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SUMMARY REPORT

QUANTUM RADAR (KVANTTITUTKA)

Sorin Paraoanu
Department of Applied Physics,
Aalto University
sorin.paraoanu@aalto.fi

Abstract:

It has been predicted theoretically that quantum entanglement can enhance the task of object detection in the presence of a strong background noise, in comparison with the best classical (non-entangled) case. This could be applied for improving radar detection. Clearly, this demands the realization of a reliable source of continuous-variable entangled state in the microwave range. In this project, we present the successful generation of reliable broadband continuous-variable entangled microwave photons from vacuum fluctuations at a rate of 11 mega entangled bits per second and single-mode squeezing of 2.4 dB. The device studied is a traveling wave parametric amplifier (TWPA) with low-loss and with the Kerr nonlinearity optimized. Our result opens the way for the utilization of TWPA devices as sources of entangled microwave photons in detection experiments.

1. Introduction

The developments in quantum physics during the last few decades suggest that a second quantum revolution is taking place, bringing about the promise of highly powerful quantum simulators, quantum computers, secure communication channels, and enhanced sensing capabilities. The quantum radar is one of the new instruments proposed theoretically. It is based on the phenomenon of quantum illumination, whereby the signal-to-noise ratio of a detection task similar to the one used in radars is considerably increased. The protocol employs photons sent towards a target, with the resulting reflected photons being detected. However, differently from classical radar operation, these signal photons are initially entangled with idler photons, and the detection scheme is such that it retains only those reflected photons which are correlated with the idler photons. In this sense, the idler photons are used to tag the signal photons, and detecting the correlations has the role of distinguishing the signal photons from the environment noise. Spectacularly, in the quantum radar the improvement in the signal-to-noise ratio is proportional with the dimension of the Hilbert space, therefore the enhancement is exponential in the number of ebits.

A significant advantage of quantum illumination with respect to other strategies of gaining quantum advantage (most notably quantum computers) is that entanglement does not necessarily need to be preserved while the photons travel towards the target and back. In fact, a high efficiency of this protocol is achieved in very noisy environments, where entanglement is indeed expected to diminish extremely fast. At some intuitive level of understanding, one can think by analogy with noise radars. In noise radar detection, a random signal is sent towards a target, and then the reflected signal is correlated with the pattern transmitted. The presence of the target is ascertained by matching the two signals. Similarly, in the quantum radar one correlates the photon reflected by the target with the one retained. Remarkably however, quantum correlations are stronger than the classical ones – a fact which is now rigorously established theoretically and experimentally verified. This means that it is impossible to emulate a quantum radar by a classical noise radar.

2. Research objectives and accomplishment plan

The main objective has been to demonstrate for the first time that a Josephson travelling wave parametric amplifier (TWPA) can be operated as a broadband source for generating two-mode squeezed vacuum state (entangled signal and idler) in the microwave range. TWPAs are a new class superconducting devices designed and fabricated mostly for the purpose of serving as amplifiers with quantum-limited added noise, a very useful component for the realization of quantum computers for example.

In addition, our aim was to use devices fabricated by our collaborators at VTT in two rounds of fabrication, demonstrating that reliable sources of entangled microwave photons can be realized in Finland.

3. Materials and methods

Our device is designed and optimized to have a large enough value of 3-wave mixing while minimizing the Kerr term, see Fig. 1 for a schematic. The Kerr term activates detrimental processes and reduces the performance of the device. The device consists of a series of nonlinear asymmetric inductive elements and has a low loss level achieved by the optimization of substrates and materials. The flux bias line is shown in blue, and acts as a lowpass filter, while the resistor prevents the bias current to leak to the ground.

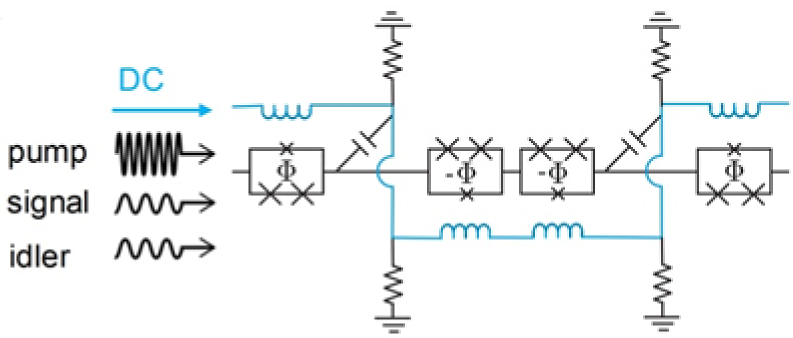

Figure 1. Schematic of a TWPA element. The blue line is the DC bias line.

