Course Title: **Optical Fiber and Quantum Communication Systems**

Credit Hrs: 3

Prerequisites: Quantum Mechanics, Quantum Optics, Classical Optical Fiber Communication, Electromagnetic Theory, UG-level Linear Algebra and Complex Vector Spaces

Course Description:

This course provides an advanced study of optical fiber communication and quantum communication systems. Students learn the fundamentals of light propagation in optical fibers, including attenuation, dispersion, and nonlinear effects, followed by quantum communication protocols such as quantum key distribution (QKD), entanglement-based communication, and secure quantum networks. Emphasis is placed on theoretical derivations, medium-level modeling, simulations of optical and quantum channels, and practical considerations such as decoherence, photon loss, and detector efficiency.

Course Objectives:

- Understand optical fiber propagation and limitations in classical and quantum regimes.
- Master quantum communication protocols, including QKD and entanglement-based schemes.
- Design and simulate quantum communication systems over fiber networks.
- Analyze performance, error rates, and practical implementation challenges.

Course Learning Outcomes (CLOs):

- Explain the physics of light propagation in optical fibers, including attenuation, dispersion, and nonlinear effects.
- Implement and simulate quantum key distribution protocols over fiber networks.
- Analyze entanglement generation, photon detection, and quantum channel performance.
- Evaluate the impact of decoherence, loss, and noise on quantum communication systems.
- Design secure fiber-based quantum communication links and assess their performance using medium-level derivations.

Course Contents

Week	Contents
1.	Introduction to optical fibers: core/cladding structure, total internal reflection, fiber modes, numerical aperture, V-number, single-mode vs multi-mode fibers. Derivation: single-mode cutoff condition.
2.	Fiber propagation: group velocity, chromatic and modal dispersion, attenuation, and fiber loss mechanisms. Derivation: pulse broadening and dispersion length.
3.	Nonlinear effects in fibers: self-phase modulation, cross-phase modulation, four-wave mixing. Practical examples and implications for classical and future quantum signals.
4.	Classical optical communication systems: intensity modulation, direct and coherent detection, link budget analysis, SNR, and BER derivations.
5.	Advanced classical optical systems: wavelength-division multiplexing (WDM), dispersion compensation, fiber amplifiers (EDFA, Raman). Derivation: power budget and multi-channel crosstalk.
6.	Signal processing for fiber systems: filtering, equalization, and error correction. Classical detection limits, noise modeling, and SNR optimization.
7.	Midterm Exam – covering Weeks 1–6 (all classical fiber communication fundamentals and quantum optics basics).
8.	Introduction to quantum communication in optical fibers: single-photon sources, Fock and coherent states, and annihilation/creation operators. Derivation: photon statistics and expectation values.
9.	Quantum key distribution (QKD) in optical fibers: BB84 protocol, polarization and phase encoding, measurement bases, eavesdropping detection. Derivation: secure key rate formulas under ideal conditions.
10.	Entanglement-based quantum communication: E91 protocol, SPDC photon generation, entangled photon pairs, Bell’s inequality, and fidelity. Derivation: correlation functions and error probability in fiber channels.
11.	Quantum channel modeling in fibers: photon loss, decoherence, polarization mode dispersion, and depolarizing noise. Simulation exercises:

qubit fidelity and secure key transmission.

12. Advanced QKD protocols: decoy-state BB84, continuous-variable QKD, and device-independent QKD. Derivation: secret key rate under lossy and noisy channels.

13. Quantum repeaters and long-distance fiber networks: entanglement swapping, purification, and quantum memory. Derivation: repeater-based scaling of key rate and fidelity.

14. Fiber network architectures for quantum communication: point-to-point, star, mesh, hybrid classical-quantum networks. Error analysis and secure multi-user communication.

15. Advanced applications and research topics: multi-photon entanglement, cluster states, teleportation over optical fibers, and photonic quantum gates. Performance evaluation, error thresholds, and security analysis.

16. Final Exam

Textbooks / References:

- Gisin, N., Ribordy, G., Tittel, W., & Zbinden, H. – *Quantum Cryptography*, Rev. Mod. Phys., 2002.
- Mandel, L., & Wolf, E. – *Optical Coherence and Quantum Optics*, Cambridge University Press, 1995.
- Agrawal, G. P. – *Fiber-Optic Communication Systems*, 4th Edition, Wiley, 2010.
- Scarani, V. – *Quantum Physics of Communication and Information*, Oxford University Press, 2019.
- Bouwmeester, D., Ekert, A., & Zeilinger, A. – *The Physics of Quantum Information*, Springer, 2000.
- Bennett, C. H., & Brassard, G. – *Quantum Cryptography: Public Key Distribution and Coin Tossing*, Proc. IEEE Int. Conf., 1984.

Assessments:

- Assignments: 10%
- Quizzes: 10%
- Midterm Exam: 30%
- Final Exam: 50%