EFTF 2014 Tutorials, Monday 23rd June, 08:00 - 18:00
University of Neuchâtel, Switzerland

1) 08:15 - 09:45

The Leeson Effect: PM and AM noise and frequency stability in oscillators, including OEOs and lasers

Enrico Rubiola
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Abstract

Simply stated, an oscillator consists of a loop in which a resonator sets the oscillation frequency and an amplifier compensates for the resonator loss. The oscillation amplitude is set by clipping or other gain-saturation mechanisms, usually in the amplifier. When phase noise is introduced in the loop, the oscillator converts it to frequency noise through a process of time-domain integration. The consequence is that the oscillator phase fluctuation diverges in the long run.

The first part explains the phase-to-frequency conversion mechanism as a general phenomenon inherent in the feedback, following an heuristic approach based on physical insight. There follow the relationships between the noise of the internal components (sustaining amplifier, resonator, etc.) and the phase noise at the oscillator output, or equivalently the frequency stability.

The second part is the analysis of the phase noise spectra found in the data-sheet of commercial oscillators: dielectric-resonator oscillator (DRO), whispering gallery oscillator (WGO), 5-100 MHz quartz crystal oscillators, opto-electronic oscillator (OEO). The analysis gives information on the most relevant design parameters, like the quality factor Q and the driving power of the resonator, and the flicker noise of the sustaining amplifier.

The last part shows the derivation of the oscillator phase noise formulae from the elementary properties of the resonator. Interestingly, the amplitude non-linearity, necessary for the oscillation amplitude to be stable, splits the resonator relaxation time into two time constants. The approach shown in this last part is general. It applies to all oscillators, including quartz, RLC, microwave cavity, delay-line, laser, etc.

Biography

Enrico Rubiola is full professor at the Université de Franche Comté and deputy director of the Department of Time and Frequency of the CNRS FEMTO-ST Institute, Besançon, France. Formerly, he was a full professor at the Université Henri Poincaré, Nancy, France, a guest scientist at the NASA JPL, a professor at the Università di Parma, Italy, and an assistant professor at the Politecnico di Torino, Italy.

He graduated in electronic engineering at the Politecnico di Torino in 1983, received a Ph.D. in Metrology from the Italian Minister of University and Research, Roma (1989), and a Sc.D. degree from the Université de Franche Comté in 1999.

Prof. Rubiola has worked on various topics of electronics and metrology, navigation systems, time/frequency comparisons, and frequency standards. His main fields of interest are precision electronics from dc to microwaves and phase noise metrology, which include analogue and digital frequency synthesis, high spectral purity oscillators, photonic systems, sophisticated instrumentation, and noise. He has developed innovative instruments for AM/PM noise measurement with ultimate sensitivity, and a variety of signal-processing methods. Currently, he is the PI of Oscillator IMP, a platform under development, dedicated to the measurement of AM/PM noise and short-term frequency stability.

A wealth of articles, reports and conference presentations are available on Enrico Rubiola's home page http://rubiola.org.

2) 10:00 - 11:30

Vapour Cell Frequency Standards

Salvatore Micalizio
INRIM, Italy

Abstract

Since their first realization in the 1960s, vapour-cell frequency standards have been considered extremely attractive devices in all those applications where good frequency stability performance joined with small size, reliability, reduced power consumption and costs are required. These applications include telecommunication, defence, energy, space and radio-navigation. The passive rubidium frequency standard with state selection performed by the incoherent light of a lamp is still nowadays widely adopted in many measurement systems, as well as in advanced technological sectors, such as GPS and GALILEO.

The development of single mode semiconductor laser diodes in the 1980s opened new perspectives in the field of gas cell frequency standards, thanks to the replacement of the discharge lamp with a coherent optical source. In terms of frequency stability, the expected performance improvement was theoretically estimated of 2-3 orders of magnitude, predicting a white frequency noise limit in the 10^{-14} $\tau^{-1/2}$ region, τ being the integration time. However, laser noise transferred to the clock signal via the light-shift effect prevented from reaching this result. In the last twenty years, innovative schemes have been considered with the aim of approaching the expected theoretical limit and new concept laser-pumped frequency standards have been developed. These clocks are the object of this tutorial.

