Precision measurements in quantum optics

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Goals and objectives

The goal of the lecture course is to deliver modern experimental and theoretical methods of precision measurements in quantum optics. The main objectives are the following

- description of stochastic processes in oscillatory systems
- discussion of precision methods in astrophysics and space, introduction to General relativity
- detailed presentation of modern methods of laser cooling, discussion of different trapping methods of atoms and ions
- discussion of modern approaches to laser stabilization and optical frequency measurements, optical clocks

Syllabus

Lecture 1. "Introduction"

Frequency and time as most accurately measured quantities in physics. Clocks: from 17^{th} century till today. Mechanical, radiofrequency, microwave and optical oscillators. Accuracy and stability. Phase and amplitude modulation, their mathematical representation and power spectrum.

Lecture 2. "Amplitude and phase fluctuations"

Mathematical description of stochastic processes, distribution function, mean value, dispersion. Allan deviation. Correlated fluctuations. Autocorrelation function. Spectral density. Wiener-Khinchin theorem. Stochastic processes in physical systems. From spectral representation of fluctuations to time representation. Spectral density and Allan deviation of different fluctuation types.

Lecture 3. "From frequency fluctuations to spectral line shape"

Power spectral density of a quasimonochromatic signal with fluctuating phase. Autocorrelation function representation. Spectral line shape. Line shape in the cases of (i) shallow high-frequency fluctuations and (ii) strong low-frequency phase fluctuations. Line width. Transformation of the line shape in non-linear processes like second harmonic generation.

Lecture 4. "General relativity in applications to time and frequency transfer"

Minkowski metric tensor. Space and time in Einstein's theory of gravitation, basics of General relativity. Time transformation in rotating frame, gravitational red shift, time dilation, Sagnac effect. Methods of time and frequency transfer, clock synchronization. One way and two way transfer. Transfer of optical frequencies.

Lecture 5. "Precision measurements in astrophysics"

Pulsars as astrophysical sources of periodic pulses. Physics of pulsars. Pulsars in double star systems. Drift of periastrium and General relativity tests. Radiation of gravitational waves. Quasar spectra. Search for drift of the fine structure constant. Calibration of astrophysical spectrometers. Search for extrasolar planets.

Lecture 6. "Introduction to Global navigation systems"

Global navigation system structure – space segment, ground segment, user segment. Satellites orbits, frequency shifts, accuracy. Data coding and decoding. CDMA, TDMA, FDMA methods. Atmospheric errors, corrections, clock synchronization. Atomic time scales TAI, UTC.

Lecture 7. "Two levels atomic system and frequency standards"

Optical Bloch equations. Pseudospin. Rabi oscillations. Excitation by sequence of coherent pulses. Ramsey method. Atom interferometry. Microwave frequency standards. Hydrogen maser. Cesium beam apparatus. Allan deviation, stability, accuracy.

Lecture 8. "Laser cooling of atoms"

Optical molasses. Doppler theory, Doppler limit. Subdoppler laser cooling: Sisyphus method, polarization gradient cooling. Recoil limit. Evaporative cooling. Applications. Bose-Einstein condensation of atomic gases.

Lecture 9. "Traps for neutral atoms"

Magnetic dipole trap, optical dipole trap, optical lattices. Magneto-optical trap. Atomic fountain clock as an ultimate representation of the SI second.

Lecture 10. "Paul trap for ions"

Traps for charged particles. Linear Paul trap. Equation of motion, Mathieu equations. Floquet-type solutions. Pseudopotential. Frequencies of micro- and macromotion. 3D Paul trap. Trap loading.

Lecture 11. "Penning trap for ions and ion cooling"

Penning trap for charged particles. Magnetron, cyclotron and axial frequencies. Precision mass comparison in the Penning trap. Synthesis of anti-hydrogen atoms in Penning traps. Cooling of ions. Doppler and sideband cooling. Sympathetic cooling. Lamb-Dicke regime.

Lecture 12. "Methods of quantum logic in optical clocks"

Precision measurements in the traps, electron shelving. Elements of quantum logic in ion traps. CNOT gate. Motional degrees of freedom. Cirac-Zoller gate. Information transfer between clock and cooling ions. Precision spectroscopy using quantum logic.

Lecture 13. "Laser stabilization"

Tunable cw lasers, spectral properties. Laser stabilization, narrowing the spectral line width. Error signal generation, Haensch-Couillard and Pound-Drever-Hall methods. Temperature and vibrationally compensated Fabri-Perot cavities. Thermal noise limit in high-finesse cavities.

Lecture 14. “Optical frequency measurements”

Frequency conversions in optical domain. Second harmonic generation, phase modulation. Frequency dividers and frequency chains. Femtosecond mode-locked lasers. Time domain and frequency domain representation of femtosecond pulse train. Phase and group velocities in the laser cavities, carrier envelope offset frequency. Spectral broadening in nonlinear photonic crystal fiber. Nonlinear interferometer. Measuring absolute frequency of laser radiation.

Lecture 15. ”Approaching ultimate accuracy. Fundamental restrictions for accuracy in quantum measurements”.

Approaching the quantum limit. Heisenberg’s uncertainty relation. Quantum fluctuations of electromagnetic field. Population fluctuations in quantum absorbers. Implementation of squeezed and entangled states for noise suppression. Quantum limit for interferometer. Ultimate sensitivity for gravitational waves detectors.

Literature

1. F. Riehle, “Frequency standards”, Wiley, 2006
2. W.P. Schleich, “Quantum optics in phase space”, Wiley, 2001
3. V. B. Braginski and F. Ya Khalili, “Quantum measurement”, Cambridge, 1992
4. S.M. Rytov, Yu.A. Kravtsov, V.I. Tatarskii, “Principles of Statistical Radiophysics”, Springer, 1989