Nanyang Technological University
Division of Physics and Applied Physics

# COURSE CONTENT FOR PAP732 for Undergraduates

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| **Academic Year** | 2022/23 | **Semester** | 2 |
| **Course Coordinator** | Prof. Sun Handong | | |
| **Course Code** | PAP732 | | |
| **Course Title** | Advanced Optics | | |
| **Pre-requisites** | PH2301 Physical Optics or equivalent and PH2101 Quantum Mechanics, and PHY (PPHY) or PHY (APHY) programme and CGPA 4.0 or higher | | |
| **No of AUs** | 4 | | |
| **Contact Hours** | Lecture: 39 hours; Tutorial: 12 hours<br>(3 hr – lecture each week; 1 hr – tutorial each week) | | |
| **Proposal Date** | 17 February 2022 | | |

## Course Aims

This course intends to equip you with the fundamental concept and principles of key topics in advanced optics and nonlinear optics. You will gain knowledge in the mechanisms of beam manipulation, generation of ultrafast laser pulses, optical resonators, wavelength conversion, nonlinear absorption etc. Based on this knowledge, you will be able to make both predictions and interpretation in important applications such as in lasers and advanced optics. In conclusion, after taking this course, your problem-solving skills will be sharpened and you will have the necessary foundation to tackle problems in advanced photonics related research.

## Intended Learning Outcomes (ILO)

Upon the successful completion of this course, you (as a student) would be **able to**:

1. use the concepts and methods (such as postulates of ray optics) to analyse and solve problems for practical applications (such as examining various optical components (planar mirrors, parabolic mirrors, elliptical mirrors and spherical mirrors, prisms, beam splitters, lenses and light guides) and their unique properties, and apply the ray equation and paraxial wave equation to graded-index optical components.).
2. apply ray transfer matrix to simple optical components, cascaded optical components and periodic optical systems.
3. examine the solutions of the Helmholtz equation for plane waves and spherical waves.
4. apply the Fresnel approximation to spherical waves to obtain the paraboloidal wave and the validity of the Fresnel approximation, and establish the relation between Wave Optics and Ray Optics.
5. apply wave optics to describe polychromatic & pulsed Light.
6. apply Ray-Transfer Matrix to characterize and manipulate Gaussian beams.
7. use optical components to generate Hermite-Gaussian beams, Laguerre-Gaussian beams and Bessel beams.
8. apply Gaussian optics to analyse and design laser resonators
9. apply Maxwell equations to describe and analyse nonlinear optical media.
10. use the concepts and method of wave optics to investigate the origin and manipulation of nonlinear optical processes
11. use the concepts and method of quantum mechanics to investigate the origin and manipulation of nonlinear optical processes
12. apply the principles of Nonlinear Optics to wavelength conversion, THz generation and detection, supercontinuum, intensity related refractive index, photorefractive effect, stimulated Raman scattering etc.

**Course Content**

**Ray Optics**
Postulates of Ray Optics
Simple Optical Components
Graded-Index Optics
The Eikonal Equation
Matrix Optics

**Wave optics**
Postulates of Wave Optics
Monochromatic Waves
Relation between Wave Optics and Ray Optics
Simple Optical Components
Interference
Polychromatic & Pulsed Light

**Beam Optics**
The Gaussian Beam
Transmission through simple optical components
Transmission through an arbitrary optical component
Hermite-Gaussian beams
Laguerre-Gaussian Beams
Bessel Beams

**Resonator optics**
Planar-Mirror Resonators

- Resonator Modes;
- Density of Modes
- Losses and Resonance Spectral Width
- Sources of Resonator Loss;
- Photon Lifetime;
- Q-Factor
- Off-axis Resonator Modes

Spherical-Mirror Resonators

- Ray Confinement – confinement conditions, g-parameters, planar, confocal and concentric resonators
- Gaussian Beam – a mode of the spherical mirror resonator
- Resonance Frequencies
- Hermite-Gaussian Modes

**Nonlinear Optical Phenomena**
Sum- and difference-frequency generation
Parametric versus nonparametric Process
Formal definition of nonlinear optical susceptibility
Anharmonic oscillator model
Properties of the nonlinear susceptibility
Time-domain description of optical nonlinearities

**Wave Description on NLO**
The Wave Equation for Nonlinear Optical Media
The Coupled-Wave Equations for Sum-Frequency Generation
The Manley–Rowe Relations
Sum-Frequency Generation
Second-Harmonic Generation
Phase-Matching Considerations
Optical Parametric Oscillators
Quasi-Phase-Matching

**Quantum-Mechanical Theory of the Nonlinear Optical Susceptibility**
Introduction of Perturbation theory
Schrödinger equation calculation of the nonlinear optical susceptibility
Density Matrix Formalism of Quantum Mechanics
Perturbation solution of the Density matrix equation of motion
Density Matrix Calculation of the Linear Susceptibility
Density Matrix Calculation of the Second-order Susceptibility
Density Matrix Calculation of the Third-Order Susceptibility
Electromagnetically Induced Transparency

