Indian Institute of Information Technology, Allahabad

Deoghat, Jhalwa- 211015, Prayagraj, Uttar Pradesh

M. Tech. in Quantum Information & Technologies

Department of Applied Sciences, IIIT Allahabad

Total course credit= 64

Semester-wise courses for M. Tech. in Quantum Information & Technologies

Table 1: First Semester

Sl. No.	Course Name	Code	Type	Credit	Hours L-T-P-S
1.	Mathematical Methods for Quantum Technologies		PCC	4	3–1-0-0
2.	Quantum Mechanics		PCC	4	3–1-0-0
3.	Quantum Technology Lab		PCC	2	0-0-4-0
4.	Quantum Materials		PCC	4	3–1–0-0
5.	Programming for Quantum Technologies		PCC	4	3-0-2-0
Total Credit:				**18**	21 Hrs./week

Table 2: Second Semester

Sl. No.	Course Name	Code	Type	Credit	Hours L-T-P-S
1.	Quantum Computation Essentials		PCC	4	3–1–0-0
2.	Quantum Information & Communication		PCC	4	3–1–0-0
3.	Classical & Quantum Machine Learning		PCC	4	3–0–2-0
4.	Nanoelectronic Devices		PCC	4	3-0-2-0
Total Credit:				**16**	18 Hrs./week

- *** Hours to be read as Credit hours**

EXIT: *After the end of the second Semester, after clearing all the papers, the M. Tech student may be eligible for a PG Diploma in Quantum Information & Technology. However, these students must secure an additional 4 credits during the summer semester to be awarded a PG diploma, which is mandatory. For regular M. Tech students, there is no need for the summer semester.*

Table 3: Exit Option- Summer Semester (for awarding PG-Diploma)

Sl. No.	Course Name	Code	Type	Credit	Hours
					L-T-P-S
1.	Summer Project		ELC	2	0–0–4-0
2.	Quantum Error Correcting Codes		PCCA	2	2–0–0-0
Total Credit:				**4**	6 Hrs./week

Table 4: Third Semester

Sl. No.	Course Name	Code	Type	Credit	Hours
					L-T-P-S
1.	Quantum Cryptography		PCC	4	3–1–0-0
2.	Program Elective I		ELC/ PCC	3	3-0-0-0
3.	Program Elective II		PEC	3	3-0-0-0
4.	Project (Minor)		ELC	6	0–0–12-0
Total Credit:				**16**	22 hrs/per week

Table 5: Fourth Semester

Sl. No.	Course Name	Code	Type	Credit	Hours
					L-T-P-S
1.	Thesis		ELC	14	0–0–28-0
Total Credit:				**14**	28 Hrs./week

Table 6: **Electives basket- I**

Quantum Information & Computing

Sl. No.	Course Name	Code	Type	Credit	Hours L-T-P-S
1.	Quantum Algorithms in the NISQ era		PEC	3	3–0-0-0
2.	Quantum-safe Cryptography		PEC	3	3-0-0-0
3.	Advanced Quantum Information Theory		PEC	3	3-0-0-0
4.	Quantum Error Correcting Codes		PEC	3	3-0-0-0
5.	Advanced Quantum Computation		PEC	3	3-0-0-0
6.	Quantum Computing in Biology		PEC	3	3-0-0-0

Table 7: **Electives basket- II**

Quantum Science & Technologies

Sl. No.	Course Name	Code	Type	Credit	Hours L-T-P-S
1.	Quantum Thermodynamics		PEC	3	3–0-0-0
2.	Quantum Optics		PEC	3	2-2-0-0
3.	Quantum Measurement and Sensing		PEC	3	3-0-0-0
4.	Photonics		PEC	3	2-0-2-0
5.	Spintronics		PEC	3	2-0-2-0
6.	Open Quantum Systems		PEC	3	3-0-0-0
7.	Quantum Many Body Physics		PEC	3	3-0-0-0
8.	Condensed Matter Physics		PEC	3	3-0-0-0
9.	Semiconductor Technology and Devices		PEC	3	2-0-2-0
10.	Black Holes and Quantum Information				

- **More electives may be offered from time to time as approved by the competent authority. Students can also register to courses at NPTEL or SWAYAM portal subject to approval of the competent authority.**

Syllabi of courses

Mathematical Methods for Quantum Technologies

Course outcomes

Students will be able to

1. Develop skills to develop the mathematical frameworks to be applied in Quantum computation and quantum information.
2. Develop problem solving skills, thinking, creativity through assignments, tutorials
3. Gain knowledge of a wide range of mathematical techniques and application of mathematical methods/tools in other scientific and engineering domains.