After resuming the main features of the traditional lamp-pumped Rb clock, the tutorial will focus into several interesting approaches that have been envisaged not only to get close to the fundamental stability limit, but also to reduce at the same time the requirements on the laser noise. These techniques include coherent population trapping, light-shift compensated schemes and pulsed optical pumping. The tutorial will describe these proposals, their main advantages and limitations and the most significant results obtained by various research groups.

Biography

Salvatore Micalizio is a researcher in the Optics Division of INRIM. After receiving the degree in theoretical particle physics from University of Torino, he joined the Time and Frequency Division of IEN where he was involved in the realization of a Rb maser without inversion of population. In 2001 he received the PhD in Metrology from Politecnico of Torino and since 2004 he is on the permanent staff of INRIM. His research activity is mainly devoted to the development of vapour cell frequency standards. He made studies on coherent population trapping, electromagnetically induced transparency, pulsed optical pumping and their possible application to frequency metrology. He was in the key personnel of several research programs funded by the ESA. He was responsible for INRIM of a contract funded by the Italian Space Agency devoted to the realization of a POP maser prototype for space applications. He is coordinating the project Mclocks IND 55 funded by the European Metrological Research Program concerning the development of vapour cell clocks for industrial applications. He is also involved in studies on primary atomic frequency standards developed at INRIM.

3) 13:00 - 14:30

Global Navigation Satellite Systems (GNSS)

Pascale Defraigne
Royal Observatory of Belgium, Belgium

Abstract

Humans have always needed time for precise navigation. To date, GNSS also relies on time: everything is based on the measurements of the signal travel time between the satellite and the receiver.

GNSS therefore needs a reference timescale maintained by the operators and broadcast by the satellites. On the other hand, the satellite navigation systems offer a wonderful tool for time and frequency metrology, as these flying atomic clocks on board the satellites can be used as a reference for the comparison of ground time and frequency standards.

The tutorial will raise both aspects of the link between GNSS and TIME. After showing concretely the need for accurate time scales for the GNSS, the "GNSS time transfer" technique will be detailed. Code and carrier phase measurements will be presented and the procedure to get a precise and accurate clock comparison will be explained, both from the instrumental point of view and in terms of data analysis. GNSS Common View (or All in View) as well as Precise Point Positioning will be detailed in the presentation. The different error sources on the measurements will be studied and hence an ideal station setup will be presented.

Biography

P. Defraigne obtained her PhD in Geophysics in 1995 at the Université Catholique de Louvain. Since 1997 she manages the time and frequency activities at the Royal Observatory of Belgium, where the Belgian reference UTC (ORB) is maintained.

Her research activities mainly concern the use of satellite navigation systems for time and frequency transfer. P. Defraigne presently chairs the CCTF working group on GNSS time transfer, and contributes to the validation of Galileo timing signals.

4) 14:45 - 16:15

Lasers for Optical Frequency Standards

Stephen Webster

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Abstract

Over the past 50 years, atomic clocks have been based on microwave frequencies and primary standards have demonstrated uncertainties at the level of a few parts in 10^{16}. Optical clocks are a new generation of atomic clock, in which the frequency of light is the signal used for timing. They are based on "forbidden" atomic transitions for which light is absorbed over a very narrow range of frequencies. Depending on the particular atomic species and transition used, the ratio of the frequency to the frequency width (Q-factor) ranges from 10^{14}-10^{23}, thus, these transitions constitute very precise frequency references. They are also insensitive to external electromagnetic fields and can be highly reproducible, and it is anticipated that optical clocks will reach uncertainties of a part in 10^{18}. Further, given that the frequency of light is ~100,000 times higher than that of microwaves, the same level of precision as a microwave atomic clock may be reached in a much shorter time. As optical clocks come of age and prove the stability and reproducibility predicted of them, the prospect will open up for a redefinition of the second in terms of an optical frequency.

