Do Propagating Lightwaves Contain Photons?

Reinhold Noe

UNIVERSITÄT PADERBORN
Die Universität der Informationsgesellschaft

Introduction

- Gehrtsen, Kneser, Vogel, “Physik”, 13. Edition, Springer-Verlag 1977 (in German). – Translation from 10.6.1, p. 406: „Beside its wave properties, which express themselves in diffraction, interference and polarization, light also has a particle aspect, which comes into play ~~especially~~ at emission and absorption.”
- B. Saleh, “Photoelectron Statistics”, Springer-Verlag, Berlin Heidelberg New York, 1978 – “Photoelectron”, even though many would say he talks about “photons” all the time.
- All “proofs” of photon existence in wave are proofs of photon detection/emission!

But:

- Piazza, L., Lummen, T., Quiñonez, E. *et al.* “Simultaneous observation of the quantization and the interference pattern of a plasmonic near-field”. *Nat Commun* **6**, 6407 (2015) – Not in the same portions of light at the same place and time!
- Jin, R.B. *et al.* “Spectrally resolved NOON state interference“, 10 April 2021, https://arxiv.org/abs/2104.01062v3 – Interference of frequency-doubled signal can be explained by wave equation $f_{pump} = f_{signal} + f_{idler}$. Particle equation $W_{pump} = W_{signal} + W_{idler}$ confirms this but is not needed!
- https://sciencedemonstrations.fas.harvard.edu/presentations/single-photon-interference – No photon interference is observed. Photons are only detected!

Do propagating lightwaves contain photons?

A lightwave is a propagating wave. As such it is understood to be an observable quantity with a sinusoidal temporal-spatial behavior. That is only the electromagnetic field, which obeys Maxwell's equations. <u>If photons are contained in lightwaves they must have fields, identical ones if belonging to the same mode of the wave.</u>

Overview

- Motivation
- Zero point fluctuations
- Coherent optical receiver
- Direct detection receiver with optical preamplifier
- Energy conservation
- No sub-photon energy, no single-photon behavior of wave
- Discussion
- Summary

Zero point fluctuations can explain shot noise ...

Shot noise can be explained either way:

- Semiclassical theory: Poisson distribution of photoelectrons has one-sided photocurrent power spectral density (PSD) $\boxed{2eI}$.
- Zero point fluctuations interfere with signal and cause shot noise PSD $\boxed{2eI}$.

Let us define field such that power is $P := |\mathbf{E}|^2$. Observation time is $\tau = 1/B_o$.

Zero point fluctuations have mean energy $W = P\tau$ equal to $hf/2$ per mode:

$$\mathbf{E}_0 = (u_{0,1} + ju_{0,2})\underline{\mathbf{e}}_1 e^{j\omega t} \qquad \sigma^2_{u0,1} = \sigma^2_{u02} = hf/(4\tau) \qquad |\underline{\mathbf{e}}_1| = 1$$

Signal field: $\mathbf{E}_S = \sqrt{P_S}\,\mathbf{e}_1 e^{j\omega t}$ Total field: $\mathbf{E}_S + \mathbf{E}_0$

Expected number of photoelectrons: $n_{S+0} = |\mathbf{E}_S + \mathbf{E}_0|^2 \tau/(hf)$

$$= \left(|\mathbf{E}_S|^2 + 2\,\mathrm{Re}\left(\mathbf{E}_0^+\mathbf{E}_S\right) + |\mathbf{E}_0|^2\right)\tau/(hf) \approx \left(P_S + 2u_{0,1}\sqrt{P_S}\right)\tau/(hf)$$

Mean: $\langle n_{S+0}\rangle = \frac{P_S\tau}{hf}$ Variance: $\sigma^2_{nS+0} = \frac{hf}{4\tau}P_S\frac{2^2\tau^2}{h^2 f^2} = \frac{P_S\tau}{hf} = \langle n_{S+0}\rangle$

one-sided electrical bandwidth

$$I = RP = \boxed{\frac{e}{hf}P} \qquad \langle I_{S+0}\rangle = \langle n_{S+0}\rangle\frac{e}{\tau} \qquad \sigma^2_{IS+0} = \sigma^2_{nS+0}\frac{e^2}{\tau^2} = \boxed{2e\cdot\boxed{\frac{e}{hf}P_S}}\cdot\boxed{\frac{1}{2\tau}}$$

... and photons in the wave would double shot noise.

- Since shot noise is taken into account by zero point fluctuation field $\mathbf{E}_0$ we expect $\left|\mathbf{E}_S\right|$, P_S to be constant.
- If the lightwave contained n photons in time τ then their expectation value would be $\langle n\rangle = P_S\tau/(hf)$. One might assume that $\langle n\rangle$ needs to be integer. But non-integer $\langle n\rangle = 0.01\ \ldots\ 0.1$ are routinely reported in QKD.
- Non-integer $\langle n\rangle$ requires more than 1 value n and is expected to change the variance of photoelectrons.
- Default assumption is that n and $\mathbf{E}_0$ are independent and n is Poisson-distributed with variance $\sigma_n^2 = \langle n\rangle$.
- Variance of a sum of independent random variables is sum of their variances.
- Total variance of photoelectrons is $\sigma_{nS+0}^2 + \sigma_n^2 = \langle n_{S+0}\rangle + \langle n\rangle = 2\,P_S\tau/(hf)$! ϟ

  Assumption of (Poisson-distributed) photons in wave doubles shot noise!
  This is wrong! It is easily falsified by a shot noise measurement.

⇒ There are no photons in the lightwave!