Course contents

Linear vector spaces; Systems of linear equations; Row reduction and echelon forms; Matrix operations, including inverses, Eigenvalues and eigenvectors; similarity transformation and diagonalization. Symmetric matrices; Positive definite matrices; normal, positive, unitary, and hermitian matrices, similar matrices; Linear transformations; Singular Value Decomposition. Tensor product spaces.

Complex variable theory; Analytic functions; Taylor and Laurent expansions; Classification of singularities; Analytic continuation; Contour integration; Fourier and Laplace transforms and their applications.

Elements of Probability theory, Conditional Probability, Distribution functions, Central Limit Theorem and its applications, Random Walk.

Text Books

- Arfken G.B., Weber H.J. and Harris F.E., Mathematical Methods for Physicists, Seventh edition, Elsevier, 2012.
- Mathews J. and Walker R.L., Mathematical Methods of Physics, Second edition, Pearson Addison-Wesley, 1971.

Reference Books:

- Strang, Gilbert. Introduction to Linear Algebra
- *Advanced Engineering Mathematics: Erwin Kreyszig*

Quantum Mechanics

Course outcomes

Students will be able to

1. Understand the matrix mechanics formulation of quantum mechanics
2. Apply the techniques of quantum mechanics to study the atomic structure
3. Apply the perturbation technique to estimate the energy spectra of quantum systems

Course contents

Review of Hamiltonian Mechanics, Canonical Transformations, and Poisson Brackets. Review of Wave Mechanics.

Stern-Gerlach experiment, two-level systems, Quantum Postulates; Matrix formulation: Dirac's bra and ket notation, discrete and continuous spectra; expectation values, uncertainty principle, linear harmonic oscillator; density matrix and operators' expectation values, commutation relations, Complete set of commuting observables.

Symmetries and conservation laws in QM: Degeneracies, Discrete symmetries. Angular momentum in quantum mechanics: raising and lowering operators, angular momentum addition, Electron spin and Pauli Matrices.

Time-independent perturbation theory: non-degenerate and degenerate cases, Stark and Zeeman effects. Semiclassical (WKB) approximation and variational methods

Text Books

- "Introduction to Quantum Mechanics" by David J. Griffiths and Darrell F. Schroeter.
- "Quantum Mechanics: The Theoretical Minimum" by Leonard Susskind and Art Friedman.
- "Modern Quantum Mechanics" by J.J. Sakurai and Jim Napolitano

Reference Books:

1. Quantum Mechanics, Volume 1: Basic Concepts, Tools, and Applications by Claude Cohen-Tannoudji, Bernard Diu and Franck Laloë
2. Quantum Mechanics, Volume 2: Angular Momentum, Spin, and Approximation Methods by Claude Cohen-Tannoudji, Bernard Diu and Franck Laloë

Quantum Technology Lab

Course outcomes

Students will be able to-

1. Basics of digital electronics and logic gates
2. Basics of analog circuits
3. Basics of optical experiments - polarisation, interference

Course Content and syllabus:

1. Digital Electronics – logic gates i. Combinational circuits a. Half and Full Adder b. Decoder and Encoder ii. Sequential circuits a. Flipflops and Shift Registers

2. Analog electronics i. RLC filters a. Frequency domain modeling of RLC circuits b. Low pass and high pass characteristics c. Quality Factor ii. Diode Circuits a. Rectification and Envelope Detection iii. Op Amp circuits a. Inverting and Non-inverting amplifiers b. Adder circuits

3. Simple experiments that show the quantum nature i. Franck-Hertz ii. Photoelectric effect iii. Balmer lines iv. Compton scattering v. Band gap of semiconductors

