Experimental quantum optics and quantum communication

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Experimental Quantum Optics and Quantum Communication

1. Coherence of light. Quantum properties of light
   (21.10, 04.11, 11.11 and 18.11)

2. Trapping and cooling of single particles
   (25.11, 02.12 and 09.12)

3. Entangling light and matter
   (16.12 and 06.01)

4. Frequency comb and Optical clocks, Nano-mechanics
   (13.01 and 20.01)

5. Quantum communications and circuits
   (27.01, 03.01 and 10.01)
Books

1. Mark Fox, “Quantum Optics”
2. R. Loudon, “The Quantum Theory of Light”
3. M. O. Scully, “Quantum Optics”
4. F. Riehle, “Frequency Standards”
1. Sometimes the reading of books is not sufficient

2. Look through original articles. They will be uploaded on the webpage.

3. If you have not grasp a message from lectures, talk to us!

4. Zi. 119. Good tee and bisquits are available!
Seminars/Übungen:

1. 7 seminars. Every two weeks. Start on?

2. Sonja Vieh, Zi. 118, Geb. E 26

3. Possible times?

4. sonja.vieh@physik.uni-saarland.de
What the lecture is about?

Quantized light,

Quantized matter,

...accompanied by historical overview.
Founders of QM faced the challenges

P.A.M. Dirac (1902-1984)

E. Schrödinger (1887-1961)

“Each photon interferes only with itself. Interference between two different photons never occurs”

“We never experiment with just one electron or atom or (small) molecule. In thought experiments, we sometimes assume that we do; this invariably entails ridiculous consequences...”

Lectures 1-4

Lectures 5-9
Nobel prize in physics (2012)

The Nobel Prize in Physics 2012 was awarded jointly to Serge Haroche and David J. Wineland "for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems".
Serge Haroche in the lab

- State of the art microwave resonator, photon lifetime is 0.1 sec
- Single rubidium atoms pass the cavity one by one
- Quantum entanglement between single atom and single photon
- Observation of collapse of the quantum state of the field in a real-time
David Wineland in the lab

- Trapping and laser cooling of single ions
- Quantum motion of the single particles
- Single ions of optical clocks (atomic clocks)
- Quantum information processing with single ions
Nobel prize every 7 years

2019-2021  ?, ?, ?
2012  Haroche, Wineland
2005  Glauber, Hall, Hänsch
2001  Cornell, Ketterle, Wieman
1997  Chu, Cohen-Tannoudji, Phillips
1989  Ramsey, Dehmelt, Paul
1981  Bloembergen, Schawlow, Siegbahn
1964  Townes, Basov, Prokhorov
1955  Lamb, Kusch

Michelson, Einstein, Heisenberg, Schrödinger, Dirac, Rabi, Bloch, Purcell
The Nature of light. Light coherence

- Light – wave or particle?
- Early days of the quantum theory
- Michelson-Morley interferometer
- Michelson stellar interferometer
- First- and second-order correlation functions
- Hanbury Brown – Twiss interferometer
Light: wave or particle?

• Problem of nature of light is older than science

• Ptolemy and Euclid:
  
  *Emission theory: vision works by eye emitting rays of light*

• Alhazen in XI century:
  
  - *Light rays proceeds to the eye from each point of an object*
  - *Camera obscura and image formation*

*Alhazen, “Arabic Treatise on Optics”, 1011-1021*
Light: wave or particle?

- Renaissance (XIV-XVII): Light has corpuscular nature
- Light consists of particle flow carried by aether
- I. Newton, P. de Fermat, W. Snellius – geometrical optics

\[ \delta S = \delta \int_{A}^{B} n ds = 0 \]

- On the other hand, C. Huygens described the light propagation as an interference of secondary waves... (1678)
Light: wave or particle?

• Th. Young (1804): Double slit experiment. Light is a wave!
• A. Fresnel (1815): Diffraction theory. Light is a wave!
• F. Arago (1819): The spot of Arago. Light is a wave!
• J. Maxwell, H. Hertz, A. Popov (1860-1890): Radiation theory, Radio
• Many believed to the end of physics
• 1900, two “clouds” still remained unclear:
  Michelson-Morley experiment and Rayleigh-Jeans (UV-catastrophe)
The concept of quanta (1900)

• Studying of Black-body radiation spectrum

• UV-catastrophe, Rayleigh-Jeans law

\[ w(\nu) \sim \nu^2 k_B T \]

• Max Plank – expert in thermodynamics

• Oscillator energy \( = h\nu \)

\[ w(\nu) \sim \frac{h\nu}{e^{h\nu/k_B T} - 1} \nu^2 \]

• Nowdays: Absolute Black Body radiation standards are used to calibrate the temparture in range 100 - 3000 C
The concept of quanta (1905)

- Photoelectric effect. Light is particle!
- $h\nu = A + K$
- Kinetic energy $K \sim \lambda^{-1}$
- Nobel prize (1926)
- His early work stimulated enormous progress in development of quantum theory

However, to explain the photoelectric effect no field quantization is required!

