclude that quantum monopulse radars are feasible.

Index Terms **─** Monopulse radar, noise radar, quantum illumination, quantum radar.

I. INTRODUCTION

Quantum radars are sensors which exploit quantum mechanical phenomena in order to improve detection efficiency over conventional radars operating at the same frequency and transmit power [1,2]. One of the most important quantum mechanical phenomena is called *entanglement*, in which two signals share a very high correlation. Most quantum radar proposals exploit entanglement in order to improve the radar's ability to differentiate between signal and noise. An example of such a proposal is *quantum illumination* (QI) radar [3,4], one of the most widely studied types of quantum radar.

Recently, a variation of QI radar called *quantum two-mode squeezing* (QTMS) radar was proposed [5-8] which is more practical to implement at microwave frequencies. A laboratory prototype that incorporates all of the components necessary in a QTMS radar has already been built. Preliminary results suggest that when a classical radar and a QTMS radar operate at the same frequency and power, the classical radar can achieve the same performance of the QTMS radar only when the coherent integration time is *eight times as long* as that of the latter [8].

In light of this large potential gain, one question which arises is whether quantum radars can support the same functions as conventional radars, e.g., SAR/ISAR imaging or interference suppression. Many such functions require an array of transmitters. We have shown that radar arrays based on certain types of quantum radars, such as QTMS radar, are indeed possible [9]. However, they require multiple quantum signal generators, which may not be practical in the short term. Then it is natural to ask the following question: is it possible to move beyond simple range-finding without the need for a quantum radar array? The central idea of this paper is to answer this question.

Monopulse radars use two or more antenna elements, slightly offset from each other either in beam direction or in phase, to determine both range and direction from a single pulse [10]. Because such radars require only one (specially-designed) transmit antenna, it does not require multiple signal generators. In this paper, we will show that QTMS monopulse radars are feasible.

II. NOISE RADARS, QTMS RADARS, AND QI RADARS

Standard noise radars [11] use conventional equipment such as an arbitrary waveform generator to generate two copies of a Gaussian noise signal (Fig. 1), one of which is retained for correlation (matched filtering) with the received signal. It is commonly assumed that these copies are exactly the same. This is not exactly true: a type of noise called *quantum noise* is inherent in all electromagnetic signals and becomes significant when signal power is low, spoiling the correlation between the copies [8,12].

QTMS radars [8] and QI radars (of the type described in [4]) overcome this by using an entangled signal generator. In this context, entanglement means that there exist correlations between the quantum noise components of the two Gaussian noise signals. The overall correlation between the pair of signals is thus higher than for a noise radar. From an electromagnetic perspective, all three types of radars emit the same *type* of signal; quantum entanglement only improves the *correlation* between the retained and transmitted signals. Classical electromagnetism as applied to antenna design still holds, at least to a first approximation.

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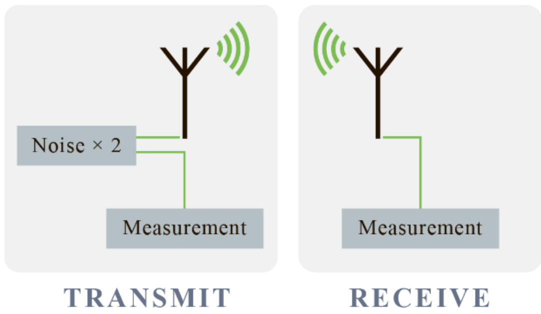

Fig. 1. Block diagram illustrating the basic idea behind noise radar.

The QTMS radar prototype described in [8] used a device called a *Josephson parametric amplifier* to generate the entangled Gaussian noise signals. The center frequencies of the signals were 7.5376 GHz and 6.1445 GHz; the bandwidth was 1 MHz; and the transmit power (after amplification) was -82 dBm. The 7.5376 GHz signal was transmitted through free space through a commercially-available horn antenna and was received at a similar antenna. This shows that the transmission of a quantum-enhanced signal does not require any special electromagnetic engineering.

Apart from the signal generation step, QTMS radars and noise radars are exactly the same. In particular, they employ standard heterodyne detection. Therefore, the received signal and the internally retained signal can be measured separately. QI radars, however, require a sophisticated joint measurement between the received and retained signals, so the latter must be *physically* preserved until the echo arrives from the target. In effect, while QTMS radars and noise radars measure the retained signal and use the resulting measurement record as a reference for matched filtering of the received signal, QI radars use the physical retained signal for "matched filtering".

III. QUANTUM MONOPULSE RADARS

As we have seen in the previous section, all three types of radars emit Gaussian noise signals. QTMS radars and QI radars use entanglement to enhance the correlation between the retained and transmitted signals. QI radars also employ a sophisticated joint measurement to correlate the received and retained signals, while noise radars and QTMS radars perform matched filtering after conventional heterodyne detection. These similarities and differences have a strong bearing on the feasibility of a quantum monopulse radar.

One key insight is that noise monopulse radars have already been shown to be feasible [13,14]. The question of the feasibility of quantum monopulse radar then reduces to whether the similarities between noise radars, QTMS radars, and QI radars are sufficient to apply this result to the quantum case.

We have already shown that all three types of radars transmit Gaussian noise; any "quantumness" lies not in the transmit signal itself, but in the correlation of that signal with a reference signal. Thus, the antennas used in a QTMS radar or QI radar need not possess any special electromagnetic characteristics beyond what is necessary in a conventional radar. This was experimentally demonstrated in [8]. There is no reason why either QTMS radar or QI radar would be incompatible with a transmit antenna designed for monopulse operation.

At receive, however, the situation is different. Since QI requires a complicated joint measurement of the received signal with the retained signal, it is not possible to form the sum and difference signals required in a monopulse radar. This is not an obstacle for QTMS radar, which receives and processes signals in exactly the same way as a noise radar and can therefore generate the sum and difference signals as required.

IV. CONCLUSION

There exists at least one type of quantum radar which can be adapted into a monopulse system, namely QTMS radar. At a conceptual level, all that is necessary is to replace the signal generator of a noise monopulse radar with an appropriate quantum signal generator. Compared to phased arrays, the monopulse solution is simple and inexpensive while still retaining good tracking capabilities. Therefore, a monopulse QTMS radar could be an important and inexpensive first step toward demonstrating that certain types of quantum radar can support functions beyond simple range finding.

However, not all types of quantum radar are similarly adaptable: quantum illumination radar is an example of a system which is incompatible with monopulse operation. This serves as a warning that quantum radar is not monolithic: statements made about one type of quantum radar cannot automatically be applied to another. We would suggest, also, that quantum radar proposals not be evaluated solely on target detection performance, but also on whether they are compatible with functions such as monopulse operation.

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