**The Intensity-Dependent Refractive Index**
Descriptions of the Intensity-Dependent Refractive Index
Tensor Nature of the Third-Order Susceptibility
Propagation through Isotropic Nonlinear Media
Nonlinearities Due to Molecular Orientation
Thermal Nonlinear Optical Effects
Semiconductor Nonlinearities

**Assessment (includes both continuous and summative assessment)**

| Component | Course LO Tested | Related Programme LO or Graduate Attributes | Weighting | Team / Individual | Assessment Rubrics |
|---|---|---|---|---|---|
| 1. CA1: Project and presentation | All | Communication (1,2,3) Creativity (1,2) Character (1,2,3) | 50% | Individual | Rubrics marking- (see Appendix 1) report and presentation carry equal weight to the CA component |
| 2. CA2: Homework | All | Competency (1,2,3,4) Character (1,2) | 20% | Individual | Point-based marking (not rubric-based) |
| 3. CA3: Mid-term Test | 1-8 | Competency (1,2, 4,5) | 30% | Individual | Point-based marking (not rubric-based) |
| Total | | | 100% | | |

**Formative feedback**

Formative feedback is given through discussion within tutorial lessons. Feedback is always provided for your response to each question.

Feedback is also given after each midterm on the common mistakes and level of difficulty of the problems.

Feedback is also given during consultant discussion.

**Learning and Teaching approach**

| Approach | How does this approach support students in achieving the learning outcomes? |
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| **Use of Learning Catalytics** (tutorial and lecture) | This helps to engage you and serves to identify any prior misconceptions that you may have in order to better assist you in your learning journey. |
| **Lectures** | Warm-up questions will be raised first, followed by lectures that further explains the physics based on the questions. Then wrap-up questions will also be provided. |
| **Tutorial** | You will review main concepts learned in lectures with TAs. This helps you to digest and understand better. |
| **Homework** | The homework comprises standard textbook practice questions that are covered during tutorial. |

**Reading and References**

Text book:

1. "Fundamental of Photonics", Bahaa E. A. Saleh and Malvin Carl Teich, Wiley-Interscience ISBN: 978-0-471-35832-9
2. "Nonlinear Optics", R.W. Boyd, Academic Press, 3rd Edition, ISBN: 978-0-323-85057-5

Other references:

1. "Quantum Electronics", A. Yariv, 3rd Edition, Wiley, ISBN: 0471609978 (ISBN13: 9780471609971)

2. "The principles of Nonlinear Optics", Y. R. Shen, John Wiley, ISBN: 978-0-471-43080-3

**Course Policies and Student Responsibilities**

*Absence Due to Medical or Other Reasons*

If you are sick and unable to attend your class / Mid-terms, you have to:

1. Send an email to the instructor regarding the absence and request for a replacement class and make-up mid-terms.
2. Submit the original Medical Certificate* or official letter of excuse to administrator.
3. Attend the assigned replacement class (*subject to availability*) and make-up mid-terms (*subject to availability*).

* The medical certificate mentioned above should be issued in Singapore by a medical practitioner registered with the Singapore Medical Association.

**Academic Integrity**

Good academic work depends on honesty and ethical behaviour. The quality of your work as a student relies on adhering to the principles of academic integrity and to the NTU Honour Code, a set of values shared by the whole university community. Truth, Trust and Justice are at the core of NTU's shared values.

As a student, it is important that you recognize your responsibilities in understanding and applying the principles of academic integrity in all the work you do at NTU. Not knowing what is involved in maintaining academic integrity does not excuse academic dishonesty. You need to actively equip yourself with strategies to avoid all forms of academic dishonesty, including plagiarism, academic fraud, collusion and cheating. If you are uncertain of the definitions of any of these terms, you should go to the academic integrity website for more information. Consult your instructor(s) if you need any clarification about the requirements of academic integrity in the course.

**Course Instructors**

| Instructor | Office Location | Phone | Email |
|---|---|---|---|
| Prof. Sun Handong | SPMS-PAP-04-12 | 65138083 | hdsun@ntu.edu.sg |