4. Basics of Optical Bench

5. Linear Optical elements i. Beam splitters ii. Polarizers, Half-wave plates, and Full-wave plates iii. Diffraction gratings

6. Michelson interferometer on an optical bench 7. Mach-Zehnder interferometer (optional)

Course References:

1. ELECTRONIC DEVICES AND CIRCUIT THEORY,Boylestad / Nashelsk, Pearson Publication
2. Optics Experiments and Demonstrations for Student Laboratories: Principles, methods and applications (IOP Series in Emerging Technologies in Optics and Photonics), Professor Stephen G Lipson, Part of: IOP Series in Emerging Technologies in Optics and Photonics
3. Fundamentals of Photonics, Bahaa E. A. Saleh, Malvin Carl Teich, 2 Volume Set, 3rd Edition, , ISBN: 978-1-119-50687-4

Quantum Materials

Course Outcomes:

In this course, students will learn

1. The basic idea of quantum materials
2. The basics of band theory of solids
3. The basics of magnetism
4. The basics of superconductivity
5. About new 2D materials like graphene, TMDCs
6. About topology and topological phases of matter

Course Content and syllabus:

Band theory basics i. Metals, Semiconductors and Insulators ii. Band structure of solids iii. Survey of semiconducting devices for quantum technologies (electronic, quantum optical devices and principle of operation) Correlated systems,

Magnetism i. Para, ferro magnetism basics ii. Magnetic measurements, Hall effect, magnetoresistance iii. Faraday and Kerr effects

Superconductivity i. BCS theory ii. Ginzburg Landau iii. Josephson Effect – AC and DC Josephson effects iv. Survey of superconducting devices for quantum technologies

2D materials i. Graphene and its properties – single and few layers ii. Transition Metal Dichalcogenides – Electronic and Optical Properties

Topological Phases of matter i. Basics of Topology ii. Geometric phases - Berry Phase iii. Aharonov Bohm effect iv. Topological phases of matter 7

Survey of material growth techniques i. Molecular beam epitaxy ii. Chemical vapor deposition, MOVPE iii. Pulsed laser deposition, etc. iv. Crystal growth technique

Course References:

1. Condensed Matter Physics, M P Marder, 2nd Edition, John Wiley and Sons, 2010
2. Introduction to Superconductivity, Michael Tinkham, standard ed., Medtech (2017)
3. Topological Quantum Materials: Concepts, Models, and Phenomena by By Grigory Tkachov

Programming for Quantum Technologies

Course Outcomes

Students will be able to-

1. Analyze the concepts of algorithm evaluation and find time and space complexities for searching and sorting algorithms.
2. Implement linear data structure such as stacks, queues, linked lists and their applications.
3. Implement basic operations on binary trees

Course contents

1. Basics of programming i. Data structures 2. Basics of algorithms i. sorting ii. searching 3. Basics of Python 4. Basics of Qasm 6. Using toolboxes for quantum technologies in these languages 7. Simulations of simple closed and open quantum systems in packages like QuTiP 8. Using Frameworks such as Qiskit, Cirq, Pennylane

Text Books/References

1. Fundamentals of Data Structures in C by E. Horowitz, S. Sahni, S. Anderson-Freed, Second Edition, 2008.
2. CUDA-Q https://nvidia.github.io/cuda-quantum/latest/index.html 2. Qiskit Textbook https://github.com/Qiskit/textbook 2023 3. Official python tutorial: https://docs.python.org/3/tutorial/index.html 4. Think Python: How to Think Like a Computer Scientist, 2nd edition, Allen B. Downey (O'Reilly, 2015)

Quantum Computation Essentials

Course outcomes

Students will be able to

1. Understand the principles of quantum mechanics relevant to quantum computation.
2. Grasp the concepts of quantum logic gates, circuits
3. Acquire knowledge on quantum algorithms

Course contents

Bloch sphere representation of qubits, Quantum Measurements, Composite systems, Entanglement, Bell's states, Schmidt decomposition.