Figure reproduced from: M. R. Perelshtein et. al. arXiv: 2111.06145 (2021).

The measurement scheme for entanglement generation and verification is shown in Fig. 2. The pump is applied through a line that is filtered (8-12 GHz) with MiniCircuit fiters and attenuated (total attenuation 60dB). The signal is amplified with a chain of low-temperature and room-temperature amplifiers and analyzed by a signal analyzer. The maximum mode separation is therefore limited technically by the bandwidth of the Anritsu MS2830A signal analyzer (19 MHz). The device was placed in a magnetically shielded package and cooled in a BlueFors dilution refrigerator to a temperature close to 20 mK.

The pump signal was obtained from an ANAPICO 4-channel signal generator and the bias DC was generated by a Stanford SIM928 Isolated Voltage Source. The signals are amplified at 4K by a LNF HEMT amplifier with 40 dB of gain and further amplified at room temperature (44 dB).

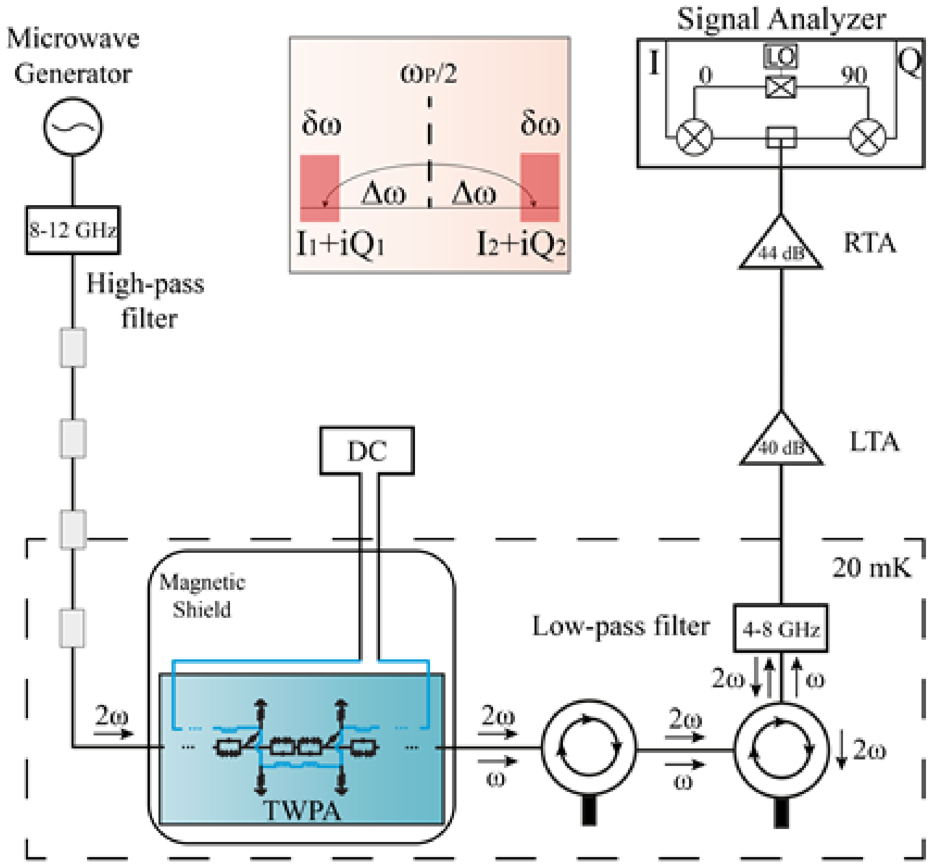

Figure 2. The experimental scheme for TWPA-based entanglement generation. The pump signal triggers the generation of correlated photons in the frequency band $[\omega - \Delta\omega - \delta\omega : \omega - \Delta\omega]$ and $[\omega + \Delta\omega : \omega + \Delta\omega + \delta\omega]$.