W.E. Lamb, M.O. Scully in “Polarization, matter and radiation”, Paris 1969
The photon (1926)

- Explanation of covalent bonding
- Discovery of $O_4$
- Heavy water
- Lewis coined the term „Photon“ for the smallest unit of radiant energy
Short summary

• “UV-Catastrophe” is explained
• Quanta are introduced
• Photoelectric effect suggest the particle like behavior
• Term of photon is introduced

• What is about „null-result“ of Michelson-Morley experiment?
Michelson-Morley interferometer (1887)

- Light is carried by an aether. “Luminiferous aether”.
- Fresnel: aether is partially dragged by moving matter
- Second order effects $\sim \frac{v^2}{c^2}$

http://en.wikipedia.org/wiki/Michelson-Morley_experiment
Michelson-Morley interferometer (1887)

- 11 meter interferometer. Concrete base in mercury bath.
- Earth motion would produce a fringe shift $\sim 0.4$ fringes
- Detected effect $< 0.02$ fringes.
- The Most famous “failed” experiment led to special relativity
- Nobel prize (1907)
Optical resonator with length (effective) of about 20 km.
Two Nd:YAG lasers at $\lambda = 1064$ nm are stabilized on cavities.
Setup is rotated with $T = 45$ sec.
Frequency difference between lasers are measured.
$\delta c/c \sim 10^{-17}$

Original M-M: $\delta c/c \sim 10^{-5}$
What do we measure with an interferometer?

Michelson interferometer

Young double slit interferometer
Fringe formation (monochromatic light)

\[ E(\alpha) = \frac{V_0}{r_1} e^{ikr_1} + \frac{V_0}{r_2} e^{ikr_2} = \frac{2V_0}{z_1} e^{ik(r_1 + r_2)/2} \cos k(r_1 - r_2)/2 \]

\[ I(\alpha) = |E(\alpha)|^2 = 2 \left( \frac{V_0}{z_1} \right)^2 (1 + \cos k(r_1 - r_2)) = I_0 (1 + \cos k\alpha B) \]

OPD – optical path difference

Fringe pattern
Fringe formation (polychromatic light)

- Finite bandwidth of the light source. Adding up interference fringes.
- K-band source with 2.2µm and $\Delta \lambda = 0.4\mu m$, $B = 10$ cm.
- For zero OPD, all wavelength have maximum – white light fringe.
- $\alpha$ is related to the different delay time of fields $\tau = \alpha B/c$. Fringes fade at $\alpha = \pm c\tau_c/B$.
- Loss of fringe contrast at delay equal to coherence time $\tau_c$.
- Coherence length $= c\tau_c = c\lambda/\Delta\lambda$. Fringes fade at $\alpha = \pm c\tau_c/B$. 

\[\begin{align*}
I(\alpha) & \quad \lambda/B = 4.5 \text{ arcsec} \\
& \\
\alpha \text{ [arcsec]} & \\
& \\
-20 & -10 & 0 & 10 & 20 \\
-20 & -10 & 0 & 10 & 20 \\
0.5 & 0.5 \\
1 & 1 \\
\end{align*}\]

a) point source, monochromatic  

b) point source, K-band
First-order coherence function \( g^{(1)}(\tau) \)

\[
E(t) = E_0(t)e^{-i\omega t}, \quad I_0 = \langle E_0(t)E_0(t) \rangle
\]

\[
V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}, \quad I(\tau) = I_0 \left( 1 + V \cos \omega \tau \right)
\]

\[
g^{(1)}(\tau) = \frac{\langle E_0(t)E_0^*(t+\tau) \rangle}{I_0} = e^{-i\omega \tau} \int_{-\infty}^{+\infty} I(\omega')e^{i\omega \tau} d\omega' / I_0
\]

\[
I(\tau) = I_0 \left( 1 + \text{Re} \left[ g^{(1)}(\tau)e^{i\omega \tau} \right] \right) = I_0 \left( 1 + |g^{(1)}(\tau)| \cos \omega \tau \right)
\]
Michelson stellar interferometer (1920)

• Resolution of conv. telescope is $\lambda/D < 10^{-6}$
• Interferometric measurements of star sizes
• Mount Wilson, USA, winter 1920
• Orion constellation, Betelgeuze
• Double telescope interference

100” Hooker telescope

Mount Wilson Observatory
http://www.mtwilson.edu
Resolution improvement with stellar (spatial) interferometer

- Seeing limited: 0.5 arcsec seeing
- AO on 8-m telescope: 50 milli arcsec resolution
- Spatial interferometer with 100 m baseline: 4 milli arcsec resolution
Michelson stellar interferometer (1920)

- Suggested by H. Fizeau (1868)
- Increase Base → Interference vanishes → Resolve start size
- Angle resolution ~ $10^{-6} - 10^{-7}$ rad
- Discovery of Red Giants
- Betelgeuze: 386 Mio. Km
- Limitations: Mechanical stability of interferometer with large Base
Fringe formation. Extended light sources.