Signal and shot noise in coherent optical receiver

$$\mathbf{E}_S = \sqrt{P_s}\,\mathbf{e}_1 e^{j\omega t} \qquad \mathbf{E}_{LO} = \sqrt{P_{LO}}\,\mathbf{e}_1 e^{j\omega t}$$

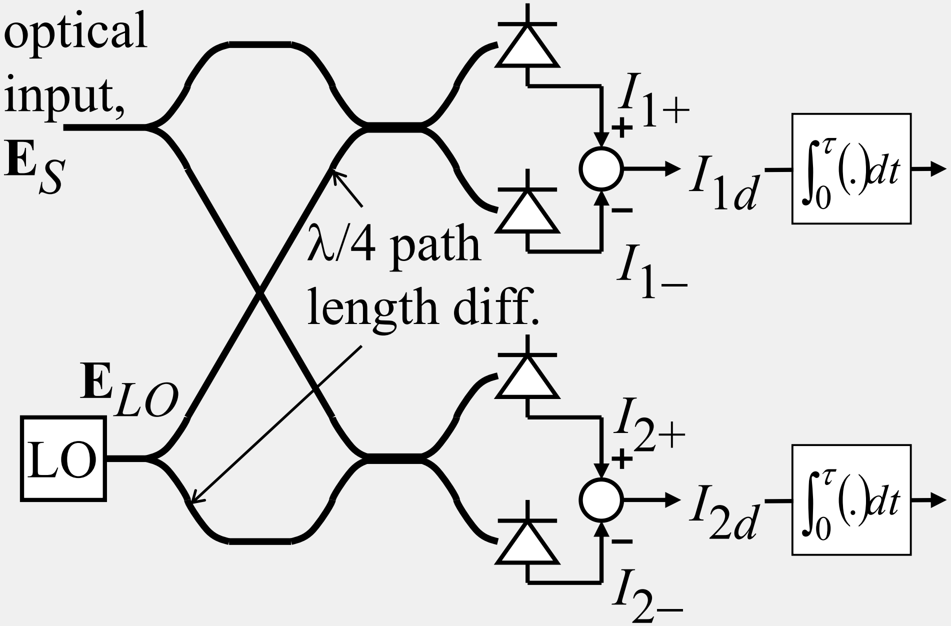
$$P =: |\mathbf{E}|^2 \qquad \langle I \rangle = RP = e/(hf)\cdot P$$

$$\langle I_{1\pm} \rangle = R\left|\pm\mathbf{E}_S/2 + \mathbf{E}_{LO}/2\right|^2$$

$$= \frac{R}{4}\left(P_S \pm 2\sqrt{P_S P_{LO}} + P_{LO}\right)$$

$$\langle I_{2\pm} \rangle = R\left|\pm\mathbf{E}_S/2 + j\,\mathbf{E}_{LO}/2\right|^2$$

$$= \frac{R}{4}\left(P_S + P_{LO}\right)$$



Coherent I&Q receiver

$$\langle I_{1d} \rangle = \langle I_{1+} \rangle - \langle I_{1-} \rangle = R\sqrt{P_S P_{LO}}$$

$$\langle I_{2d} \rangle = \langle I_{2+} \rangle - \langle I_{2-} \rangle = 0$$

Interference signal(s)

$$\langle I_{1s} \rangle = \langle I_{1+} \rangle + \langle I_{1-} \rangle = R\left(P_S + P_{LO}\right)/2$$

$$\langle I_{2s} \rangle = \langle I_{2+} \rangle + \langle I_{2-} \rangle = R\left(P_S + P_{LO}\right)/2$$

Current sums determine shot noise.

For homodyne leave out splitters and lower photoreceiver. P_S and P_{LO} are thereby doubled.

Photons in wave would increase coherent receiver noise

Let us assume there is just a very weak signal with n = 0, 1, 2, 3, ... photons during τ. Signal energy is $P_s\tau = hf\cdot n$. This means for the interference signal: Charge

$$\boxed{\langle I_{1d}(n)\rangle}\cdot\tau = R\sqrt{P_S P_{LO}\tau} = R\sqrt{P_{LO} hf\tau\cdot n}$$

is quantized, with Poisson probabilities .

PDF of output signal:

$$\underset{\textbf{wrong}}{p_{I1d}}\left(I_{1d}\right) = \sum_{n=0}^{\infty}\frac{\boxed{P_n(n)}}{\sqrt{2\pi\sigma_{I1d}^2}}\, e^{-\left(I_{1d}-\boxed{\langle I_{1d}(n)\rangle}\right)^2/\left(2\sigma_{I1d}^2\right)}$$

wrong

$$P_n(n) = e^{-\langle n\rangle}\langle n\rangle^n/n!$$

$$p_{I1d}\left(I_{1d}\right) = \frac{1}{\sqrt{2\pi\sigma_{I1d}^2}}\, e^{-\left(I_{1d}-\langle I_{1d}\rangle\right)^2/\left(2\sigma_{I1d}^2\right)}$$