Figure reproduced from: M. R. Perelshtein et. al. arXiv: 2111.06145 (2021).

4. Results and discussion

We characterize the device and we find that the gain is 15.3 dB of gain over a bandwidth of 3 GHz. Also we find that the noise temperature is close to the single-photon limit at the operational pump power. This demonstrates that the TWPA operates properly for the task that was designed for, namely quantum-limited amplification.

Next, we perform an experiment that aims at demonstrating entanglement: we measure the covariance matrix. To show entanglement, we should calculate the minimum symplectic eigenvalue v_{min}, and show that it is smaller than 1. We can also calculate the logarithmic negativity E = max[−log2 v_{min},0], which is non-zero only if $v_{min} < 1$. The experimental results together with the theoretical fittings are shown in Fig. 3.

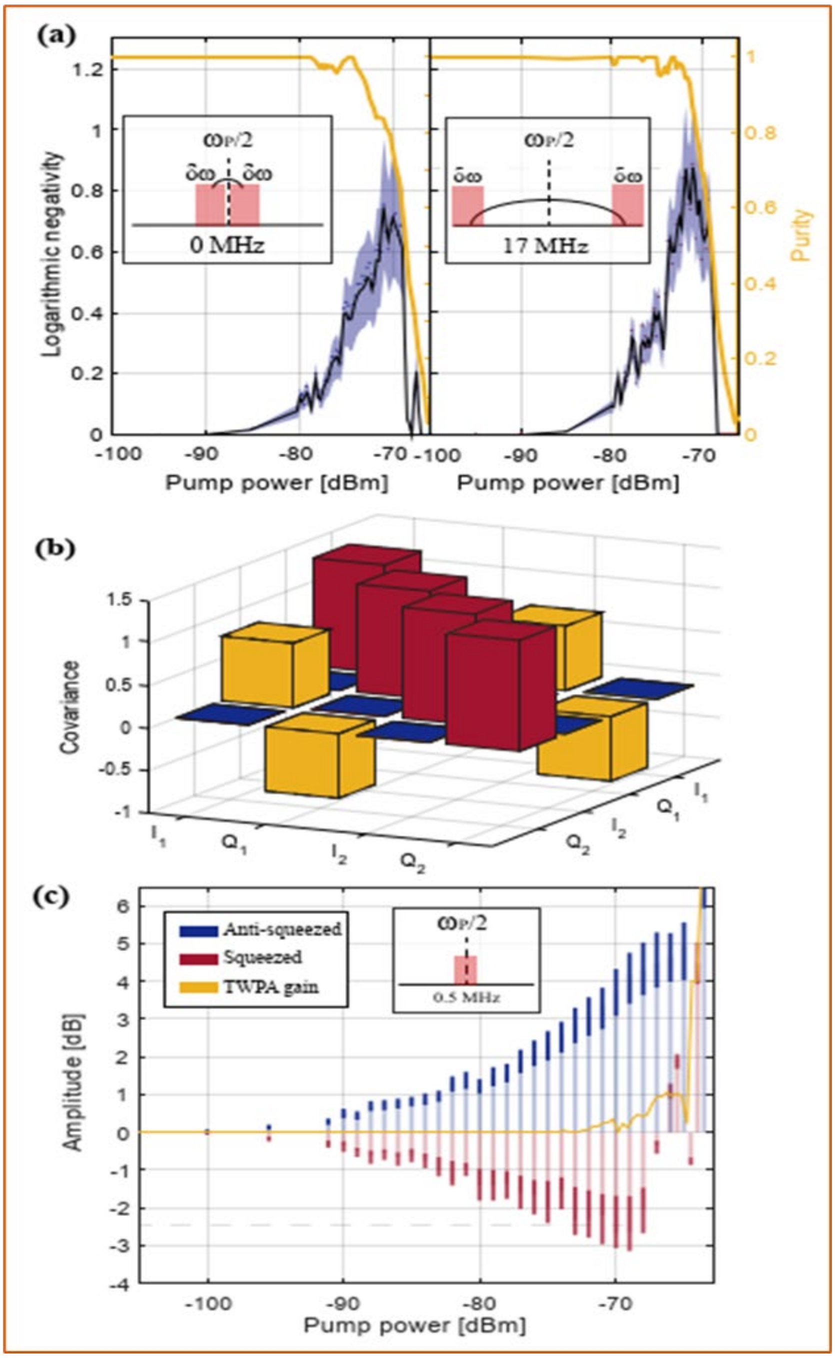

Figure 3. Demonstration of entanglement generation in a TWPA.