Quantum Gates, Quantum circuits, Quantum No Cloning Theorem and Teleportation, Quantum Fourier Transform. Simple quantum algorithms-Deutsch Algorithm, Deutsch-Jozsa Algorithm, Grover's search problem, Simon Problem, Shor's algorithm, etc.

Text Books

1. M. Nielsen and I. Chuang, Quantum Computation & Information, Cambridge University Press; Anniversary edition (9 December 2010).
2. Quantum Computer Science: An Introduction; N. David Mermin Cambridge University Press, 2007

References:

1. Fundamentals of Quantum Computing: Theory and Practice; Kasirajan, Venkateswaran

2. John Preskill's notes on his homepage;
3. Umesh Vazirani's lecture notes

Quantum Information & Communication

Course Outcomes:

Upon successful completion of this course, students will:

1. acquire a broad understanding of the mathematical concepts behind quantum communication and computing.
2. be able to recognize and design various quantum communication systems and modulation schemes and be prepared to venture into more advanced areas of quantum communication research.

Course contents:

Introduction to classical information theory: Shannon entropy, classical channels, and channel coding. Notion of von Neumann entropy, quantum channels, accessible information, and Holevo bound transmission through a noisy quantum channel. Fragility of quantum information: Decoherence, Quantum Superposition and Entanglement, Quantum Error Correction: Fault tolerance

Analysis of a quantum communication system, introduction to the Helstrom decision theory of quantum binary communication systems, decision theory of K-ary Quantum communication systems, quantum dense coding, multipartite communication protocols, Holevo's theorem, and constellation of quantum states.

Introduction to Glauber's representation of coherent quantum states, Quantum binary communication systems and different modulation schemes: OOK, BPSK, QAM, PSK, PPM, overview of quantum squeezed states.

Text Book:

1. Protecting Information: From Classical Error Correction to Quantum Cryptography by Susan Loepp and William K. Wootters; Cambridge University Press; 1st edition

2. "Quantum Communications", Gianfranco Cariolaro, Springer, 2015.

3. "Quantum Communication, Quantum Networks, and Quantum Sensing", Ivan B. Djordjevic, Academic Press, 2022.

Reference Books:

1. "Principles of Quantum Communication Theory: A Modern Approach", Sumeet Khatri, and Mark M. Wilde, 2021, Pre-release version, available freely at https://www.markwilde.com/teaching/2021-fall-qit/.

2. "Quantum Computation and Quantum Information", Michael Nielsen and Isaac Chuang, Cambridge University Press, 2010

Classical & Quantum Machine Learning

Course outcomes

Students will be able to-

1. understand the basic ideas of machine learning.
2. able to compare modeling aspects of various machine learning approaches.

Course contents

Decision Trees and K-Nearest-Neighbors, Bias-Variance decomposition, Linear Regression, Perceptron, Logistic Regression, Support Vector Machines (SVM), Kernels and nonlinear SVMs.

Model Selection, Feature Selection, Ensemble Methods, and Gaussian Mixture Models. Hierarchical and Flat Clustering,

Linear Dimensionality Reduction, Matrix Factorization, Nonlinear Dimensionality Reduction, and Manifold Learning

Artificial Neural Network (Forward/Back propagation); Quantum Neural Networks- Quantum support vector machine ii. Quantum back propagation iii. Quantum RNN iv. Quantum CNN

Text Book:

Christopher Bishop, “Pattern recognition and machine learning”, Springer, 2007.

References:

1. Richard Duda, Peter Hart, David Stork, “Pattern Classification”, Wiley; Second edition
2. Tom Mitchell, “Machine Learning”.
3. Hal Daumé III, A Course in Machine Learning (http://ciml.info), 2015
4. Kevin Murphy, “Machine learning: a probabilistic perspective”, MIT Press, 2012.
5. Maria Schuld and Francesco Petruccione, 2018. Supervised Learning with Quantum Computers (1st. ed.). Springer Publishing Company

Quantum Cryptography

Course outcomes

1. Understand the principles of quantum mechanics and how they apply to cryptography
2. Learn about quantum key distribution (QKD) and its applications
3. Understand the vulnerabilities of classical cryptographic systems to quantum attacks
4. Learn about quantum-resistant cryptographic algorithms and how to implement them

Course Content

Introduction to Cryptography, principles of cryptographic design, building cryptography from RSA, Discrete Log.

