PHY-446 Quantum Sensing and Metrology

Credit Hours: 3-0

Pre-requisite: None

Course Objectives: This course explores how quantum systems can achieve ultra-precise measurements beyond classical limits, leveraging phenomena like entanglement, squeezing, and coherence. This course mainly covers Fundamentals of quantum metrology (Heisenberg limit, quantum Fisher information) and quantum sensing, physical platforms (NV centers, atomic ensembles, superconducting qubits, optomechanical systems) and Applications in magnetometry, gravimetry, timekeeping, and biomedical imaging.

Core Contents: Functional basis and partial differential equations. Fundamentals of quantum sensing and metrology, its physical implementation using quantum optical systems, and its application distributed sensing and quantum Radars.

Detailed Course Contents: Quantum parameter estimation theory, Fisher Information, Estimation error and precision, Cramer-Rao bound, Quantum Fisher information, Quantum Cramer-Rao Bound, Standard Quantum Limit, Heisenberg Limit, Photonic quantum sensing and metrology: quantum optical fields, Field operators, Fock states, Quadrature Operators, Quantum Fluctuations, Coherent states, Quantum optical interferometry, Quantum optical interferometry, Nonclassical States, Squeezed states, Quantum phase sensing, and Quadrature Sensing, Standard Quantum Limit, Supersensitive regime and Heisenberg Limit, Resource theory for quantum sensing and metrology, Entanglement-enhanced sensing, non-classicality enhanced sensing, Distributed quantum sensing, Quantum Radar, Interferometric quantum Radars, Quantum illumination-based quantum radars, Entanglement-assisted quantum radars, Other Applications in magnetometry, gravimetry, timekeeping, and biomedical imaging

Course Outcomes: At the end of the course, students will be able to:

- Fundamentals of Quantum parameter estimation theory, such as Fisher Information, Estimation error and precision

- Various fundamental bounds on precision measurements, such as Cramer-Rao bound, Quantum Fisher information, Quantum Cramer-Rao Bound, Standard Quantum Limit, Heisenberg Limit
- Physically implement using photonic platforms
- understand various applications in Distributed quantum sensing, Quantum Radar, magnetometry, gravimetry, timekeeping, and biomedical imaging

Textbook: 1. Ivan B. Djordjevic, Quantum Communication, Quantum Networks, and Quantum Sensing, Academic Press, 2022. (referenced as IBD)

2. Christopher Gerry and Peter Knight, Introductory Quantum Optics, Cambridge University Press, (2005). (referred as GK)

Reference Books:

- Michael A. Nielson and Isaac L. Chuang, Quantum Computation and Quantum Information, Cambridge University Press, 2000. (NC)
- Emanuele Polino , Mauro Valeri, Nicolò Spagnolo and Fabio Sciarrino, Photonic quantum metrology, *AVS Quantum Sci.* **2**, 024703 (2020). (PVSS)
- M. Fox, Quantum Optics: An Introduction, Oxford University Press, (2005).
- M. O. Scully and M. S. Zubairy, Quantum Optics, Cambridge University Press (1997).

Weekly Breakdown		
Week	**Section**	**Topics**
1	IBD 3.1 3.2	Review on Fundamentals of Quantum Theory, quantum States and Observables,
2	IBD 3.3	Qubits, Superposition Principle, Quantum measurement, density operator, and Entanglement
3	PVSS	Quantum parameter estimation theory, Fisher Information, Estimation error and precision, Cramer-Rao bound
4	PVSS	Quantum Fisher information, Quantum Cramer-Rao Bound

5	PVSS	Standard Quantum Limit, Heisenberg Limit
6	Handouts	Introduction to physical implementation platforms for quantum sensing and metrology, e.g., Photonic systems, NV centres, atomic clocks
7	PVSS, GK 2.1-2.3	Photonic quantum sensing and metrology: quantum optical fields, Field operators, Fock states, Quadrature Operators, Quantum Fluctuations, Coherent states
8	GK 6.2, 6.3	Quantum optical interferometry,
		Midterm Exam
9	GK 7.1, 7.2	Nonclassical States, Squeezed states
10	IBD 11.1	Quantum phase sensing, and Quadrature Sensing
11	IBD 11.2	Standard Quantum Limit, Supersensitive regime and Heisenberg Limit
12	Handouts	Resource theory for quantum sensing and metrology, Entanglement-enhanced sensing, non-classicality enhanced sensing
13	IBD 11.3	Distributed quantum sensing, Quantum Radar
14	IBD 11,4	Interferometric quantum Radars, Quantum illumination-based quantum radars, Entanglement-assisted quantum radars
15	Handouts	Other Applications in magnetometry, gravimetry, timekeeping, and biomedical imaging