correct

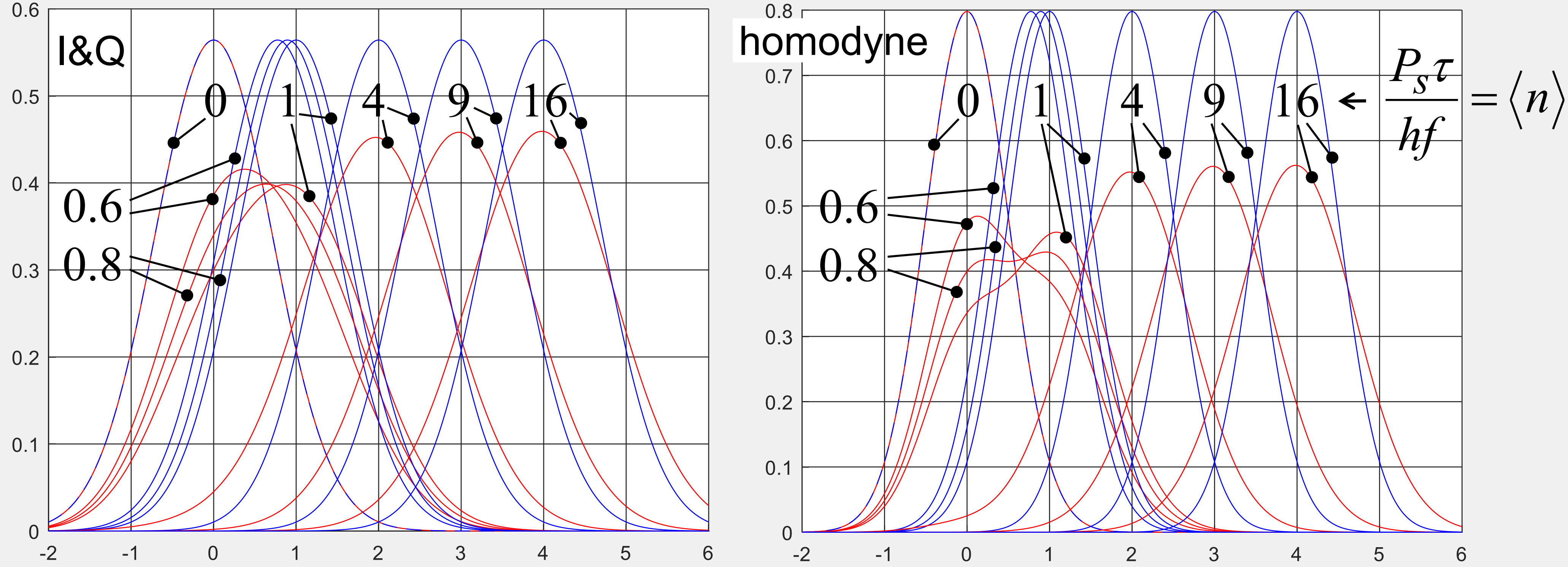
Double quantization of signal, as a portion of shot noise and in wave interference! ↯

This would be **measurable** but it is **not measured**!

⇒ Photons are not part of the lightwave.

Photons explain quantized energy addition / subtraction upon light generation / detection.

No interference caused by signal photons in lightwave



Probability density function vs. normalized charge $\langle I_{1d} \rangle \tau \sim \sqrt{\langle n \rangle}$ of interference signal

True interference signal $\langle I_{1d} \rangle \tau$ + shot noise; correct and undisputed since decades

If signal contained photons: Poisson-distributed interference signal + shot noise;

~1.8...5.7 dB penalty. Limit at $\langle n \rangle > 4$: 1.8 dB (≅ 3/2) for I&Q; 3 dB (≅ 2) for homodyne.

Coherent communication would work ~1.8 dB worse if lightwave contained photons!

Master equation of photon statistics

- How many photons can be detected behind optical amplifiers / attenuators?
- Probability evolution of photon number ($dt \rightarrow 0$; multiple transitions neglected)

$$P(n,t+dt) = P(n|n)P(n,t) + P(n|n-1)P(n-1,t) + P(n|n+1)P(n+1,t)$$

stimulated emission spontaneous emission absorption

$$\boxed{P(n|n-1) = ((n-1)a + c)dt \qquad P(n|n+1) = (n+1)b\,dt}$$

Optical noises are derived from this.

$$P(n|n) = 1 - P((\neq n)|n) \approx 1 - P(n-1|n) - P(n+1|n) = 1 - (n(a+b)+c)dt$$

Master equation of photon statistics

$$\boxed{\frac{dP(n,t)}{dt} = -(n(a+b)+c)P(n,t) + ((n-1)a+c)P(n-1,t) + (n+1)bP(n+1,t)}$$

Solution example for absorption only ($a = c = 0$): Poisson distribution

$$P(n) = e^{-\mu_0}\frac{\mu_0^n}{n!} \qquad \langle n \rangle \equiv \mu_0(t) = \mu_0(0)e^{-bt}$$

Moment generating function

$$M_n\left(e^{-s}\right)=\left\langle e^{-sn}\right\rangle=\sum_{n=-\infty}^{\infty}P(n)e^{-sn} \qquad M_x\left(e^{-s}\right)=\left\langle e^{-sx}\right\rangle=\int_{-\infty}^{\infty}p_x(x)e^{-sx}dx$$

Can be inverted by inverse Laplace or z transform ($e^{-s}=z^{-1}$)

MGF allows calculating all moments: $\left\langle n^k\right\rangle,\left\langle x^k\right\rangle=(-1)^k\left.\frac{d^kM\left(e^{-s}\right)}{(ds)^k}\right|_{s=0}$

Addition of statistically independent RVs: convolution of PDFs or multiplication of MGFs

MGF will now be applied to both sides of the master equation ...

Solution of partial differential equation for MGF

$$\boxed{\frac{\partial}{\partial t} M_n\left(e^{-s},t\right) = c\left(e^{-s}-1\right)M_n\left(e^{-s},t\right) - \left(a-be^{s}\right)\left(e^{-s}-1\right)\frac{\partial}{\partial s} M_n\left(e^{-s},t\right)}$$

Derived from master equation of photon statistics. Solution:

$$\boxed{M_n\left(e^{-s},t\right) = \left(1+\mu\left(1-e^{-s}\right)\right)^{-N} M_n\left(1-\frac{G\left(1-e^{-s}\right)}{1+\mu\left(1-e^{-s}\right)},0\right)}$$

MGF at time *t* is given in terms of the MGF at time 0 !

power gain: $G = G(t) = e^{(a-b)t}$

number of modes: $N = c/a$

spontaneous emission factor: $n_{sp} = \dfrac{a}{a-b}$

noise photon number per mode: $\mu = n_{sp}(G-1)$

Discrete distributions (photoelectrons)