(a) Logarithmic negativity for the case when the bandwidth modes are not separated in frequency (left) or separated by 17 MHz (right).
(b) Example of correlation matrix of the IQ quadratures.
(c) Squeezing and anti-squeezing values as a function of pump power.

Figure reproduced from: M. R. Perelshtein et. al. arXiv: 2111.06145 (2021).

In Fig. 3 (a) we present the data for entanglement, together with the values for purity. For non-space modes, we obtain a logarithmic negativity of E = 0.76 ± 0.20 at −69 dBm, while for modes separated by 17 MHz we get E = 0.86 ±0.21. In Fig. 3 (b) we show the obtained covariance matrix at maximum entanglement. This corresponds to approximately 11 Mebits/s, and, with a different setup (a wider band analyzer), we estimate that we could have obtained 1.3 Gebits/s (giga entangled bits per second). Finally, in Fig. 3 (c) we show the squeezing and anti-squeezing values for single modes.

Next, to address the effect added noise to the two-mode squeezing and how the entanglement decreases as noise is ramped up, we present results for a simple setup in which the noise of an amplifier is used to simulate the environmental noise. We thus check how the minimum symplectic eigenvalue of the partially transposed resulting state behaves as the amount of added noise increases.

Consider two modes (the signal and idler) with the squeezing parameter r,
$\hat{a}_s = \cosh(r)\,\hat{v}_s + \sinh(r)\hat{v}_i{}^\dagger$,
$\hat{a}_i = \cosh(r)\,\hat{v}_i + \sinh(r)\hat{v}_s{}^\dagger$,
where the vacuum mode operators are $\hat{v}_x$. Here the index *x=i,s*. Now, amplifying these modes using an amplifier with a gain G and noise operator h yields
$\hat{a}_x{}' = G\hat{a}_x + \sqrt{G-1}\hat{h}^\dagger$.
To see the effect of the added noise due to the noise operator above, we construct the covariance matrix of the modes after the amplification and normalize it by the gain G, such that

$$V = \begin{pmatrix} P & 0 & -C & 0 \\ 0 & P & 0 & C \\ -C & 0 & P & 0 \\ 0 & C & 0 & P \end{pmatrix},$$

where we have denoted $P = \cosh(r)^2 + \sinh(r)^2 + \frac{G-1}{G}\left(1 + 2\langle \hat{h}^\dagger \hat{h}\rangle\right)$, and $C = 2\cosh(r)\sinh(r)$. Consider the added noise photons determined by $N = \langle \hat{h}^\dagger \hat{h}\rangle$ as fixed to say, N=2. We thus can simulate an ambient noise by controlling the value of the gain G and change the signal to noise ratio. In the limit of no gain i.e., $G = 1$, there is no added noise, and the state corresponds to the original two-mode squeezed state. In the limit of large gain, however, we approach to the maximum added noise by the fixed value of N. The minimum symplectic eigenvalue of the partially transposed version of the covariance matrix above has a simple form $v_{min} = P - C$. Below we plot the v_{min} as a function of the noise photons controlled by the gain G for the squeezing parameter $r = 0.788$, which corresponds to the 2.4 dB squeezing level observed in our experiment.

