Experimental Evidence for the Continuity of the Electromagnetic Field: Contradictions between a Quantum-Mechanical Model of the Photon and the Detection Principle of FMCW Measurements

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ABSTRACT

This article presents a study that provides robust evidence supporting the continuity of the electromagnetic field, while highlighting contradictions between a quantum-mechanical model of the photon and the detection principle of Frequency-Modulated Continuous Wave (FMCW) measurements. The primary objective was to investigate the detection method of FMCW for extremely weak signals, reaching energy levels akin to photons. Through thorough examination, significant contradictions emerged, favoring classical field theory and challenging the notion of electromagnetic field quantization. To strengthen this claim, a carefully designed experiment was conducted to measure sub-photon energy levels. The comprehensive analysis of both theoretical insights and experimental data presents compelling evidence, demonstrating the untenability of a quantized model for the electromagnetic field. These findings have profound implications for understanding the continuity of the electromagnetic field, prompting further exploration in this field of research.

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Introduction

Frequency-Modulated Coherent Wave (FMCW) detection is a well-established measurement technique used in many fields, such as optical coherence tomography and LiDAR. While FMCW is explained by classical field theory[1], understanding its operation at the quantum-mechanical level presents challenges. One significant challenge in FMCW LiDAR is that it has the capability of detecting single photons, but the detection is based on frequency, which changes over time. This raised the question of whether a photon can change its frequency over its course[1]. Another study that delves into the exploration of FMCW detection in the quantum regime can be found in[2].

In order to explore the detection principle of FMCW and address pertinent questions, the article is organized as follows: firstly, a comprehensive overview of the detection principle of FMCW is provided, along with an explanation of the underlying mathematical concepts. Subsequently, both the classical and quantum-mechanical perspectives are examined. The article then highlights the limitations of a quantum-mechanical model with a quantized electromagnetic field in explaining the measurement principle. Notably, it demonstrates that classical field theory not only offers a complete description of the measurement outcome, but also mathematically establishes the untenability of a quantum model.

Detection principle of FMCW

Figure 1 illustrates a typical setup for FMCW LiDAR detection. The system consists of a swept-source laser, which is divided into two paths: the local oscillator (LO) and the signal path. The optical signal transmitted through the signal path interacts with a target and subsequently combines with the LO signal on a balanced detector (BD). The resulting signal is then amplified using an electrical amplifier before being digitized and processed. Additionally, to mark the initiation of the chirps generated by the laser system, a trigger signal is provided by the laser, which facilitates the capture of the time series of measurements at the detector.

At the detector, the field strengths of the local oscillator (LO) and the signal reflected from the target combine, resulting in their classical observation. The detector measures the intensity of the combined signals, which corresponds to the absolute square of the field strength. Due to the sweeping nature of the laser and the round-trip propagation time of the signal to and from the target, the frequencies of the combined signals are not identical. As a consequence, a beat signal is generated, characterized

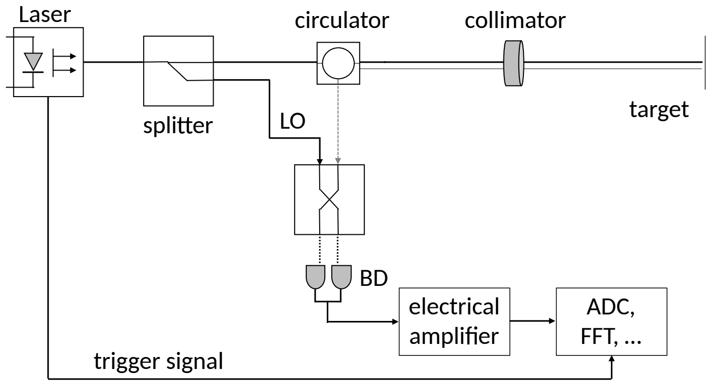

Figure 1. Typical setup for Frequency-Modulated Continuous Wave (FMCW) LiDAR detection

by a frequency significantly lower than the optical frequencies of the laser signal, and it is sampled by the detector. Typical sampling frequencies utilized in FMCW LiDAR systems fall within the range of 1GHz. The energy of the squared field strength can be quantified in terms of photons and the resultant signal can be mathematically represented as follows:

$$i_{bd}(t) = \frac{2\eta q}{T}\sqrt{N_{LO}N_{sig}}\cos(2\pi\kappa\tau t + \phi) + i_s(t) \tag{1}$$

In Equation 1, the variable κ represents the linear chirp of the laser with its associated chirp rate, τ corresponds to the round trip time, η denotes the quantum efficiency of the detector, q signifies the elementary charge, ϕ represents a fixed phase, and N_{sig} and N_{LO} denote the number of photons in the signal and local oscillator, respectively. The signal is subject to noise $i_s(t)$, primarily stemming from the shot noise of the local oscillator.

