Draft structure of a minor program on Quantum Computing and Quantum Technologies at the UG level

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Preamble:

We propose the structure of a minor program spanning a minimum of 18 credits. Assuming each course is 3 credits (1 credit translating to 1 in-class contact hour per week for a theory course or 1 session of lab for 3 hours for a lab course), this will mean about 6 theory courses. Quantum Technologies is considered here to include the four verticals – quantum computation and simulation, quantum communication and cryptography, quantum sensing and measurement, quantum materials.

Given the very technically advanced nature of the subject, and the prospective unavailability of teachers in all colleges in all the fields, we propose to suggest around 30 credits of courses, out of which any institution can choose 18 credits, that includes some mandatory courses, to suit their in-house teaching resources.

At the very outset, we also feel that the lack of UG-level text books on the various subjects should be addressed by AICTE by contacting experts and taking up a separate project on book-writing over the next two to three years.

Proposed structure of the program:

Minimum credits to fulfil – 18

- A 3.0.0 course has 3 theory lectures per week and considering an average length of 14 weeks for a semester,
- A 3:0 course amounts to at least 36 hours of lectures (considering holidays, exam days etc).
- A **n:m** lab course has **n** hours of lectures and **m** sessions (3 hours each) of lab per week.

QT01: Foundations of Quantum Technologies, 3:0 (Mandatory)

Course Content and syllabus:

- Mathematical Foundations (4 hours) –
  - Linear Algebra
    - Linear Vector Space, Normed Space, Inner Product Space
    - Linear Independence, Completeness, Orthogonality, Rank
    - Hilbert Space
    - Complex matrices – Hermitian and Unitary
    - Eigenvalue Problem – Spectral Theorem
  - Probability and Statistics (basics of statistics, axioms of probabilities, probability distributions, Central Limit Theorem)
- Quantum Mechanics (20 hours):
  - Postulates of Quantum Mechanics
  - Density operator formalism of quantum mechanics – pure and mixed states
  - Superposition and Entanglement in quantum mechanics
  - Time independent and Time-dependent perturbation theory
    - DC and AC Stark shifts
    - Rabi problem
    - Dyson Series
    - Transition probabilities
    - Fermi Golden rule
    - Sudden and slow perturbations
  - Applications of postulates –Particle in a box, Hydrogen atom, Harmonic Oscillator
- EM theory (6 hours)
  - Maxwell’s equations in free space – wave equation, TEM waves
  - Rectangular waveguides, TE and TM modes
  - Maxwell’s equations in material media – dielectrics, conductors
  - Optical fibres
  - Quantisation of EM fields
- Statistical Physics (6 hours)
  - Thermal Equilibrium and Gibbs principle
  - Applying Gibbs principle to Classical and Quantum harmonic oscillators
  - Bosons and Fermions

Course Outcomes: Students of this course learn –

1. The most relevant mathematical techniques
2. Basic postulates of quantum mechanics and applications
3. Basic EM theory with applications
4. Basic statistical physics with applications to quantum systems

Course References:

1. A.B. Bhattacharya and Atanu Nag - Engineering Physics, Khanna Book Publishing.
2. A.B. Bhattacharya and Atanu Nag - Quantum Mechanics for Engineers
3. David G Griffiths – Quantum Mechanics, Pearson
4. David G Griffiths – Electrodynamics, Cambridge University Press
5. F. Reif – Thermal Physics, Waveland Press

QT02: Engg. Foundations of Quantum Technologies 3:0 (optional)

Course Content and syllabus:

- Electrical Networks (4 hours)
    - Analog RLC circuits – resonances, impedances, quality factors
    - Transmission line basics (2 hours)
        - Telegrapher equations, wave impedance, impedance matching, transmission line resonators
- Computer Science (15 hours)
    - Basics of computer architecture (1 hour)
        - Arithmetic Logic Unit
        - Memory
    - Abstract models of computation (12 hours)
        - Finite State Machine
        - Turing Machines
        - Overview of Hierarchy of languages – Regular, Context-Free, Turing Decidable and Turing Recognisable
    - Complexity Theory (2 hours)
        - Time and Space complexity
        - P vs NP, NP-completeness
- Electrical Communications (1 hour)
    - Analog Communications (1 hour)
        - Quadrature amplitude modulation
        - Heterodyne and Homodyne demodulation
- Noise and Signals (6 hours)
    - Characterising Noise
    - Types of Noise
        - Shot Noise
        - Johnson-Nyquist Noise
        - Telegraphic noise or flicker or 1/f noise
    - Signal conditioning and noise mitigation
    - Amplification and Added Noise
        - Linear Amplifier theory
        - Signal-Noise Ratio, Added Noise, Noise Figure of amplification
        - Dynamic Range
        - Noise temperature
        - Quantum limits on noise in linear amplifiers
- Digital Communications (4 hours)
    - Information entropy
    - Noiseless channel encoding
    - Noisy channel encoding
- Basics of cryptography (6 hours)
    - Basics of Number Theory