(type)	$P(n)\ \ (n \geq 0\ \ )$	$M_n\left(e^{-s}\right)$	$\langle n \rangle$	σ_n^2
Poisson (signal alone)	$e^{-\mu_0} \frac{\mu_0^n}{n!}$	$e^{-\mu_0\left(1-e^{-s}\right)}$	μ_0	μ_0
Central negative binomial (noise alone)	$\binom{n+N-1}{n} \frac{\mu^n}{(1+\mu)^{n+N}}$	$\frac{1}{\left(1+\mu\left(1-e^{-s}\right)\right)^N}$	$N\mu$	$N\mu(\mu+1)$
Noncentral negative binomial, Laguerre (signal + noise) General case	$\frac{\mu^n e^{-\frac{\mu_0}{1+\mu}}}{(1+\mu)^{n+N}} L_n^{N-1}\left(\frac{-\mu_0}{\mu(1+\mu)}\right)$	$\frac{e^{\frac{-\mu_0\left(1-e^{-s}\right)}{1+\mu\left(1-e^{-s}\right)}}}{\left(1+\mu\left(1-e^{-s}\right)\right)^N}$	μ_0 $+N\mu$	$N\mu(\mu+1)$ $+(2\mu+1)\mu_0$

Poisson transformation and normalization

Assume that the probability distribution of the photon number n can be expressed by the **Poisson transform** of the PDF of a continuous nonnegative RV x:

$$\boxed{P(n)=\int_0^\infty p_x(x)e^{-x}\frac{x^n}{n!}dx}$$

For $G\rightarrow\infty$ no limit of $P(n)$ is found because the mean photon number scales with G.

A normalized variable $\tilde{x}=x/G$ has a $p_{\tilde{x}}(\tilde{x})$ which depends only weakly on G and allows finding $\lim\limits_{G\to\infty} p_{\tilde{x}}(\tilde{x})$.

$$p_x(x)dx=p_{\tilde{x}}(\tilde{x})d\tilde{x} \qquad p_{\tilde{x}}(\tilde{x})=Gp_x(\tilde{x}G) \qquad \boxed{P(n)=\int_0^\infty p_{\tilde{x}}(\tilde{x})e^{-\tilde{x}G}\frac{(\tilde{x}G)^n}{n!}d\tilde{x}}$$

This is the continuous form of $P(n)=\sum P(n|(\tilde{x}_iG))P(\tilde{x}G=\tilde{x}_iG)$ where the conditional probability $P(n|(\tilde{x}_iG))$ is that of a Poisson distribution with a mean $\tilde{x}_iG$. We find:

$$\boxed{\lim_{G\to\infty} M_n\left(e^{-s/G}\right)}=\lim_{G\to\infty}\sum_{n=0}^{\infty}e^{-(s/G)n}P(n)=\lim_{G\to\infty}\sum_{n=0}^{\infty}e^{-(s/G)n}\int_0^\infty p_{\tilde{x}}(\tilde{x})e^{-\tilde{x}G}\frac{(\tilde{x}G)^n}{n!}d\tilde{x}$$

$$=\int_0^\infty p_{\tilde{x}}(\tilde{x})\lim_{G\to\infty}e^{-\tilde{x}G}\sum_{n=0}^{\infty}\frac{\left(e^{-s/G}\tilde{x}G\right)^n}{n!}d\tilde{x}=\int_0^\infty p_{\tilde{x}}(\tilde{x})\lim_{G\to\infty}e^{-\tilde{x}G}e^{e^{-s/G}\tilde{x}G}d\tilde{x}$$

$$=\int_0^\infty p_{\tilde{x}}(\tilde{x})\lim_{G\to\infty}e^{-\tilde{x}G\left(1-e^{-s/G}\right)}d\tilde{x}=\int_0^\infty p_{\tilde{x}}(\tilde{x})\lim_{G\to\infty}e^{-\tilde{x}G(s/G)}d\tilde{x}=\int_0^\infty p_{\tilde{x}}(\tilde{x})e^{-s\tilde{x}}d\tilde{x}\boxed{=M_{\tilde{x}}\left(e^{-s}\right)}$$

$p_{\tilde{x}}(\tilde{x})$ is obtained by backtransforming $M_{\tilde{x}}\left(e^{-s}\right)$.

Continuous distributions (intensity, power, photocurrent)

(type)	$p_{\tilde{x}}(\tilde{x})\ \ (\tilde{x} \geq 0\ )$	$M_{\tilde{x}}\left(e^{-s}\right)$	$\langle \tilde{x} \rangle$	$\sigma_{\tilde{x}}^2$
Constant (signal alone)	$\delta\left(\tilde{x}-\tilde{\mu}_0\right)$	$e^{-\tilde{\mu}_0 s}$	$\tilde{\mu}_0$	0
Central χ_{2N}^2 , Gamma (noise alone)	$\frac{1}{\Gamma(N)} \tilde{\mu}^N \tilde{x}^{N-1} e^{-\tilde{x}/\tilde{\mu}}$	$\frac{1}{(1+\tilde{\mu}s)^N}$	$N\tilde{\mu}$	$N\tilde{\mu}^2$
Noncentral χ_{2N}^2 (signal + noise) General case	$\frac{\tilde{x}^{(N-1)/2} e^{-(\tilde{\mu}_0+\tilde{x})/\tilde{\mu}}}{\tilde{\mu}_0^{(N-1)/2} \tilde{\mu}} \cdot I_{N-1}\left(2\sqrt{\tilde{x}\tilde{\mu}_0}/\tilde{\mu}\right)$	$\frac{e^{\frac{-\tilde{\mu}_0 s}{1+\tilde{\mu}s}}}{(1+\tilde{\mu}s)^N}$	$\tilde{\mu}_0 + N\tilde{\mu}$	$N\tilde{\mu}^2 + 2\tilde{\mu}\tilde{\mu}_0$

Eliminating and adding shot noise

$P(n)$: Poisson distribution, Central negative binomial distribution, Noncentral negative binomial distribution	$\Rightarrow M_n\left(e^{-s}\right) \Rightarrow$ $M_{\tilde{x}}\left(e^{-s}\right) = \lim\limits_{G\to\infty} M_n\left(e^{-s/G}\right) \Rightarrow$ Eliminate shot noise by amplification, normalize with respect to G.	$p_{\tilde{x}}(\tilde{x})$: Constant (Dirac function), Central χ^2 distribution, Noncentral χ^2 distribution
	$\Leftarrow P(n) = \int\limits_0^\infty p_{\tilde{x}}(\tilde{x}) e^{-\tilde{x}G} \frac{(\tilde{x}G)^n}{n!} d\tilde{x} \Leftarrow$ Add shot noise, undo normalization ($x = \tilde{x}G$).	