For an LO photon flux much larger than the signal flux, $i_s(t)$ is a Gaussian random process with zero mean and variance

$$\sigma^2(t) = \frac{2\eta q^2}{T}BN_{LO} \tag{2}$$

Equation 1 elucidates how the beat frequency is determined by a target located at a distance d, c represents the speed of light.

$$f_{beat} = \kappa\tau = \kappa\frac{2d}{c} \tag{3}$$

The extraction of distance information from the detected signal in the time domain can be achieved through the utilization of a Fourier transformation. To facilitate this process, the signal is multiplied by a window function, such as Hamming or Hanning, before undergoing Fourier transformation. The resulting frequency spectrum reveals the detected beat frequency, which directly corresponds to the distance information. It is important to note that for comprehensive coverage, the application of up- and down-chirps is employed to detect moving targets. This approach allows for the calculation of the frequency shift resulting from the Doppler effect in relation to the distance information. However, in the case of static targets located at fixed positions, the distinction between up- and down-chirps becomes inconsequential, and a single chirp is sufficient for accurate measurements.

The determination of the number of detected photons in the signal path can be achieved using the detected signal[1]. By averaging a large number of power spectra, the average of the resulting power spectra associated with the signal is directly proportional to the quantity $N_{LO}N_{sig}$, while the averaged noise floor is proportional to N_{LO}. Consequently, in a system limited by shot noise, the normalized averaged power spectra exhibit a noise floor value of 1. The value corresponding to the signal frequency in the normalized power spectra therefore represents:

$$sig_{fourier} = \eta N_{sig} \tag{4}$$

In Equation 4, η denotes the quantum efficiency, and N_{sig} represents the number of photons in the signal. The normalized signal strength in the shotnoise-limited system therefore corresponds to the number of detected photoelectrons plus 1.

In real FMCW systems there are further noise sources. While for strong LO signals the detector noise is less important, the noise of the electrical amplifier is not really negligible. Therefore, when detecting very small signal strengths, the following procedure can be followed: First, the average noise power of the amplifier is determined by disconnecting both LO and receive signal from the balanced detector. Then the average noise power of the LO is determined by connecting only the LO signal to the balanced detector. The noise power of the LO is determined from the now averaged noise power, minus the noise power of the electrical amplifier. To determine the signal strength in units of photon quanta, the obtained power spectra are averaged, from which the averaged noise of the electrical amplifier is subtracted, and the signal thus obtained is normalized by the LO noise. If further noise sources occur, they show up as a noise floor above the value "1". The signal value in photoelectrons is the signal value above that overall noise floor.

In automotive FMCW detection systems, the power of the signal reflected from targets at a distance is typically scarce. These systems must be engineered at the very limits of physics to meet automotive requirements in terms of achievable range with a certain probability of detection. It is commonly accepted that, for such systems, a probability of detection of nearly 100 percent can be achieved with as few as 25 received photoelectrons. The Python script "sim_fmcw_N25.py"[3] depicts the simulation for an ideal shot-noise-limited detection scenario with 25 photoelectrons in the receiving path. Signal and shot noise are already in their normalized form. In the simulation, windowing has been omitted since the simulated frequency is precisely centered within a bin, thus eliminating any potential leakage.

Figure 2 (left) displays the averaged power spectrum obtained from the simulation, and shows the power spectrum of a simulated single measurement with 25 received photoelectrons, the beat frequency occuring at $f = 1000/T$.