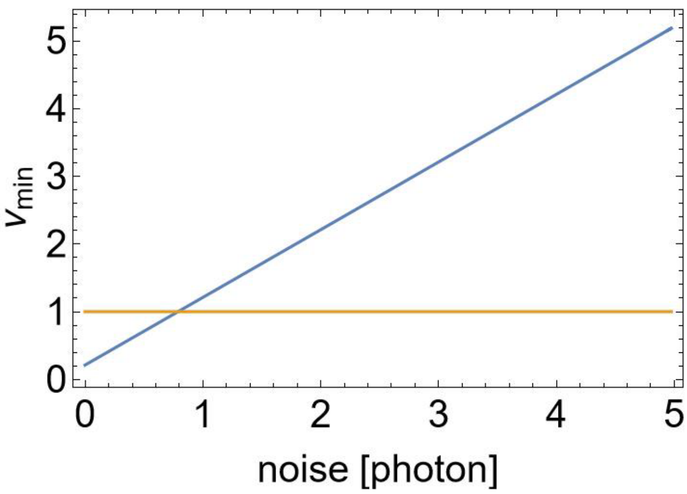

Figure 4: Minimum symplectic eigenvalue plotted in blue as a function of the added noise. Here, we increase the added noise by increasing the gain parameter G. The brown line shows the quantum border when the minimum symplectic eigenvalue is 1.

As we can see in the figure, the minimum symplectic eigenvalue starts to increase as we add more and more noise and eventually passes the quantum limit of 1, when the state is no longer entangled.

5. Loppupäätelmät / Conclusions

We have conclusively demonstrated experimentally the broadband generation of frequency entangled photons at a rate of 11 mega entangled bits per second from vacuum fluctuations. The device, a TWPA fabricated at VTT, can be also used as a quantum-limited amplifier, with 13 dB of gain achieved over 3 GHz bandwidth with noise temperature close to the single-photon quantum limit. We have achieved 2.4±0.7dB of single-mode squeezing achieved.

This project also demonstrates that devices that act as sources of entangled photons can be fabricated using local resources and know-how available in Finland. As described in the research plan, devices from two rounds of fabrication have been characterized, showing consistent characteristics.

The device has already been optimized to operate in a nearly Kerr-free regime, but even better performance can be achieved with future designs. The bandwidth of 17 MHz is only a technical limitation of our setup. We believe that the device can yield a potential rate above giga entangled bits per second. Future experiments could also address the problem of storing an idler photon and measuring the correlations when the signal photon arrives.

6. Scientific publishing and other reports produced by the research project

The following publications have been produced during this project, with support from MATINE acknowledged.

Theory paper: R. Di Candia *et. al.* Two-Way Covert Quantum Communication in the Microwave Regime, PRX Quantum **2**, 020316 (2021)

The paper presents a very extensive theoretical analysis of the phenomenon of quantum illumination as part of the general framework of quantum covert communication. We introduce a protocol for covert communication between two parties using phase modulation, with the carrier signal embedded in the noise from the environment. We find that quantum correlations can enhance the signal-to-noise by at most 6 dB. A schematic for the receiver, using cryogenic technologies, is provided. Our protocol advances a new quantum communication paradigm using backscattering concepts adapted to superconducting circuits in the microwave regime.

Proceedings paper: T. Korkalainen *et. al.* Vacuum-induced correlations in superconducting microwave cavity under multiple pump tones, AIP Conference Proceedings **2362**, 03001 (2021)

This is a theoretical conference paper where we study numerically the dynamics of the entangling correlations generated in a parametrically pumped system, in the more unusual case when the pump is modulated. This is a first step toward understanding and designing a distributed radar detection system, where multi-mode entanglement is generated in the microwave range. By analyzing pairwise correlations between three frequency bands in the double and triple pump modulation we observe that triple pumping leads to stronger correlations than double pumping. Thus, pairwise squeezed tones provide a new, richer quantum resource for detection.

Experimental paper submitted: M. R. Perelshtein *et. al.* Broadband continuous variable entanglement generation using Kerr-free Josephson metamaterial, arXiv: 2111.06145 (2021).

This was the core of the project, and the results have been reviewed in this report.

Outreach paper: G.S. Paraoanu *et. al*. Europhys. News **51**, 18 (2020).

Here we review for non-expert physicists the experimental progress in the dynamical Casimir effect, by giving a different more elementary derivation based on the density of states. This is one of the founding stones of quantum illumination, onto which the quantum radar ideas are based. We believe that this outreach paper will help raise the interest in the physics community and also outside it regarding applications of continuous variable entanglement.