    - One time pad, Private key, public key, symmetric and asymmetric cryptography protocols
    - RSA

Course Outcomes:

Students of this course learn –

1. Relevant topics from Electrical Networks to design and analyse analog circuits
2. Relevant topics from RF and Microwave Engineering to design systems
3. Relevant topics in Theory of computation to benchmark algorithms
4. Relevant topics in analog and digital communications
5. Basics of cryptography

Course References:

1. Design of Analog Circuits – A.V.N. Tilak
2. Electrical Machinery – P.S. Bimbhra
3. Electrical Power System – Tanmoy Deb
4. Electronic Principles – Malvino
5. Electrical Circuit Analysis – William Hayt
6. Digital Systems – Morris Mano
7. Theory of Computation – Michael Sipser
8. Theory of Computation – Prem Nath
9. Information Theory – Robert B Ash
10. Protecting Information – From Classical error correction to quantum cryptography – Loepp and Wootters
11. Microwave Engineering – David Pozar

QT03: Basic Programming Lab (2:2) (Out of QT03 and QT04, ONE is mandatory)

Course Content and syllabus:

- Basics of programming
    - Data structures, classes, Object-oriented programming
    - Data storage and retrieval, Memory allocation
    - Scientific plotting, documentation of codes
- Simple algorithms and benchmarking run time
    - Sorting
    - Searching
    - Arithmetic algorithms like GCD, Prime factorisation
- Numerical Integration and differential equations
    - Linear 2nd Order ODEs with constant coefficients
    - Linear 2nd order ODEs with variable coefficients
    - Boundary value problems
        - Poisson equation
        - Laplace equation
        - Wave equation
        - Diffusion Equation
- Numerical techniques in linear algebra
    - Matrix inverse
    - Eigenvalue problem
    - Diagonalisation of matrices
    - Singular value decomposition
- Numerical techniques in Probability and Statistics
    - (Pseudo) Random number generation
    - Computing statistical moments for data samples
    - Least Squares fitting
    - Error Analysis
    - Hypothesis Testing
    - Monte Carlo sampling
- Applications to Quantum Mechanics
    - Eigen energies of coupled two level systems
    - Eigen energies of two-level system coupled to oscillator (Jaynes-Cummings Model)
    - Driven two level system – Rabi Problem
    - Driven damped oscillator — coherent states
- Applications to EM theory (e.g. magnetic field simulation)
    - Electrostatic charge distributions
    - Magnetostatic current distributions
    - Finite Element techniques for electromagnetic simulations

Course outcomes:

In this course the students will learn –

1. Basics of programming
2. To write programs to solve scientific problems
3. Techniques for scientific computing
4. Applications to quantum mechanics and electromagnetism

Course References: TBD

QT04: Basic Laboratory Course for Quantum Technologies (1:2) or (2:1) (Out of QT03 and QT04, ONE is mandatory)

Course Content and syllabus:

- Optics
  - Interferometry – wavelength measurements, intensity measurements
  - Diffraction – single slit, grating
  - Microscopy – magnification, aberration
- RLC circuits
  - Series and parallel RLC circuits – Verifying the quality factor formulae
  - Extracting intrinsic losses
- Digital circuits
  - Adder, Multiplier
  - Encoder, Decoder
  - D flipflop, shift registers
  - How to use common Integrated Circuit chips
- Radio Frequency Technology:
  - Using Oscilloscope
    - Ring-up and ring-down time measurements of RLC circuits
    - Measurements of different pulse-shapes generated by a function generator
  - Using Vector Network Analyser
    - Transmission and reflection measurements of coaxial cable in open, short and matched termination
    - Voltage standing wave ratio measurement
    - Amplitude and Phase quadrature, In-phase and Out-of-phase quadrature plots and Quality factor measurement of RLC circuits
    - Characterising S-parameters, ABCD and Z matrices of common 2 port networks – coaxial cable, attenuator, low pass high pass bandpass filters etc.
    - Characterising 3 port networks – directional couplers, circulators, isolators
  - Using a spectrum analyser
    - Noise from a resistor at different temperatures