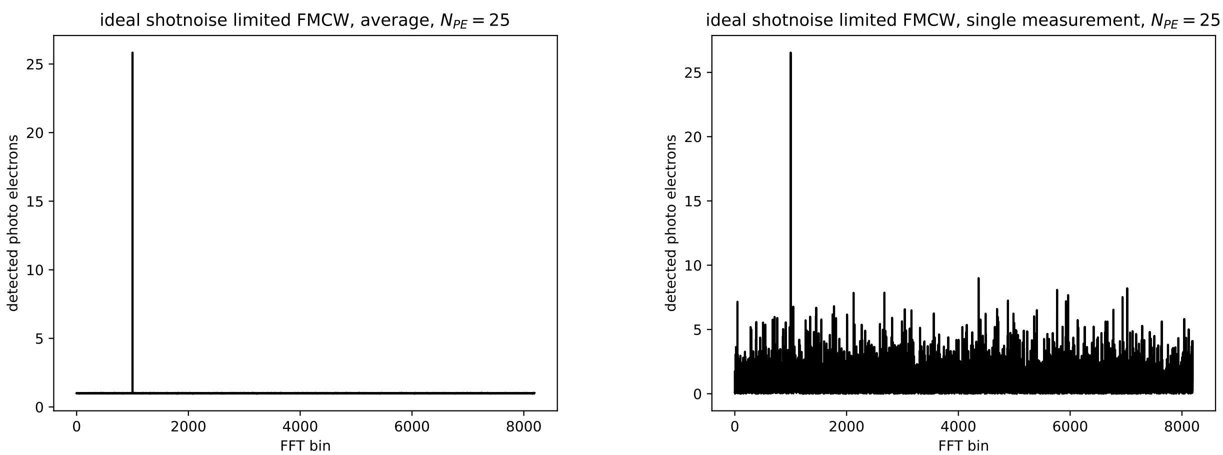

Figure 2. Left: simulated averaged, normalized power spectrum for 25 received photoelectrons (shot noise limited system) - the averaged, normalized noise floor equals to 1 and the signal is elevated by the noise floor; Right: simulated power spectrum for a single measurement (shot noise limited system) with 25 received photoelectrons

The simulation employed a measurement window of 16384 arbitrary units, corresponding to a sample rate of 500MSamples/s and a measurement time of $32.768\mu s$. The signal added to the noise is given by the equation:

$$\text{signal}(t) = 2\sqrt{\frac{N_{PE}}{\text{fftlen}}}\sin(1000 \cdot 2\pi f t) \tag{5}$$

Classical interpretation of FMCW detection

The classical view is elegantly straightforward: by applying equation 1, one can readily convert energy units into quantities of photons and photoelectrons. This approach solely relies on utilizing the number of photons or photoelectrons from the local oscillator and signal as energy units, without delving into the intricate quantum-level mechanisms that come into play when the count of received signal photons reaches single-unit values.

Quantum-mechanical interpretation of FMCW detection

As soon as one attempts to explain the detection principle using quantum-mechanical interactions, complications arise. Let us begin by reviewing the quantum-mechanical perspective of propagation and detection, employing a somewhat simplified model. A large number of 'photons' is emitted from the collimator towards the target. Due to the Gaussian beam shape, a considerable portion of these photons will reach the target, even at significant distances. When considering a Lambertian target, the reflected photons will be uniformly spread in a hemisphere facing the collimator. However, due to the relatively small surface area of the collimator compared to the surface area of the hemisphere with radius d (where d represents the distance to the target), the probability of a 'photon' striking the collimator is quite low. Let us further simplify the coupling efficiency from the aperture to the detector, assuming it to be perfect, meaning that all photons that pass the aperture of the collimator will reach the detector, resulting in N_{PE} photoelectrons being detected. For the purposes of illustration, let us assume $N_{PE} = 25$ within a measurement interval of $32.768\mu s$. The detection events in many such FMCW measurements follow a Poisson distribution, expressed by the equation

$$P(\lambda, x = k) = \frac{\lambda^k e^{-\lambda}}{k!} \tag{6}$$

where lambda is equal to 25. The variable 'k' represents integer values indicating the number of detection events per measurement interval, such as 0, 1, 2, and so on. It's important to note that in FMCW, a measurement interval refers to a series of consecutive measurements rather than a single detection. The time between two consecutive events is governed by the equation $t = -\log(\text{rand})/N_{PE}$, where *rand* denotes a uniform random distribution in the interval $[0, 1]$. Therefore, if we were to replace the balanced detector with a photon counter, on average, 25 detections per measurement interval would be registered, with an average time of $1.31\mu s$ between two detections.

To further simplify the discussion, let's consider FMCW measurements with a rate of 25 measured photoelectrons per interval, while utilizing a balanced detector. Let's assume a measurement interval of $32.768\mu s$ and a sample rate of $500 MSamples/s$. The outcome of such a measurement would correspond to the result depicted in Figure 2 (left). Similarly, the outcome of averaging the relative power spectrum would resemble Figure 2 (right). When the number of averages increases significantly, the noise floor of the relative power spectrum converges to exactly one, while the signal becomes $1 + N_{PE}$. Since Fourier transformation is a linear function, if the relative noise floor reaches precisely one, then the Fourier coefficient of the signal, without any noise, becomes exactly N_{PE} at the signal frequency and exactly zero at all other frequencies. A Fourier transform that appears as a delta pulse in the Fourier domain corresponds to a pure sine function in the time domain. However, out of the 16,384 detections per measurement interval, only 25 detections contribute to the signal if they would originate from discrete detections caused by a quantized field. It is impossible to construct a sine wave with only 25 values for a signal length of 16,384 values, which presents a contradiction (contradiction 1).