Direct detection receiver model (1)

Assume independent zero-mean Gaussian noise variables with equal variances!

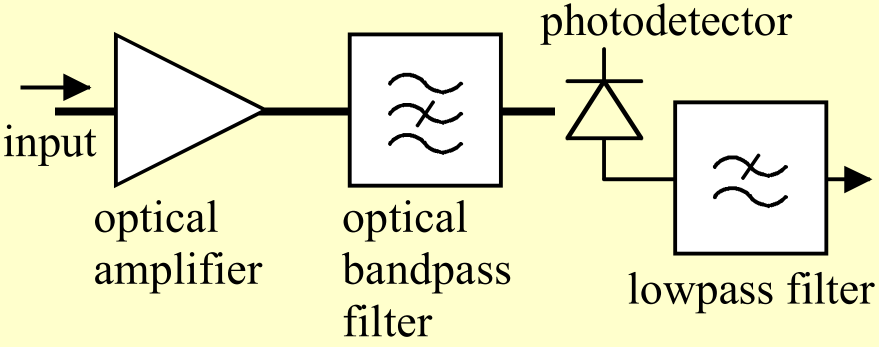
Bandpass filter has rectangular impulse response of duration τ_1. Electrical field at its output:

$$\underline{\tilde{\mathbf{E}}}(t) = \left(\left(\sqrt{\tilde{\mu}_0 / M} + \tilde{u}_1 + j\tilde{u}_2\right)\underline{\mathbf{e}}_1 + \left(\tilde{u}_3 + j\tilde{u}_4\right)\underline{\mathbf{e}}_2\right)e^{j\omega t}$$

Photocurrent: $$\left|\underline{\tilde{\mathbf{E}}}(t)\right|^2 = \left(\sqrt{\tilde{\mu}_0 / M} + \tilde{u}_1\right)^2 + \tilde{u}_2^2 + \tilde{u}_3^2 + \tilde{u}_4^2$$

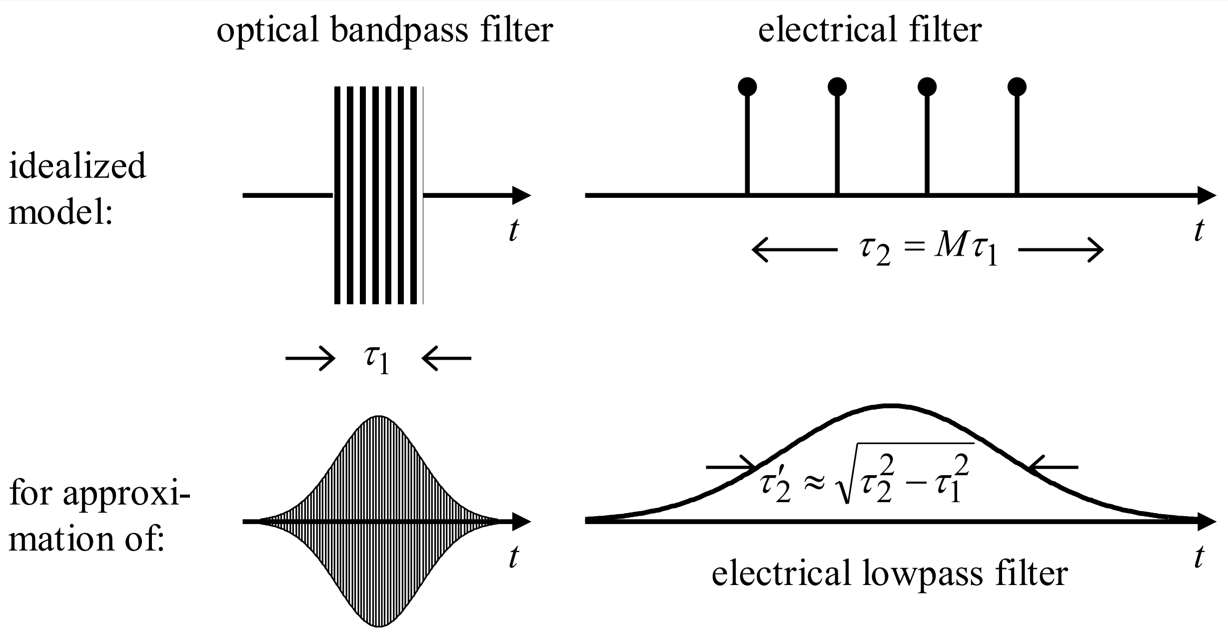
A lowpass filter with a continuous impulse response of length τ_2 or better $\sqrt{\tau_2^2 - \tau_1^2}$ is modeled as a (ficticious, infinite bandwidth) lattice filter having M Dirac impulses spaced by τ_1 each. The signal at its output is χ^2 distributed with $4M = 2N$ degrees of freedom:

$$\tilde{x} = \sum_{i=1}^{M} \left|\underline{\tilde{\mathbf{E}}}(t + i\tau_1)\right|^2$$