- Interfacing instruments with a computer

- Data acquisition
  - Signal demodulation – heterodyne vs Homodyne, Mixing of signals
  - Sampling, digitisation using ADCs – undersampling and aliasing, oversampling and noise
  - Averaging and interpolation techniques

Course outcomes:

This course teaches the student to:

1. Learn basic experimental techniques in optics
2. Learn Basic experimental techniques in characterising resonators and RLC circuits
3. Learn basic digital circuits
4. Learn fundamental techniques in RF engineering
5. Learn interfacing instruments with computers and carry out data acquisition

Course References:

1. Optics – Eugene Hecht
2. Art of Electronics – Horowitz and Hill
3. All in One Electronics Simplified – A.K. Maini
4. Electrical Machines – P.S. Bimbhra
5. Digital Design – Morris Mano
6. Microwave Engineering – David Pozar
7. Discrete-time signal processing – Oppenheim and Shaffer

QT05: Solid State Physics for Quantum Technologies 3:0

Course Content and syllabus:

- Structure of solids –
    - Symmetry, Bravais lattices
    - Laue equations and Bragg's law,
    - Brillouin Zones
    - Atomic scattering and structure factors.
- Characterisation of crystal structures – XRD etc.
- Bonding in solids –
    - van der Waals and Repulsive interactions,
    - Lennard Jones potential,
    - Madelung constant
- The Drude theory of metals –
    - DC & AC electrical conductivity of a metal;
    - Hall effect & magnetoresistance,
    - Density of states, Fermi-Dirac distribution, Specific heat of degenerate electron gases
    - Free electron model
- Beyond the Free electron model
    - Kronig-Penney Model
    - Periodic potential – Bloch Theorem
    - Band theory
    - Tight binding model
- Phonons in Solids
    - One dimensional monoatomic and diatomic chains
    - Normal modes and Phonons
    - Phonon spectrum
    - Long wavelength acoustic phonons and elastic constants
    - Vibrational Properties- normal modes, acoustic and optical phonons.
- Magnetism
    - Dia-, Para-, and Ferromagnetism
    - Langevin's theory of paramagnetism
    - Weiss Molecular theory
- Superconductivity:
    - Phenomenological description – Zero resistance, Meissner effect
    - London Theory
    - BCS theory
    - Ginzburg-Landau Theory
    - Type-I and type-II superconductors
    - Flux quantization
    - Josephson effect.
    - High Tc superconductivity

Course Outcomes: The students of this course will learn the

1. Basics of solid states physics
2. Various approximations for electronic states in matter
3. The theory of phonons in solids
4. The theory of magnetism
5. The theory of superconductivity

Course References:

1. Engineering Physics – A.B. Bhattacharya & Atanu Nag
2. Solid State Physics – Charles Kittel
3. Solid State Physics – Ashcroft and Mermin
4. Condensed Matter Physics – Marder
5. Introduction to Superconductivity – Michael Tinkham

QT06: Introduction to Quantum Computation 3:0

Course Content and syllabus:

- Axiomatic quantum theory
    - Quantum states, observables, measurement
    - Hilbert Space, Unitary Transformations
    - Schrodinger Equation and Unitary evolution
    - No cloning theorem
- Qubits versus classical bits
    - Spin-half systems and photon polarizations
    - Trapped atoms and ions
    - Artificial atoms using circuits
    - Semiconducting quantum dots
    - Single and Two qubit gates – Solovay - Kitaev Theorem
- Pure and mixed states
    - Density matrices
    - General quantum evolution and superoperators
    - Positive and Completely Positive Trace-Preserving Maps and Kraus Operators
- Quantum correlations
    - Entanglement and Bell’s theorems
- Review of Turing machines and classical computational complexity
- Reversible computation
- Universal quantum logic gates and circuits
- Quantum algorithms
    - Deutsch algorithm
    - Deutsch Josza algorithm
    - Bernstein - Vazirani algorithm
- Database search
    - Grover’s algorithm
- Quantum Fourier Transform and prime factorization
    - Shor’s Algorithm.
- Introduction to Error correction
    - Fault-tolerance
    - Simple error correcting codes
- Survey of current status
    - NISQ era processors
    - Quantum advantage claims
    - Roadmap for future