Quantum mechanics attributes the Poisson distribution of photon events to the inherent uncertainty principle. Let's consider a scenario where the target is static and non-moving. In this case, the frequency of a photon sent to the target will remain unchanged until it reaches the detector. If the number of photons reaching the detector decreases, according to the uncertainty principle, the arrival time uncertainty should increase, resulting in statistically different arrival times for photons of a specific frequency. Since the beat frequency depends on the frequency of the local oscillator and the frequency of the signal photons at a given time, an increased uncertainty in arrival times should lead to a broadening of the frequency peak. However, such broadening is not observed in actual measurements, which presents a contradiction (contradiction 2).

The photons emitted in the FMCW system follow a chirp, exhibiting a frequency ramp. Consequently, between two consecutive samples, the frequency of the local oscillator has changed. As the beat frequency relies on a constant frequency difference, the frequency of the signal photons must have also changed. Thus, different detections must originate from distinct signal photons since a photon maintains its frequency throughout its propagation. Therefore, even if the signal content of the FMCW signal is extremely low (as exemplified in[1] with approximately 2 photons), the energy comprising this FMCW signal is derived from numerous 'photon sources'. This situation presents another contradiction since, according to quantum mechanics, a detection must occur instantaneously and cannot be distributed over multiple instances (contradiction 3).

The signal measured at the detectors of the balanced detector represents an interference signal. Upon closer examination of equation 1, it becomes apparent that the amplification of the signal in the quantum regime lacks an explanation. The term $N_{LO}N_{sig}$ indicates the interference between a small number of signal photons and a larger number of local oscillator photons. This phenomenon remains unexplained within the framework of quantum mechanics, leading to a contradiction (contradiction 4).

The most plausible explanation is that the electromagnetic field is not actually quantized, and the numerous 'photons' that reach the target are radiated as a conventional electromagnetic field into the hemisphere. A portion of this energy, equivalent to the relative size of the collimator aperture in relation to the surface area, interferes with the field generated by the local oscillator and constitutes the FMCW signal. If this hypothesis holds true, it should be feasible to detect less than one 'photon' per measurement interval. However, measuring less than one photon would introduce another contradiction to the concept of a quantized electromagnetic field (contradiction 5).

The team of authors in[1] overlooked this crucial detail: the presented measurement series involves the measurement of 2 photons within a single measurement interval. However, the number of measurement data points per spectrum is not specified. If the spectrum is not shortened, there should be a total of 2*328 data points per measurement series, of which 8000 were recorded. It would have been intriguing to examine shortened measurement series, such as those containing only 164 points. In such a scenario, according to the conventional equation, only 0.5 photons would be detected per measurement interval.

The experimental setup in this work aims to provide evidence supporting contradiction 5, which suggests that the detection of less than one photon per measurement interval contradicts the notion of a quantized electromagnetic field.

Materials and Methods

The experimental setup, corresponding to a standard setup as depicted in Figure 1, is based on Bridger's swept source, which produces frequency sweeps (power 3.2mW at 1550nm) and triggers a detection board. The laser source is utilized as the swept source. For detection, a balanced detector (Thorlabs PDB570C) with a responsivity of $R = 1A/W$ and a quantum efficiency of $\eta = 0.8$ at 1550nm is employed, incorporating an integrated electrical amplifier. The amplified analog signal is captured using a National Instruments (NI PXIe-1082, NI PXIe-5763) DAQ system. The collimator used is a Thorlabs C40APC-C, and the targets consist of sample targets with reflectivity values provided by LabSphere (uncalibrated). All other components are standard.

The frequency transition rate of the sweep is specified at 100GHz/s, generating two sweeps in both directions lasting approximately 35µs each. The sampling rate is set to 500MSamples/s.