Key exchange, Symmetric and public key encryption, Random Oracle Model, RSA and Elgamal encryption, Boolean Fourier Analysis,, Hidden subgroup problem, Post Quantum Crypto: Introduction to lattices, Useful Lattice Problems. Learning with Errors and Short Integer Solution problems. Connection to dihedral hidden subgroup problem.

Public key encryption and fully homomorphic encryption, Quantum key distribution, Quantum one time pad, Quantum public key encryption, Quantum fully homomorphic encryption.

Text books

1. Protecting Information: From Classical Error Correction to Quantum Cryptography by Susan Loepp and William K. Wootters; Cambridge University Press; 1st edition
2. Quantum Computation and Quantum Information" by Michael A. Nielsen and Isaac L. Chuang.
3. Quantum Cryptography and Secret-Key Distillation" by Gilles Van Assche

Reference Books

1. "Quantum Cryptography: An Introduction" by Eleanor Rieffel and Wolfgang Polak.
2. "Principles of Quantum Computation and Information" by Giuliano Benenti, Giulio Casati, and Giuliano Strini.

Quantum Error Correcting Codes

Course outcomes

Students would be able to-

1. learn how to reduce the error rate of quantum computers, which are sensitive to noise.
2. know how to operate quantum computers reliably and perform more complex algorithms.

Course contents

Quantum error-correction: quantum codes; the Knill-Laflamme conditions; Pauli error basis; discretization of quantum errors

Constructions: Shor's code, CSS codes, stabilizer codes, topological codes (surface codes, color codes), quantum LDPC codes

Entanglement-assisted quantum error-correcting codes

Fault-tolerant quantum computation

Text Books

1. M.A. Nielsen and I.L. Chuang, *Quantum Computation and Quantum Information*, Cambridge University Press, 2010 (10th Anniversary Edition)
2. D.A. Lidar and T.A. Brun (eds.), *Quantum Error Correction* Cambridge University Press, 2013.
3. John Preskill, Lecture notes on quantum error correcting codes, Physics 219 course website, Caltech
4. Daniel Gottesman's course on Quantum Error Correction and Fault Tolerance, Perimeter Institute, Waterloo, Ontario, Canada

Quantum Optics

Course Outcomes:

Students of this course will learn -

1. To quantise the electromagnetic field
2. The various experimental techniques in photonics
3. The various representations of states of light
4. Classical, semi-classical and fully quantum models of light-matter interaction
5. Modelling decoherence through Master equation

Course Content:

Quantization of the electromagnetic field i. Number states, coherent states, squeezed states ii. Hanbury-Brown and Twiss experiments – Photon bunching, Photon anti bunching iii. Hong-Ou-Mandel interference

Theory of Optical coherence i. Young's double slit experiment and first order coherence ii. Coherence functions of arbitrary order iii. Normal ordering, symmetric ordering and ani-normal ordering of operators iv. Interferometry

Phase-space representations of states of light i. Wigner distribution ii. P-function and the notion of non-classicality with some examples of nonclassical states like squeezed states and their applications iii. Husimi Q function

Light-matter interaction i. Classical model of light-matter interaction ii. Semi-classical model of light-matter interaction iii. Quantum light-matter interaction iv. Rabi Model v. Jayne's-cummings model

Open quantum systems i. Fermi golden rule ii. Born-Markov Lindblad Master Equation

Course References:

1. Introductory Quantum Optics, Christopher Gerry and Peter Knight, Cambridge University Press (2004)
2. Quantum Optics, D. F. Walls, Gerard J. Milburn, 2nd Edition, Springer (2008)
3. Quantum Optics: An introduction, Mark Fox, Oxford University Publishers (2006)
4. Quantum Optics for Beginners, Z. Ficek and M. R. Wahiddin, 1st edition, Jenny Stanford Publishing (2014)
5. Agarwal, Girish S. Quantum optics. Cambridge University Press, 2012

Condensed Matter Physics

Course outcomes:

1.The student will learn the basics techniques to deal with interacting quantum systems, e.g. mean field theory, second quantized operators.