Course outcomes: Students in this course will learn

1. To review the basic postulates of quantum mechanics
2. The theoretical basics of qubits and their physical realisations
3. To work with density operators and time evolution for mixed states
4. The basic ideas of quantum gates

5. The working of important quantum algorithms
6. The basics of quantum error correction
7. The state of the field and future roadmap.

Course References:

1. Quantum Mechanics for Engineers – A.B. Bhattacharya & Atanu Nag
2. Quantum Computation and Quantum Information – Nielsen and Chuang
3. Quantum Information Science – Motta and Manenti
4. Quantum error Correction - Frank Gaitan
5. Quantum computing explained- David McMahon.
6. Introduction to Quantum Computing – Hui Yung Wong
7. Quantum Computing and Techniques – Rajiv Chopra

QT07: Hardware Platforms for Quantum Technologies 3:0 (Mandatory)

Course Content and syllabus:

- Quantum Computation
    - Divincenzo criteria for realising qubits
    - Basics of qubit gates
    - Basics of quantum circuits
    - Solid State Qubits
        - Semiconducting Qubits – quantum dots, spins
        - Superconducting Qubits – charge, flux and phase
        - Topological Qubits – proposals and advantages
    - Atoms and Ions
        - Trapped ions
        - Rydberg atoms
        - Neutral atoms
    - Photonic Qubits
        - Conventional linear optical l setups
        - Integrated Photonics
    - NMR qubits
        - Conventional NMR qubits
        - NV centres
- Quantum Sensing
    - Basics of Photon (single and entangled) generation
    - Basics of photo detection
    - Gravimetry
    - Atomic clock
    - Mangnetometry
- Quantum Communications
    - Terrestrial – fibrebased
    - Free space, Satellite-based
- **Quantum Materials is going to be covered in the other portions of the course whenever required.**

Course Outcomes: Students in this course:

1. Learn about the general physical principles of realising qubits for computation
2. Learn about the various hardware implementations of qubits for computation
3. Learn about the basic ideas of quantum sensing
4. Learn about the applications of quantum sensing
5. Learn about the implementations of quantum communications protocols in fibre-based and free-space

Course References:

1. Quantum Information Science – Motta and Manenti
2. Quantum computation and quantum information – Nielsen and Chuang
3. Quantum Computing and Techniques – Rajiv Chopra

QT08: Introduction to Quantum Communication

Course Content and syllabus:

- Basics of EM waves and wave equation
    - Maxwell’s equations in free space
    - Maxwell’s equations in dielectric media
    - Maxwell’s equations in lossy media
- Basics of linear and square-law detectors
    - Quadrature amplitude modulation
    - Heterodyne and Homodyne demodulation and linear detectors
    - Intensity measurements and square law detectors
    - Photomultipliers, Avalanche Photo diodes
- Digital communication – information theory (basics)
    - Information entropy
    - Noiseless channel encoding
    - Noisy channel encoding
- Axiomatic quantum theory
    - Principle of superposition
    - Unitary evolution
    - Pure and mixed states
    - Measurement Postulate
    - No cloning theorem
- Entanglement and Bell Theorems
- Bell Measurements and Tests
- Quantum Teleportation protocol
- Quantum Dense coding
- Quantum Key Distribution protocols
    - BB84
    - E91
    - BBM92.
    - B92
- Survey of Hardware implementations
    - Free space communications
    - Satellite based communications
    - Fibre optics-based communications

Course Outcomes:

Students in this course:

1. Review the basics of EM theory
2. Learn the basics of photodetection
3. Learn the basics of information theory
4. Learn the central ideas in quantum communications

Course References:

1. Quantum Computing and Techniques – Rajiv Chopra, Khanna Publishing House, 2024.
2. Quantum computation and quantum information – Nielsen and Chuang Cambridge University Press, Cambridge, 2010
3. A Pathak, Elements of Quantum Computation and Quantum Communication, Boca Raton, CRC Press, 2015