Accurate preparation of the test system is crucial when measuring extremely low signals. Signal detection requires averaging over multiple measurements. Initially, targets were positioned at two different distances (measured: 6.8m and 11.1m) and aligned with the collimated beam. The beam was then focused on the more distant target. To achieve a detection level below 4 photons using a target with 50% reflectivity, various attenuators were inserted before the collimator. Fine adjustment was carried out by defocusing the collimator, and an attenuator with approximately 11dB attenuation was chosen. Subsequently, the target was replaced with targets of 5% (distance d_1) and 10% reflectivity (distance d_2), and long-term measurements commenced. To minimize speckle effects, the targets were slowly rotated during the measurements. To mitigate undesired noise, the optical gain was minimized, and the detection was set to the "Balanced" mode. This configuration was chosen instead of auto-balancing, as auto-balancing introduced additional noise that could not be reduced through averaging. The laser source generated up and down sweeps while triggering at each start. The acquisition system recorded 44,000 samples for each up and down sweep. From the recorded data, 16,384 samples were selected for each ramp, focusing on a region where the laser was clearly locked.

Each measurement underwent windowing with a Hamming window, followed by FFT calculation. To mitigate relative intensity noise (RIN), each FFT was normalized by the energy in FFT bins 1000 through 5000.

The obtained signal contains inherent noise originating from the system and the electrical amplifier. To mitigate this noise, the measurements were processed by subtracting the averages of the signal obtained from the balanced detector without an optical signal. This subtraction was performed over approximately 10,000 samples.

In order to determine the signal level of the local oscillator, additional averages were taken with the receive path disconnected. These averages, also comprising around 10,000 samples, were utilized for reference in the analysis.

The number of received photons per frequency band was determined by normalizing the averaged signal with the average local oscillator (LO) signal. However, the resulting signal still contains other sources of noise, such as phase noise from internal reflections of the circulator and collimator. While matching the optical path lengths can minimize this noise, the system yielded satisfactory results without this adjustment.

Results

Acquired data, along with the corresponding signal processing, can be found in Dataset 1,[4].

Initially, targets with a reflectivity of 50% were positioned at distances $d_1 = 6.8$m and $d_2 = 11.1$m. The collected data was then utilized to determine the optical path offset of the collimator. Additionally, the true value of the frequency transition rate, which was found to deviate slightly from the specified value, was determined at 1.06×10^{14}Hz/s.

Figure 3 displays the averaged power spectrum obtained from 100,000 samples collected while measuring low-reflectivity targets. Although the signal peaks are weak, they are discernible.

After removing the amplifier noise, the power spectrum shown in figure 3 is normalized with respect to the local oscillator (LO).

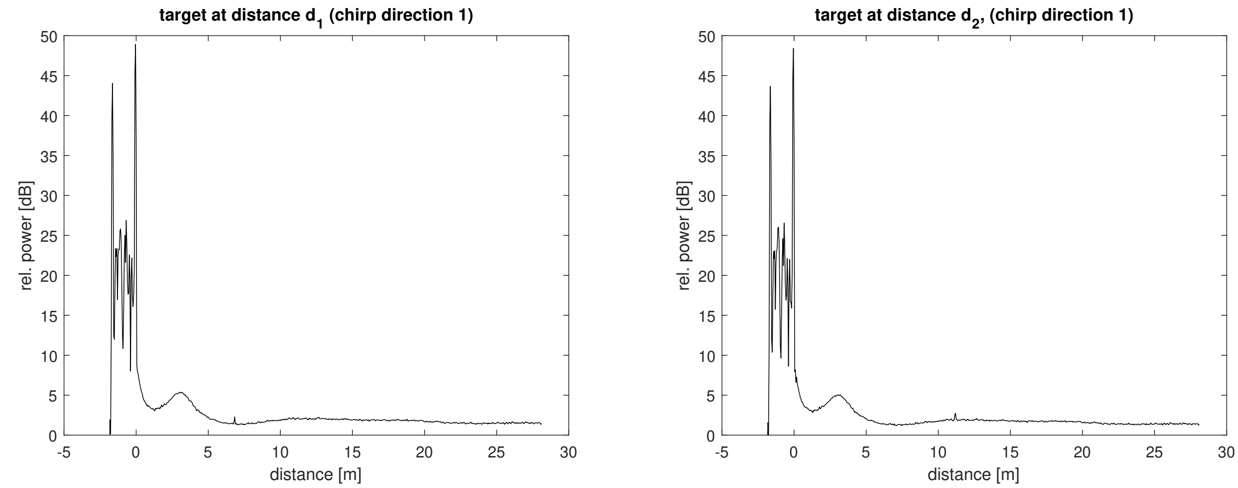

Figure 3. The figure illustrates the average of 100,000 samples, with amplifier noise removed and normalized to the level of the local oscillator (LO). Clear and discernible small peaks can be observed at distances $d_1 = 6.8m$ and $d_2 = 11.1m$..