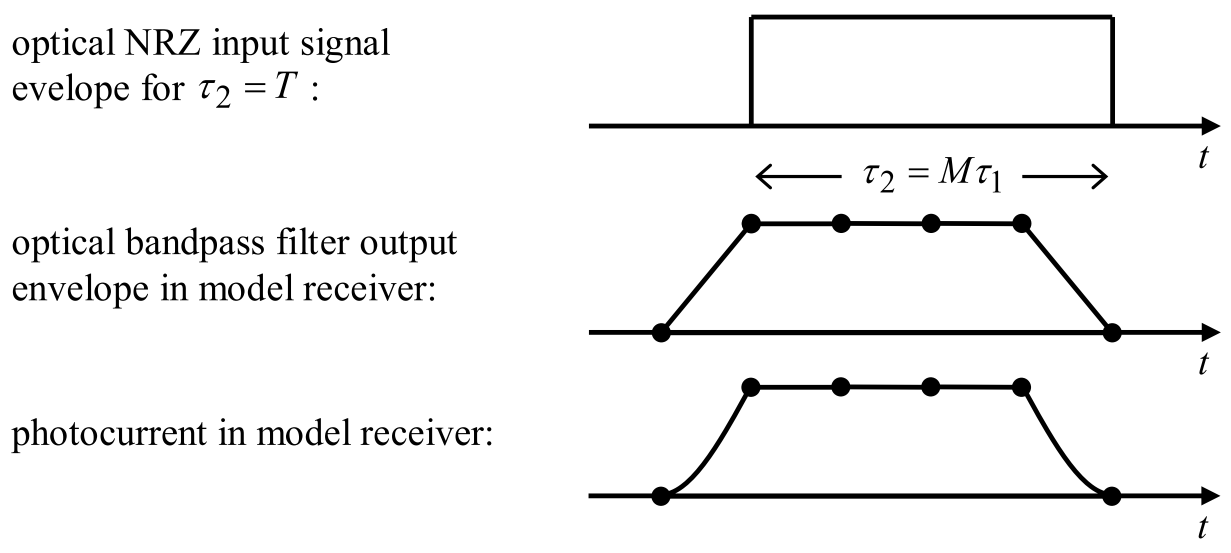


N modes = p polarizations · M samples

Direct detection receiver model (2)



Optical and electrical impulse responses in optical receiver



Optical field envelopes and photocurrent for idealized model sketched above

Understanding optical amplifier and photodetection

- Signal and noise together have a noncentral negative binomial photoelectron distribution. It contains optical amplifier noise + shot noise.
- For $G \to \propto$, shot noise of detection becomes negligible. We get a noncentral χ^2 intensity distribution. Its noise is only optical amplifier noise.
- Noncentral χ^2 intensity distribution occurs in DD RX with Gaussian field noise.

$\Rightarrow$ Amplifier adds Gaussian field noise in phase and in quadrature (wave aspect).

$\Rightarrow$ Detection adds shot noise (particle aspect).

$\Rightarrow$ Photons do not exist or manifest in the lightwave.

Photons with fields violate law of energy conservation (1)

Let us assume each photon has a field $\mathbf{E}_{hf}$ with given mode and frequency. Let a coherent optical pulse with n photons have power P and duration τ:

$$W = P\tau = |\mathbf{E}|^2 \tau = nhf \qquad \mathbf{E} = \sqrt{hf/\tau \cdot n}\, \mathbf{e}_1\, e^{j\omega t}$$

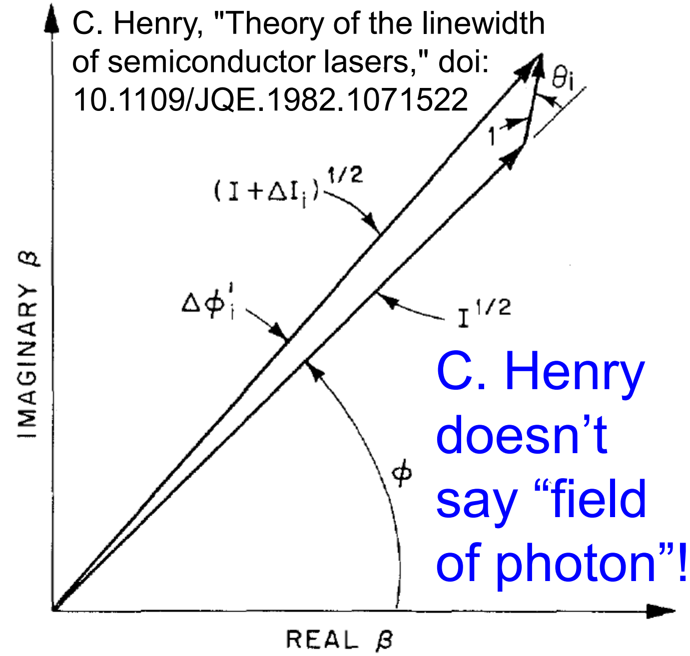
Now there is a **stimulated** emission with field $\mathbf{E}_{hf} = \sqrt{hf/\tau}\, \mathbf{e}_1\, e^{j\omega t}$, exactly in phase with $\mathbf{E}$.

Fields are added. Resulting new energy: $W + \Delta W$

$$= \left|\mathbf{E} + \mathbf{E}_{hf}\right|^2 \tau = \left(\sqrt{n} + \sqrt{1}\right)^2 hf = \left(n + 2\sqrt{n} + 1\right) hf$$

Added energy: $\Delta W = \left(2\sqrt{n} + 1\right) hf$

Added photon number: $\boxed{\Delta n = 2\sqrt{n} + 1}$



C. Henry, "Theory of the linewidth of semiconductor lasers," doi: 10.1109/JQE.1982.1071522

C. Henry doesn't say "field of photon"!

Fig. 1. The instantaneous changes of the phase ϕ and intensity I of the optical field caused by the ith spontaneous emission event. The field amplitude $\beta = I^{1/2} \exp(i\phi)$ increases by $\Delta\beta_i$ having an amplitude of unity and phase $\phi + \theta_i$, where θ_i is a random angle.