QT09: Introduction to Quantum Sensing 3:0 (optional)

Course Content and syllabus:

- Classical sensing
  - photo detection
- Classical Noise
  - Johnson Noise, Telegraph noise, flicker or 1/f noise
- Sensitivity of classical measurements
  - Classical Fisher information
  - Cramer - Rao bounds (information theory basics may be required here).
- Quantum measurements
  - projective/orthogonal measurements
  - Approximate/non-orthogonal measurements
  - Weak continuous measurements
  - Error-disturbance relations
  - Standard quantum limits
  - Quantum non-demolition measurements
- States of light
  - fock states
  - Coherent states
  - Squeezed states
  - Tomography
  - Wigner quasiprobability distribution
  - P-distribution
  - Husimi Q function
- Quantum photo detection
  - Square-law detectors, Intensity measurements and Photo-detection
  - Linear Detectors and Quadrature Measurements
- Quantum Cramer-Rao bounds
- Single photon-based sensing applications
- Entanglement based sensing applications
- Atomic state-based sensing, solid-state spin-based sensing applications (gravimetry, magnetometry)

Course Outcomes: In this course, students will learn how

1. The basics of classical sensing
2. Aspects of quantum measurement
3. Ways to quantify quantum sensing
4. About measurements of quantum states of light
5. About the applications of quantum sensing

Course References:

1. Quantum Measurement and Control – Wiseman and Milburn

2. Quantum Measurement – Braginsky and Khalili
3. Quantum Information Science – Motta and Manenti
4. Quantum Computing and Techniques – Rajiv Chopra

QT10: Introduction to Quantum Materials 3:0 (optional)

Course Content and syllabus:

- Band theory basics
  - Metals, Semiconductors and Insulators
  - Band structure of solids
  - Survey of semiconducting devices for quantum technologies (electronic, quantum optical devices and principle of operation)
- Correlated systems
- Magnetism
  - Para, ferro magnetism basics
  - Magnetic measurements, hall effect, magnetoresistance
  - Faraday and Kerr effects
- Superconductivity
  - BCS theory
  - Ginzburg Landau
  - Josephson Effect – AC and DC Josephson effects
  - Survey of superconducting devices for quantum technologies
- 2D materials
  - Graphene and its properties – single and few layers
  - Transition Metal Dichalcogenides – Electronic and Optical Properties
- Topological Phases of matter
  - Basics of Topology
  - Geometric phases - Berry Phase
  - Aharonov Bohm effect
  - Topological phases of matter
- Survey of material growth techniques
  - Molecular beam epitaxy
  - Chemical vapor deposition, MOVPE
  - Pulsed laser deposition, etc.
  - Crystal growth techniques

Course Outcomes:

In this course, students will learn

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

Course References:

1. Engineering Physics – A.B. Bhattacharya & Atanu Nag
2. Condensed Matter Physics – Marder
3. Introduction to Superconductivity – Michael TInkham

QT11: Quantum Optics 3:0 (optional)

Course Content and syllabus:

- Quantization of the electromagnetic field
  - Number states, coherent states, squeezed states
  - Hanbury-Brown and Twiss experiments – Photon bunching, Photon anti bunching
  - Hong-Ou-Mandel interference
- Theory of Optical coherence
  - Young's double slit experiment and first order coherence
  - Coherence functions of arbitrary order
  - Normal ordering, symmetric ordering and ani-normal ordering of operators
  - Interferometry
- Phase-space representations of states of light
  - Wigner distribution
  - P-distribution
  - Husimi Q function
- Light-matter interaction
  - Classical model of light-matter interaction
  - Semi-classical model of light-matter interaction
  - Quantum light-matter interaction
  - Rabi Model
  - Jayne's-cummings model
- Open quantum systems
  - Fermi golden rule
  - Born-Markov Lindblad Master Equation

Course Outcomes:

In this course, students will

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

Course References:

1. Engineering Physics – A.B. Bhattacharya & Atanu Nag
2. Introductory Quantum Optics – Gerry and Knight
3. Quantum optics – Walls and Milburn
4. Quantum Optics – Girish Agrawal
5. Quantum Measurement and Control – Wiseman and Milburn