Figure 4 provides a zoomed-in view. At distance d_1, the target position is precisely centered within the frequency bin. However, at position d_2, this alignment is not observed. Since the measurements for the target at distance d_2 are solely utilized to establish the reference noise level for the target at distance d_1, this misalignment does not pose a problem.

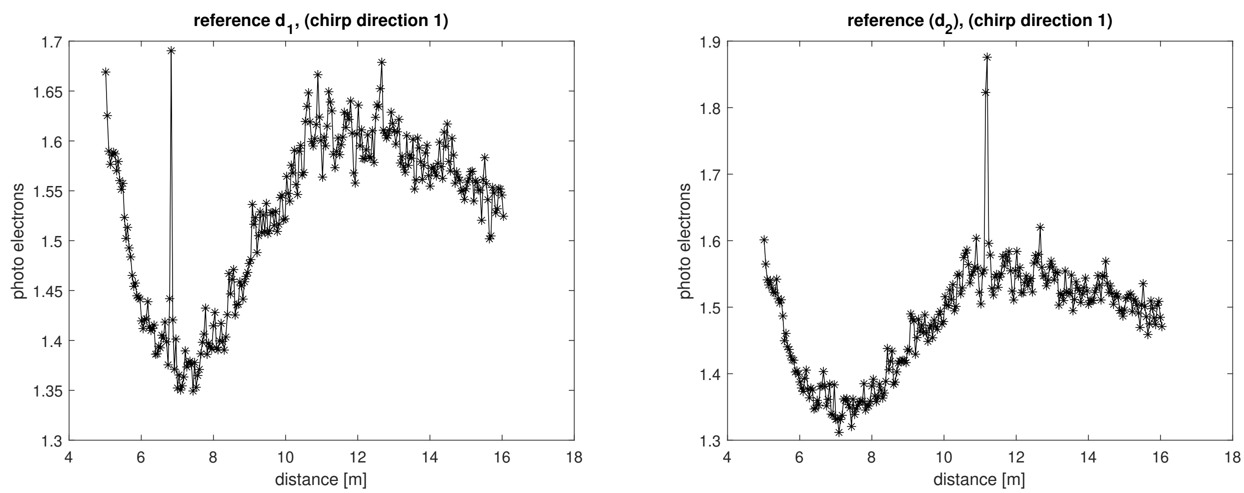

Figure 4. Zoom into signal levels of Figure 3 for target positions d_1 and d_2. The target at d_1 is well positioned, energy is centered at a bin. The target at d_2 is not well centered and the energy is spread over two bins.

Figure 5 depicts the signal level difference between measurements for target distance d_1 and target distance d_2. Subtracting these measurements yields the relative signal level compared to the noise floor, resulting in improved noise performance. As the local oscillator contribution cancels out during the subtraction, the relative signal level in decibels (dB) can be utilized to accurately calculate the received signal power, in conjunction with the noise floor value:

$$N_{PE,signal} = N_{PE,noise}(10^{\frac{signal_{dB}}{10}} - 1) \quad (7)$$

The presented results correspond to the first chirp direction (likely the up chirp), and similar results are observed for the other chirp.

Here, a measurement interval of $32.768\mu s$ was used to determine the number of photoelectrons per interval. Additionally, it is possible to examine smaller measurement intervals. When considering these shorter intervals, it is important to account

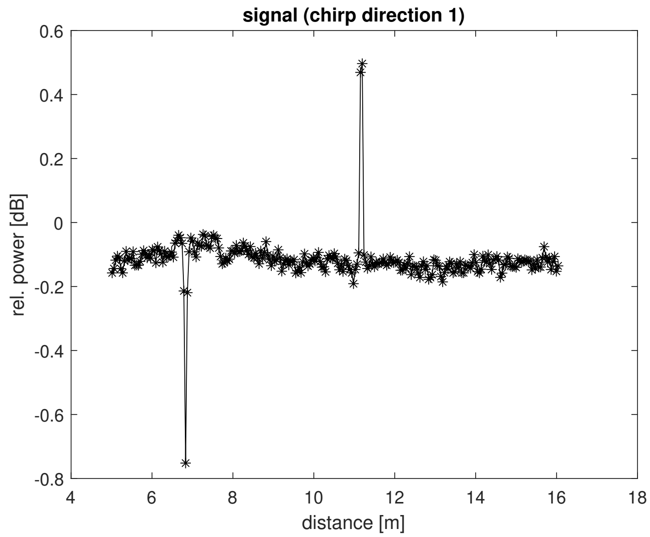

Figure 5. Zoom into difference of signals $d_2 - d_1$

for the changing laser power during the chirp. The local oscillator must also be recalculated for each specific interval, and averaging can only be performed after this step. Notably, the number of received 'photons' is 25% higher due to an 80% quantum efficiency. The remaining variance in the noise after long-term averaging was used to determine the confidence level. The outcomes for shorter measurement intervals are presented in Table 1.