The atomic absorber in an optical clock takes one of two forms: it is either a single ion confined in an electro-dynamic trap (Paul trap), or an ensemble of neutral atoms held in an electric dipole force trap (optical lattice). The atomic absorbers are laser cooled so that they are nearly at rest and, to first order, do not experience a Doppler shift on interaction with the light used to probe the atomic transition. To make use of the high-Q of the atomic transition, the probe light must also have a very narrow frequency width and this is achieved by stabilizing a laser to a secondary reference, a high-finesse Fabry-Pérot etalon. A mode-locked femtosecond-pulsed laser (femtosecond comb) converts the very rapid oscillations of the light from some 100's of THz down to a radio frequency so that output of the optical clock can be counted by commercial electronics and compared to the SI second and the outputs of other optical clocks.

This tutorial will give an overview of the essential elements of an optical clock: the atomic reference, the ultra-stable laser and the femtosecond comb. It will describe how each of these elements is realized in practice and the experimental challenges involved in operating such an apparatus. In particular, a review will be made of the laser sources required for operation of an optical frequency standard, the techniques employed in their stabilisation and the characterization of their noise.

Biography

Stephen joined M Squared lasers as their Scientific Products Specialist in September 2012. The company specialises in the research, development and manufacture of solid-state lasers and photonic instruments for a wide range of industrial and scientific applications; his role is to engage with scientific customers and develop new products to meet scientific needs.

Previous to his work at M Squared, Stephen was a senior research scientist at the National Physical Laboratory in the UK for over a decade, where he worked on optical frequency standards, ultra-stable lasers and vibration-insensitive cavities. Highlights of his work there were publications on a force-insensitive optical cavity, the lowest reported acceleration sensitivity for an optical cavity, subhertz laser linewidth, observation of the thermal-noise limit for a cavity and frequency measurements of the electric quadrupole and octupole transitions in $^{171}Yb^{+}$ ion with a fractional uncertainty of 10^{-15}. In 2008, he received the Young Scientist of the Year Award at the European Frequency & Time Forum.

Stephen was awarded a D.Phil from the University of Oxford in 2000 for work on Bose-Einstein Condensation of atomic gases.

Outside of work, Stephen is a keen musician and enjoys hiking and cycling. He is married with two children, aged 4 and 1.

5) 16:30 - 18:00

Frequency & Time Transfer using Optical Fibres

Gesine Grosche
PTB, Germany

Abstract

"Ever more accurate clocks and frequency references are being developed in dedicated laboratories around the world, reaching astonishingly low instability and high accuracy, currently near 1 part in 10 to the 18.

Making the ultra-stable output of these powerful instruments available beyond the walls of the metrology laboratory, to enable physics experiments, remains a challenge. In the wake of the optical telecommunication revolution, transfer techniques that make use of optical fibre have greatly developed: within one decade, improvements of more than three orders of magnitude in precision have been achieved.

Frequency transfer accuracy at the level of 1 part in 10 to the 19, and, for 1 km-scale links, synchronisation at the level of femtoseconds has been reported. Fibre based transfer of frequency and time has been achieved over distances exceeding 500 km, enabling international comparisons and joint experiments.

In this tutorial I will illustrate the advantages and challenges of using optical fibre as a transmission medium for precision metrology. This will cover basic concepts, techniques and limitations, focussing on optical telecommunication fibre (1.5 µm), which is both cheap and optimised for low loss, making it suitable for long-distance transfer. The tutorial will give an overview and comparison of different frequency and time transfer techniques, including methods based on radio-frequency modulation, on using the optical carrier phase, and on the transmission of fs-pulses generated by mode-locked lasers. "

Biography

Gesine Grosche is head of the research group for optical frequency dissemination at the German Metrology Institute, PTB, in Braunschweig, Germany. She received her B.A. degree in Physics from Cambridge University, UK (Trinity College, 1993) and her PhD in Semiconductor Physics from University of London (Imperial College, 1997). After initially joining PTB to invent optical methods for measuring fluid flow velocities from an airplane, she moved on to coordinate a European project providing reference wavelengths for optical telecommunications, and, from 2003, to establish and develop frequency comb metrology based on mode-locked fiber lasers at PTB. From 2001, she has pursued the vision of ultra-stable frequency dissemination using telecommunication fibre, pioneering and refining techniques for remote metrology, which includes remote frequency measurements and frequency synthesis. Her group currently concentrates on long-distance phase-stable fibre links to connect metrology institutes across Europe.