Multiheterodyne spectroscopy of $Eu^{3+}:Y_2SiO_5$ based on GNU Radio

XIUJI LIN[1], SHUO ZHANG[1], MICHAEL HARTMAN[1], SIGNE SEIDELIN[2], BESS FANG[1], YANN LE COQ[1,*]

[1] LNE-SYRTE, Observatoire de Paris, Universit´e PSL, CNRS, Sorbonne Universit´e, Paris, France
[2] Univ. Grenoble Alpes, CNRS, Grenoble INP and Institut N´eel, 38000 Grenoble, France
*Corresponding author: yann.lecoq@obspm.fr

Abstract: We report the use of GNU Radio to realize multiheterodyne spectroscopy of $Eu^{3+}:Y_2SiO_5$ crystal at cryogenic temperature. The flexible multiheterodyne scheme developed by GNU Radio also has the potential to be applied in other applications for precise physical state probing.

The next generation of atomic clocks use ultra-high purity lasers in the optics domain with an oscillation frequency of hundreds of terahertz. Traditional laser systems use analog servo-loops to match the frequency of the laser with that of an ultra-high finesse Fabry-Perot cavity's resonant mode, resulting in a Q factor around 10^10. However, these systems have now reached their limits, and a new approach is needed to create even better lasers for future optical atomic clocks. This is particularly crucial since the second is set to be redefined using optical atomic clocks around 2030.

Our approach is based on $Eu^{3+}:Y_2SiO_5$. At cryogenic temperature (4K or lower) one can photo-imprint a narrow spectral feature in those crystals, such that it can exhibit spectrally narrow transmission peaks suitable to servo the frequency of a laser.

We have realized an Ettus Research USRP X310 + GNU Radio platform that is well suited for this approach. This platform allows us to photo-imprint any spectral pattern on rare-earth doped crystals and to probe the pattern using multiple optical modes simultaneously. This enables us to create complex error-signal generation setups, which can reduce both technical noise from parasitic Fabry-Perot cavities caused by weak reflections on various glass elements and fundamental noise set by optical shot noise, which scales as the square root of the number of photons used per unit time during probing.

Our novel approach utilizes the GNU Radio platform to facilitate prototyping and exploration of fully digital multiheterodyne spectroscopic techniques, which would be nearly impossible to achieve using traditional analog approaches. Creating a dedicated FPGA system to develop these techniques would have been excessively time-consuming since the exact "best" data treatment operation was not known beforehand and may still evolve in the future.

The system which we will be describing (the simplified flowgraph is in Fig. 1) has a demonstrated capability to reach a detection noise compatible with realizing a laser whose frequency fluctuations are reduced to below the 17th decimal point. Despite GNU Radio being optimized for throughput rather than latency, we were able to achieve a feedback bandwidth capability of 100Hz by optimizing the flowgraph and using multiple-core processors.

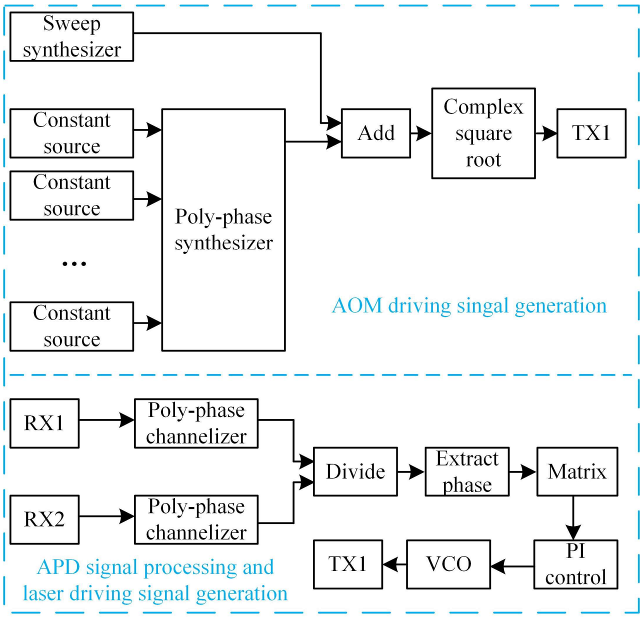

Fig. 1. Simplified flowgraph of our system. AOM: acousto-optic modulator. APD: avalanche photo diode.