Table 1. Measured signal levels of the normalized (difference) power spectrum in dB and received number of photoelectrons N_{PE} and 'photons' N per measurement interval for a 5% target at distance d_1 and different measurement intervals T. The reference level is the noise floor of 1.387 photoelectrons at target distance d_1, see Figure 4.

	Reference level	$T = 32.768\mu s$	$T = 16.384\mu s$	$T = 8.192\mu s$	$T = 4.096\mu s$
signal / dB	-	0.7916	0.4120	0.2156	0.0870
σ_{dB}	-	0.0231	0.0160	0.0097	0.0068
confidence / σ	-	34.3	25.8	22.2	12.8
N_{PE}	1.387	0.2773	0.1380	0.0706	0.0281
N	-	0.3466	0.1725	0.0882	0.0351

Discussion

The conducted experiment demonstrates that FMCW is capable of detecting signal thresholds significantly below one photon per measurement interval. While the signal-to-noise ratio in a single sample series may be low, extensive averaging effectively reduces noise and significantly enhances the visibility of these minute signals, providing high statistical significance.

It has been previously demonstrated that Fourier transformations cannot accurately represent photoelectron numbers in the low-digit range. However, this non-representability becomes even more pronounced when the measured photoelectron count falls significantly below 1, despite attempts to mitigate this through averaging. Table 1 presents an average of 0.0281 photoelectrons received per detection interval of $4.096\mu s$. This value is smaller than the expected value of $0.2773/8$. Taking into account the increased noise associated with smaller detection windows, we will consider a value of $0.2773/8 = 0.035$ photoelectrons per detection interval. According to Equation 6, we anticipate the following average number of detected photoelectrons per 800,000 measurement intervals: 772,484 measurements without any detection, 27,037 measurements with one detection, 473 measurements with two detections, and 6 measurements with three detections. As a result, the majority of detections in a quantized photon model are zero, with the remaining primarily consisting of measurements with only one detection. As mentioned earlier, the linear Fourier transform enables the separation of signal and noise averages. It is evident that the Fourier transform of a single value in the time domain is uniformly distributed across the frequency range and does not yield any peak values. Upon examining the data from FMCW measurements, it becomes apparent that the propagation of energy cannot be adequately explained by a quantized field.

The data indicates that the energy flow is continuous, yet a photon counter would still register detections following a Poisson statistical distribution. This observation suggests the presence of an accumulation process during detection. The discrete absorption of energy packets in these detections is an inherent aspect of quantum mechanics and initially led to the development of the concept of 'photons'. This discrepancy presents yet another contradiction (contradiction 6). Clearly, there is an accumulation process at play, and understanding its underlying cause requires further investigation and research.

In the work by Winzer et al.[2], the authors acknowledge that the term "photon" serves as an abbreviation for the discrete quanta in which energy can be absorbed by matter. They recognize that classical electromagnetic field quantities are combined with Maxwell's equations, and the resultant sum is what is detected. This understanding aligns with the notion that the electromagnetic field itself is not inherently quantized. Unfortunately, the authors deviate from this understanding by erroneously applying the concept of uncertainty where it is not applicable, as discussed earlier.

This study provides compelling evidence challenging the existence of a quantized electromagnetic field and the conventional understanding of photons as discrete entities transmitted and detected in their entirety. Instead, it suggests that the electromagnetic field is continuous, while the release of energy and its detection occur discretely in packets of energy equal to $h\nu$. The propagation of energy, however, remains continuous, and the detected energy does not necessarily originate from the same energy packet released. Rather, detected energy packets accumulate over time. In essence, classical field theory adequately describes the observed propagation. Maxwell's equations provide a comprehensive framework for describing the propagation of fields and can account for the propagation of any released energy within the electromagnetic field. The continuity becomes mathematically more than clear. In equation 5 the field energy is evenly distributed in the measurement interval and only this allows the constant course of the beat signal. A simple simulation for FMCW signal processing of an ultra-low receive signal can be found in script "sim_fmcw_process.py" ([3]). Considered noise sources are local oscillator noise, noise of the electrical amplifier and ADC noise. Detection and digitalization are modelled as quantized processes. Phase noise and parasitic reflexes were not modelled. All parameters were set to be similar to the performed experiment. Local oscillator power per detector of the balanced detector was set to $100\mu W$ each. Quantum efficiency η was set to 0.8. TIA gain was set to 5000V/A, TIA noise to $1pA/\sqrt{Hz}$. ADC was set to $2Vpp$, sample rate $500MSamples/s$, SNR to $-72dBFS$.