1 stimulated emission was ideally caused by 1 electron flowing through PN junction of semiconductor (amplifier or EDFA pump laser diode) with forward voltage ~1,5 V (?).

Needed energy: $\boxed{e \cdot 1{,}5\ \mathrm{V}}$

Light pulse is detected in photovoltaic cell which produces ~0.4 V (?) under load.

Added harvested energy: $\boxed{\Delta n \cdot e \cdot 0.4\ \mathrm{V}}$

Energy efficiency can easily surpass 1, thereby violating energy conservation!

Photons with fields violate law of energy conservation (2)

As an alternative, assume that each photon has a field $\mathbf{E}_{hf} = \sqrt{hf/\tau}\,\mathbf{e}_1\, e^{j\omega t}$ and these elementary fields are added to form a total field $\mathbf{E} = \sqrt{hf/\tau} \cdot n\, \mathbf{e}_1\, e^{j\omega t}$ (proportional to n, not $\sqrt{n}$!). Total energy of n photons shall then be $n^2 hf$. ↯
This is contradicted by the known energy nhf of n photons.

What would be needed in order to allow adding the fields of stimulated emissions? For energy conservation in the total field the field of a stimulated emission photon would have to be $\mathbf{E}_{hf} = \sqrt{hf/\tau}\left(\sqrt{n+1} - \sqrt{n}\right)\mathbf{e}_1\, e^{j\omega t}$. The dependence on n would make such photons distinguishable whereas photons as particles are defined to be indistinguishable. And the law of energy conservation would still be violated because the individual photon energy $\left(2n+1-2\sqrt{(n+1)n}\right)hf$ would not be the difference hf between the energies $(n+1)hf$ and nhf of $n+1$ and n photons. ↯

⇒ Photons do not have fields and hence are not contained in the lightwave.

Double slit experiment = space division DEMUX + MUX

Consider a double slit diffraction experiment with very low light intensity, so that photons are rare. Since there is diffraction each photon should have gone through both slits. But this is impossible because in each slit a sub-photon energy $hf/2$ would be transported. If the photon traveled through only one slit then there should be no double slit diffraction, at least not when light intensity is low. This well-known fact is no paradoxon because it can be resolved:

Sub-photon energies are of course possible in the wave. But not in the form of photon(s) because that would be against the photon definition.

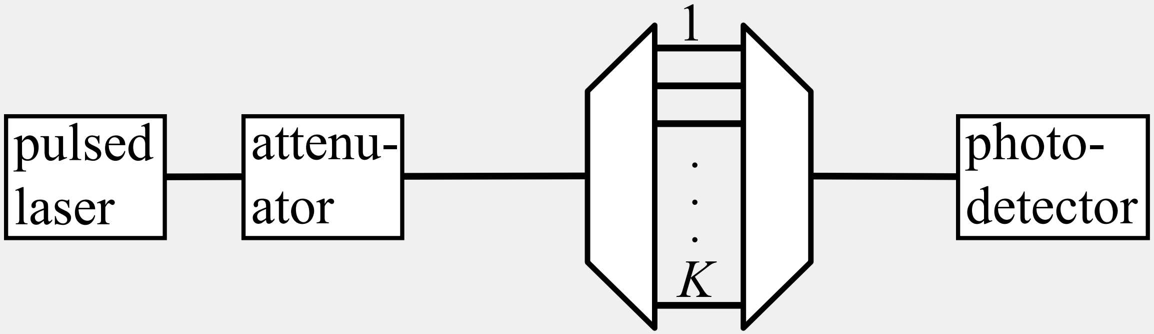
⇒ Lightwave contains no photons.

⇒ Photons (re)appear only upon their detection.

https://sciencedemonstrations.fas.harvard.edu/presentations/single-photon-interference: At the end the authors comment that, strictly speaking, not photons [meant: flying in the wave] were detected, only photoelectrons.

Frequency-division DEMUX + MUX

- Ultrashort laser pulses with very large bandwidth
- Strong attenuator lets pass only single photons.
- Total bandwidth of DEMUX+MUX: $1/T$

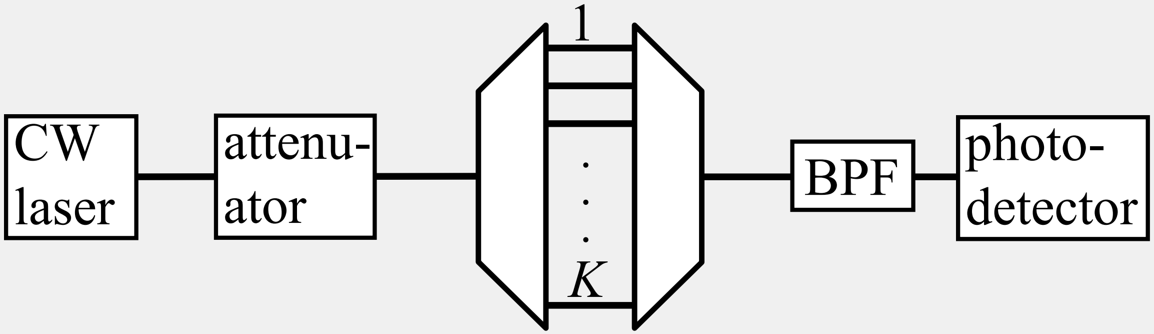


frequency-domain DEMUX + MUX

- Individual bandwidth of one of K DEMUX/MUX channels: $1/(KT)$
- Time spacing between impulses is $>KT$, in order to avoid temporal overlap.
- Synchronization between laser pulses and photodetector (using scope or triggered photon counter) allows determining pulse width even of (repeated) single photons.
- At large powers, measured pulse width is T.
- At low powers, single photons cannot have gone through all K interconnections because then in each interconnection there would be a sub-photon energy hf/K.
- If single photons went through only 1 interconnection then the impulse width should be KT. I claim this is not observed in practice! Pulse width is T, like at high power!

