Multi-frequency RF sensor based on Rydberg atoms

Context

Rydberg atoms, which are atoms with a large principal quantum number n, are one of the most versatile quantum systems: their unique sensing properties can be enhanced and controlled by the selection of the states and the application of external electromagnetic fields. The large size of these atoms (proportional to n^2), and therefore a potentially high dipole moment, raised primarily fundamental interest: it enabled numerous pioneering demonstrations in quantum physics, including those of Serge Haroche who won the Nobel Prize in 2012 [1]. More recently, Rydberg atoms have been at the heart of the quantum technology revolution: if the strong interactions between these atoms makes them very interesting for quantum information, we are here interested in exploiting their extreme sensitivity at very low field levels for possible applications in the field of detection and processing of RF signals [2,3]. LUMIN and TRT labs have been working for a few years on building an experiment and recently demonstrated new features such as the possibility increasing the detection bandwidth using optical modulation techniques [4].

Rydberg-based sensors have the potential to achieve high-sensitivity RF detection across a broad frequency range (1 to 500 GHz) using the same compact sensor head (a hot atomic vapor gas cell). However, realizing such a sensor presents scientific challenges and requires an in-depth understanding of laser-matter interactions. The ambitious objective of this PhD project is to develop a high-performance multi-frequency RF sensor based on Rydberg atoms, demonstrating the capability to rapidly switch RF frequencies within the same deported sensor head while maintaining a high sensitivity RF detection.

Objectives

To address this issue, the first area of focus will be to theoretically study the interrogation conditions and the attainable performances as a function of the RF frequency, for the two-photon or three-photon protocols, both in Rb and Cs vapor cells. This work will build upon the modeling and theoretical studies conducted by LUMIN over the past years. These simulation efforts will also enable the exploration of new protocols facilitated by the agility and modulation capabilities afforded by the laser architectures also developed during the PhD thesis.

Indeed, to demonstrate a rapidly switch RF frequencies within the same sensor head, the pump laser should be rapidly tunable, while keeping its frequency stability. One of the objectives of the PhD is to develop a compact agile laser system with these requirements. To achieve that goal, original optoelectronics architectures will be investigated based on frequency conversion. Early work has been realized at TRT to address quantum memories at 606nm [5]. The challenge addressed by the PhD thesis is to demonstrate a compact frequency stability transfer using a laser frequency discriminator based on a stabilized unbalanced Mach-Zehnder interferometers, allowing to extend the bandwidth of fiber-based transfer cavities [6]. These techniques will be first explored for lasers addressing Rb (480 nm; 780nm), compatible with LUMIN current experiments. Then these techniques will be transposed for Cs 3-photon experiment (involving 2.26 µm agile laser and 636 nm, 895 nm lasers) in order to work toward the demonstration of a Doppler free multifrequency sensor. The original developed laser architectures have a key advantage to offer fast agility but also unprecedented modulation capabilities at the pump wavelength (480 nm for Rb), which will allow in particular the investigation of transient regime operation and could lead to new interrogation protocols.

The third and final axis of this research involves the development of a fibered deported sensor head, that minimizes its impact on the RF field. To achieve this, RF simulations will be conducted to optimize the design of these fibered cells, first based on glass-blown cell, and secondly MEMs which will be developed and fabricated by IEMN and FEMTO-ST laboratories. This approach aims to enhance sensor performance and accuracy while mitigating interference from the RF environment. The challenges of fibering and heating these cells will be addressed in order to develop a fully deported sensor head.

This highly enriching thesis combines the physics of laser-matter interaction, original lasers and opto-electronic architectures, and microwave field propagation simulations, with significant impacts on high performance RF sensing.

Organization of Research Activities

The following table presents the different research areas and their temporal distribution over the 3 years of the thesis.

	-> 2025	2026				2027				2028		
	1st year				2nd year				3rd year			
I) Multifrequency RF sensing (theory)												
Bibliography, theory and simulation	■	■	■	■	■	■	■	■	■	■	■	
II) Compact and agile laser architectures												
Laser architecture for Rb experiment	■	■	■	■								
Investigations of multifrequency sensor and new interrogation protocols requiring fast modulation				■	■							
Laser architecture for 3-photons Cs experiment					■	■	■	■				
Investigations of doppler-free multidfrequency sensor									■	■	■	
III) Low RF impact and fibered sensor head												
investigations of micro-patterning MEMS cells (RF simulations, characterization)	■	■	■	■	■	■	■	■	■	■		
Towards high performance deported sensor head (Heating and fibering of cells)	■	■	■	■	■	■	■	■	■	■		
glass-blown cells	■	■	■	■	■							
MEMs cells						■	■	■	■	■		
IV) PhD manuscript and Defense											■	■

This thesis will take place in close collaboration between Thales Research and Technology (TRT) and LUMIN, and will primarily be conducted at TRT in Palaiseau (70% at TRT, 30% at LUMIN) and will benefit from the existing collaborations between TRT and LUMIN (Common laboratory, and projects French ASTRID CARDAMONE, EU FED ADEQUADE, French PEPR CARAMELS). The PhD supervisor will be Fabien Bretenaker (LUMIN). The PhD student will be co-supervised by Sacha Welinski and Perrine Berger (TRT).

The doctoral candidate will also benefit from the experience of national and European project consortiums in which TRT and LUMIN participate, and will interact with some of the partners, in particular for the development of MEMs cells (IEMN, FEMTO ST). Their participation in European and international conferences such as CLEO (Optica/IEEE), Photonics West (SPIE), Microwave Photonics (IEEE MWP), or the annual workshop on hot vapor physics will be strongly encouraged in order to present their research work. Finally, the doctoral candidate will write in-depth articles for specialized and high impact journals.

Bibliographie

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