Numerous experiments provide evidence for the discretization of matter/field interaction in both emission and detection processes. However, none of these experiments directly demonstrate discrete energy transport within the field. The conclusion of discrete energy transport has traditionally been a theoretical assumption without strong experimental support. It is important to acknowledge that this assumption can be easily derived from the misleading characteristics of the Poisson distribution. In experiments involving slits, when 'photons' are directed towards the slit(s), they result in detections on the screen. However, the observed effect is an optical illusion. To explain this assertion, let us consider a hypothetical scenario. Imagine a fiber where a continuous electromagnetic field would generate 'photons' at a rate of two photons per interval. If a 50/50 splitter is placed in the optical path, the rate at the output of each branch would be one photon per interval. Nevertheless, the overall rate across both outputs would remain two photons per interval. The same principle applies to the slit experiments. While the electromagnetic field after the slit(s) propagates according to Maxwell's equations, and the field strength at the screen precisely matches the calculations according to classical field theory, the overall counting rate on the screen will be the same as at the slit because the energy remains constant. However, this does not imply that a 'photon' physically passes through the slit(s) with a wave function collapsing at the screen. Instead, energy passing through the slit(s) distributes in space, and detections on the screen result from energy accumulation at specific screen locations. The concept of discrete energy quanta detected at random screen positions due to a collapsing wave function is a misleading illusion caused by the properties of the Poisson distribution.

Additionally, it is important to clarify that the focus of this study is not on those experiments but rather on providing an alternative explanation for the detection principle of FMCW based on the notion of 'photons', which is shown to be inadequate. While it is plausible that not every argument put forth in this work will withstand scrutiny, any attempt to refute the falsification of a quantized field would require robust and compelling arguments that invalidate or disprove the contradictions highlighted. Moreover, for the model of a quantized electromagnetic field to be tenable, it must comprehensively account for the detection principle of FMCW measurements without encountering any contradictions. A model claiming to accurately describe reality must account for all aspects of reality. Even a single counterexample can undermine its validity. To the best knowledge of the author, there are no prior experiments that surpass the limit of quantized detection, except for FMCW measurements relying on coherent detection principles in the frequency domain. Therefore, the assertion of a quantized field in these experiments is already questionable from the outset. Attempting to measure phenomena smaller than the resolution of our instruments is akin to employing a microscope with a limited magnification power and confidently concluding that no objects exist beyond its observable range.

Conclusions

The concept of a 'photon' as a discrete wave packet is not viable, as it contradicts the mathematical foundations of the measurement principle of FMCW measurements. Moreover, experimental evidence showcasing the detection of sub-photon energy levels with a high level of statistical confidence directly invalidates this model. Experimental data indicate a continuous field where classical field theory should be applied. The term 'photon' then is simply an abbreviation for the discretization of energy during emission or reception. This idea was previously discussed in[2]. Unlike previous works, this study does not attempt to force reality into the concept of discrete 'photons', but rather investigates its details. It can be considered as an attempt to establish a connection between classical field theory and quantum mechanics. Although it suggests a correction to one of the fundamental tenets of quantum mechanics, this study does not address all the questions that arise from its findings. The interaction between fields and matter, particularly the mechanisms through which a continuous field can elicit detections relying on quantized energies, remains a subject of ongoing research.

The implications of considering a continuous electromagnetic field in the quantum regime are numerous and far-reaching. Several quantum experiments, which currently rely on complex and sometimes counter-intuitive explanations, such as those involving anti-causality[5], could be easily elucidated. The interaction between matter and the electromagnetic field would become inherently local, and phenomena like "spooky action at a distance" would no longer have a place in the description of 'photons'. Entangled 'photons' could be understood as correlated fields with predetermined polarization from the initial state. These implications highlight the potential for a more intuitive and comprehensive understanding of quantum phenomena by embracing the concept of a continuous electromagnetic field.

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Additional information

Conflicts of interest

The author declares no conflict of interest.