⇒ Lightwave contains no photons

Time-division DEMUX + MUX



time-domain DEMUX + MUX

- CW laser
- Strong attenuator lets pass only single photons.
- DEMUX + MUX are arranged to be completely transparent.
- They are trees of lossless 1×2 / 2×1 cells: Mach-Zehnder modulator with Y fork/junction at one end and 2×2 coupler at other end.
- Each interconnection is active during time T and inactive during $(K-1)T$.
- Bandpass filter is tuned to determine its bandwidth, for instance $B_o = 1/T$.
- At low powers, single photons cannot have gone through all K interconnections because then in each interconnection there would be a sub-photon energy hf/K.
- If single photons went through only 1 interconnection then their impulse width should be T and their bandwidth should be $1/T$. This should be observed when the BPF is tuned. I claim it is not observed in practice! Total width remains equal to B_o!

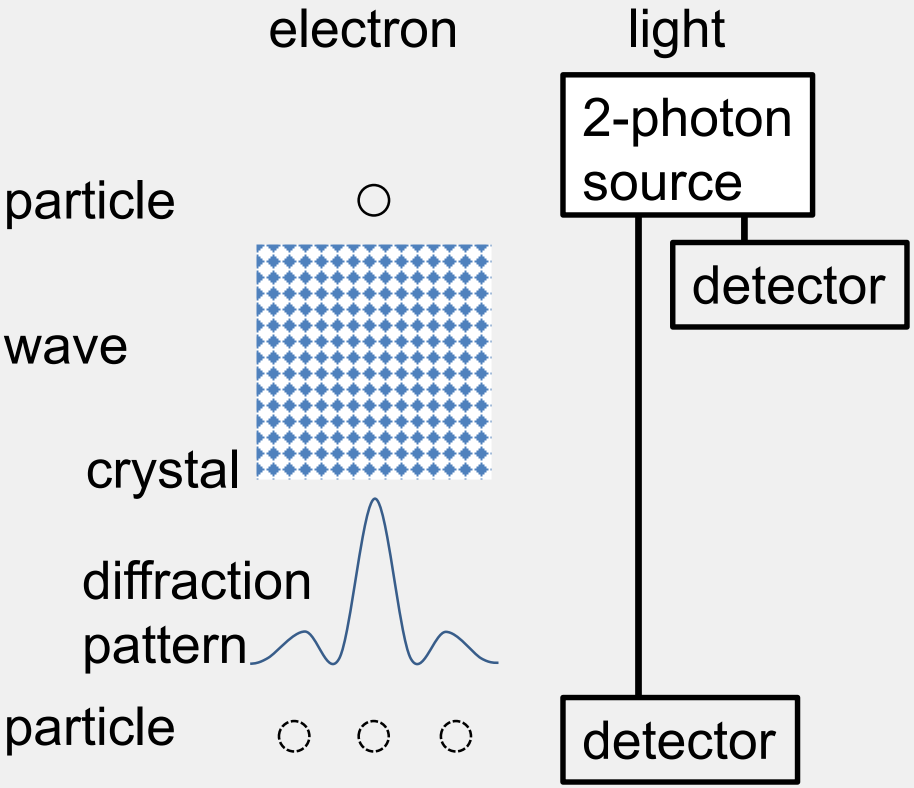
⇒ Lightwave contains no photons

Noise figures

- Traditional optical noise figure: $F_{pnf} = 1/G + 2n_{sp}(1-1/G) = F_{fas} = F_{o,I}$
- Correct optical I&Q noise figure: $F_{o,IQ} = 1/G + n_{sp}(1-1/G)$
- Extrapolate $n_{sp} = \ldots 3, 2, 1, 0$ (physically impossible). Noise figure becomes $1/G$.
- If signal and noise photons flowed into the amplifier, SNR would stay constant and the first term in the noise figure would be 1, not $1/G$. Even though a noisless amplifier cannot be built its noise figure $1/G$ is correctly calculated. Assuming that there are photons at the amplifier input, the term $1/G$ means that noise gain would be smaller than signal gain. Not even a noise-free amplifier could do this!

$\Rightarrow$ Lightwave contains no photons.

Propagation delay determined by particles and waves



- When electrons travel through a crystal they behave only like a wave. Yet, before and behind the crystal they can be observed as a particles. There is a certain particle propagation delay.
- A 2-photon source emits photon particles. Their light propagates as waves. Single photon detectors allow determining the propagation delay (difference). This is accomplished with the particle aspect.
- Also generally, when photons are emitted their light propagates only as a wave. Detection shows a certain particle propagation delay.
- So, <u>photons may be there all the time</u>, though not in the electromagnetic lightwave.
- Propagation delay may also be determined by only the wave aspect: A Mach-Zehnder modulator directs part of the wave into an unguided mode. A balanced coherent receiver detects the wave.
- See end of next page!

Summary

- Light behaves as electromagnetic wave and as photon particles, but not in the <u>same</u> portion of light at the <u>same</u> time and place.
- Photons are not contained in lightwaves. This has been shown by ...
  - Zero point fluctuations
  - Coherent receiver
  - Direct detection receiver with optical preamplifier
  - Energy conservation
  - No sub-photon energies, no single-photon behavior of wave in space, frequency and time division DEMUX + MUX
  - Noise figures
- Yet, photons may be there all the time, though not in the electromagnetic lightwave:
- Beside W (particle energy) $=$ h (Planck) $\cdot$ f (wave frequency) the propagation/observation time delay may be a second connection between wave aspect and particle aspect.