- Finite angular size of the light source. Adding up interference fringes.
- Working example. K-band source with 2.2 μm and Δλ = 0.4 μm, B = 10 cm.
- The diameter of source is 2 arcsec
Extended light sources. Fringe formation

- Finite angular size of the light source.
- Monochromatic: Visibility is reduced due to interference adding up.
- The diameter of source is $2 \text{ arcsec} + \text{temporal coherence} = \text{fringes fade out}$.
- All points on surface are independent (uncorrelated).
- Let's develop simplified theory
Spatial interferometer

Van-Cittert - Zernike Theorem

\[ I(\alpha, \alpha'_0) = I_0 \left( 1 + \cos k(\alpha + \alpha'_0)B \right) \]

\[ I(\alpha) = \int_{-\alpha'_0/2}^{+\alpha'_0/2} I(\alpha, \alpha') d\alpha' = I_0 \left( 1 + \text{Re} \left[ g^{(1)}(\vec{B}) e^{i\vec{\alpha} \vec{B}} \right] \right) \]

\[ g^{(1)}(\vec{B}) = \int_{-\infty}^{+\infty} I(\alpha') e^{i\alpha' B} d\alpha' / I_0 \]
Spatial and temporal coherence

- Venus size is about 15 arcsec.
- K-band source with $2.2\mu m$ and $\Delta \lambda = 0.4\mu m$, variable base $B = 1-8$ cm.
- Fringe spacing $\lambda/B$. We observe about 11 fringes – temporal coherence
- Model Venus as disk of uniform intensity.
- Visibility follows $\text{Besinc}(x) = 2J_1(x)/x$.
- Spatial coherence is visibility at white light fringe.
Image formation in spatial interferometer

\[ V = \left| \frac{J_1(kB\alpha/2)}{kB\alpha/2} \right| \]
Very Large Telescope Interferometer (VLTI)

- Paranal, Chile
- VLTI array
- 2 telescopes, 8 m in diameter
- Base up to ~100 m
- Resolution of ~$10^{-9}$ rad

List of results:

http://www.eso.org/sci/facilities/paranal/telescopes/vlti/
Drawbacks of **amplitude** interferometer

1. **Mechanical Stability** of the construction

2. **Phase distortion** due to atmospheric fluctuations!

**Phase sensitive measurements!**
Radio Astronomy

- Very long base radio interferometers
- Studying quazars, pulsars, galaxies
- Synthesized large aperture due to earth rotation and many stations

http://www.vlba.nrao.org
http://www.nrao.edu

Composite image of Whilpool galaxy M51
**Intensity interferometer (1956)**

- R. Hanbury Brown and R. Twiss in 1956, Australia
- Interference with Base up to 180 m
- Phase insensitive measurements
- RF signals in band 5-45 MHz
- Measurements of Correlation

\[
S(B, t) = \langle i_1(0, t)i_2(B, t) \rangle
\]

\[
S(B) \sim \langle I_1 \rangle \langle I_2 \rangle \left(1 + |g^{(1)}(\tau_B)|^2 \right)
\]

\(\tau_B\) is the delay time due to Base

\[
\Gamma(B) \sim \langle I_1(0)I_2(B) \rangle - \langle I_1 \rangle \langle I_2 \rangle
\]

Signal which is measured
Observing of sirius A (1954)
Intensity interferometer (1954)

- Small Base → signals come from one source
- Large Base → signals may differentiate
- Decrease of correlation with increase of B
- Angular resolution better than $10^{-8}$
- Angular diameter of Sirius A
- Method used in Radio Astronomy

If each individual photodetection event is a statistical quantum process, how can separated events be correlated with each other?

Fluctuations at the input results in Correlation of photocounts
Intensity interferometer (1956)

435.8 nm filtered
From Hg-lamp

Beam-Splitter

PMT 1

AC-coupled amplifier

Delay generator

$\langle \Delta i_2(t + \tau) \rangle$

Multiplier

Integrator

$\langle \Delta i_1(t) \rangle$

$\langle \Delta i_1(t) \Delta i_2(t + \tau) \rangle$

R. Brown, R. Twiss, Nature 177, 27 (1956)
The second-order correlation function $g^{(2)}(\tau)$

- Second-order correlation function of the light:

$$g^{(2)}(\tau) = \frac{\langle E^*(t)E^*(t+\tau)E(t+\tau)E(t) \rangle}{\langle E^*(t)E(t) \rangle \langle E^*(t+\tau)E(t+\tau) \rangle} = \frac{\langle I(t)I(t+\tau) \rangle}{\langle I(t) \rangle \langle I(t+\tau) \rangle} = \frac{\langle I(t)I(t+\tau) \rangle}{\langle I(t) \rangle^2}$$

$I(t) = \langle I \rangle + \Delta I(t)$, $\langle \Delta I(t) \rangle = 0$

$$g(0) = \frac{\langle I(t)^2 \rangle}{\langle I(t) \rangle^2}$$

$$g(\tau >> \tau_c) = \frac{\langle I(t) \rangle^2}{\langle I(t) \rangle^2} = 1$$