2. Also transport and linear response theories that connect between theory and experimental observations are taught.

3. It introduces theoretical framework such as BCS theory of

Course content:

Review of one-electron band theory. Effects of electron-electron interaction: Hartree -Fock approximation, exchange and correlation effects, density functional theory, Fermi liquid theory, elementary excitations, quasiparticles. Dielectric function of electron systems, screening, plasma oscillation. Optical properties of metals and insulators, excitons. The Hubbard model, spin-and charge-density wave states, metal-insulator transition. Review of the harmonic theory of lattice vibrations. Anharmonic effects. Electron-phonon interaction, phonons in metals, mass renormalization, effective interaction between electrons, polarons. Transport phenomena, Boltzmann equation, electrical and thermal conductivities, thermo-electric effects. Superconductivity-phenomenology, Cooper instability, BCS theory, Ginzburg-Landau theory.

Text/Reference books:

Resources

1. Ashcroft, N.W., and Mermin, N.D., Solid State Physics, Saunders College, Philadelphia.

2. Madelung, O., Introduction to Solid State Theory, Springer-Verlag, Berlin. Jones, W., and March, N.H., Theoretical Solid State Physics, Dover Publications, New York.

3. Philip Phillips, Advanced solid state physics.

4. Giuliani and Vignale, Quantum theory of the electron liquid.

5. P. W. Anderson, Basic notions of condensed matter physics

Bridge -courses (if required)

Elements of Modern Physics (bridge course for engineers)

Outcome of the course: This course would also provide a basic foundation of subsequent courses for the program

Course contents

1. Electrodynamics: review of electrostatics and magnetostatics, Maxwell's equations and applications, elements of special relativity

2. Quantum Mechanics: Solving Schrodinger's equations for stationary states. Harmonic oscillator, Hydrogen Atoms.

3. Statistical Physics: the idea of macroscopic and microscopic variables. The Microcanonical Ensemble, Entropy and the Second Law of Thermodynamics, Temperature An Example: The Two State System; First Law of Thermodynamics, The Canonical Ensemble, The Partition Function, Entropy, Free Energy, The Chemical Potential, Grand Canonical Ensemble

Text Books

1. Classical Mechanics: Classical Mechanics; H. Goldstein, C. Poole, J. Safko.
2. Quantum Mechanics: Introduction to Quantum Mechanics by D . J. Griffiths
3. Modern Physics by A. Beiser. Solid State Physics Physics of semiconductor devices, S M Sze, John Wiley & Sons, 2006.
4. Fundamentals of statistical and thermal physics. F. Reif; Waveland Press, 2009

Data Structure & Algorithms

Course Outcomes

Students will be able to-

- Analyze the concepts of algorithm evaluation and find time and space complexities for searching and sorting algorithms.
- Implement linear data structure such as stacks, queues, linked lists and their applications.
- Implement basic operations on binary trees

Course contents

Introduction, Complexity Analysis, Recursion, Searching, Sorting.

Linked List, Abstract Data Types, Stacks and Queues.

Trees, Traversal, Binary Search Tree, Height Balanced Tree (AVL Tree), Heap, Priority Queue, Heap Sort, Hashing, Dictionaries.

Graphs, Graph Representation, Graph Traversal - DFS, BFS, Minimum Spanning Tree - Prim's and Kruskal's, Single Source Shortest Path - Dijkstra, Geometric data structures.

Text Books/References

- Fundamentals of Data Structures in C by E. Horowitz, S. Sahni, S. Anderson-Freed, Second Edition, 2008.
- Data Structures Using C and C++ by Y. Langsam, M. J. Augenstein, A. M. Tenenbaum, PHI, New Delhi, 2001.
- Data Structures and Algorithm Analysis in C (DSAC) by Mark Allen Weiss, Second Edition, 2002
- Introduction to Algorithms by Thomas H. Cormen, Charles E. Leiserson, Ronald L. Rivest and Clifford Stein, Third Edition, The MIT Press
- Algorithms Design by Jon Kleinberg and Eva Tardos, Pearson