**Planned Weekly Schedule**

| Week | Topic | Course LO | Readings/ Activities |
|---|---|---|---|
| 1 | Ray Optics | 1,2 | Lecture notes – Ray Optics(I) |
| 2 | Ray Optics, Wave Optics | 1,2,3 | Lecture notes – Ray Optics(II)+ Wave Optics(I) |
| 3 | Wave Optics | 3,4,5 | Lecture notes – Wave Optics(II) |
| 4 | Beam Optics | 6 | Lecture notes – Beam Optics(I)+ Beam Optics(II) |
| 5 | Beam Optics, Resonator Optics | 7,8 | Lecture notes – Beam Optics(III)+ Resonator Optics(I) |
| 6 | Resonator Optics | 8 | Lecture notes – Resonator Optics(II) |
| 7 | Revision and Midterm test | | |
| 8 | Nonlinear Optical Phenomena | 9 | Lecture notes – NLO 1-Fundamental- NLO Susceptibility |
| 9 | Wave Description on NLO | 10 | Lecture notes – NLO 2-wave description of NLO |
| 10 | Quantum-Mechanical Theory of the Nonlinear Optical Susceptibility | 11 | Lecture notes – NLO 3-QM Theory of NLO-I&II |
| 11 | Quantum-Mechanical Theory of the Nonlinear Optical Susceptibility | 11 | Lecture notes – NLO 3-QM Theory of NLO-II&III |
| 12 | The Intensity-Dependent Refractive Index | 12 | Lecture notes – NLO 4- Intensity dependent Refractive Index |

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| 13 | Project Presentation, Revisions | | |

**Appendix 1**

## Project Presentation

| Criteria | Does not meet standard (0 - 2) (Prestructural) | Nearly Meets Standard (3 – 4) (Unistructural) | Meets Standard (5 - 6) (Multi-structural) | Exceeds Standard (7 - 8) (Relational) | Far Exceeds Standard (9 - 10) (Extended Abstract) |
|---|---|---|---|---|---|
| **Organization and structure** | No clear structure apparent to the presentation. Ideas appear scattered and incoherent. No clear distinction between introduction of background concepts, presentation of main results, and conclusions. | Somewhat structured presentation. Distinct sections such as introduction, results, conclusions, etc. exist, but sections are incomplete and their content scattered / unstructured. | Structured presentation. Distinct sections such as introduction, results, conclusions, etc. exist, and their content is mostly organized. Key conclusions are only apparent after reading the conclusions slide. | Well-structured presentation. Distinct sections such as introduction, results, conclusions, etc. exist, their content is well-organized throughout the presentation, and the key conclusions are clear throughout. | Above standard structured presentation. Content of introduction, results, conclusions, etc. are well organized throughout the entire presentation, presenting content not only comprehen-sively, but efficiently. |
| **Visual presentation (e.g. design of presentation slides)** | Ineffective or no use of presentation technology (e.g. PowerPoint) at all. | Somewhat effective use of presentation technology (e.g. PowerPoint slides). Technology is used but content presented is mostly illegible and disorganized | Effective use of technology (e.g. PowerPoint slides). Information legible and well-organized throughout most of the presentation. | Effective use of technology (e.g. PowerPoint slides). Information legible and well-organized throughout the entire presentation. | Effective and creative use of technology (e.g. PowerPoint slides). Information is not legible but also well-structured. Additional technology / applets (e.g. PPT animations are being used to further illustrate complex concepts. |

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| **Effectiveness of oral presentation and Q&A** | Does not communicate ideas effectively. Uses pace, tone and style ineffectively (monotonous style) and hence loses attention of audience through most of the presentation. | Communicates ideas somewhat effectively. Ideas are mostly comprehensible and communicated somewhat effectively by use of pace, tone and style. Maintains attention of audience in some parts of the presentation. | Communicates ideas in an effective and understandable manner. Uses pace, tone and style effectively, most of the time. Catches the interest of the audience through most of the presentation | Communicates difficult or complex ideas in an effective and understandable way. Uses pace, tone and style effectively all the time, and catches the interest of the audience, or engages the audience throughout | Far exceeds expectations of a fourth year student in communicating complex scientific concepts. Uses pace, tone and style not only effectively but also creatively. Never loses interest and engagement of the audience |
| **Individual Contribution** | Little to no effective contribution in the presentation and Q&A portions, displays little knowledge in the chosen topic. | Contribution in the presentation and Q&A portions reflect only one aspect the chosen topic. Limited insights. | Contribution in the presentation and Q&A portions reflect more than one aspect of the chosen topic, but does not connect them as a coherent whole. Insights may be unoriginal. | Contribution in the presentation and Q&A portions reflect depth of knowledge not only in an individual segment, but in the whole topic. Insights are thoughtful and analytical. | Contribution in the presentation and Q&A portions reflect coherence, fluency, and depth of knowledge in the whole topic. Comes across as an integral part of the team. Insights are critical and offer new or unique perspectives on the topic. |

**Project Report**

| **Criteria** | **Does not meet standard (0 - 2) (Prestructural)** | **Nearly Meets Standard (3 – 4) (Unistructural)** | **Meets Standard (5 - 6) (Multi-structural)** | **Exceeds Standard (7 - 8) (Relational)** | **Far Exceeds Standard (9 - 10) (Extended Abstract)** |
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| **Problem or Research Statement** | Unclear and inaccurate or illogical statement. | Somewhat unclear or unable to accurately portray the problem. | Mostly clear and accurately communicated for the focused reader. | Clearly and accurately communicated, and gives most background or context and motivation. | Comprehensive description and overview of the topic, satisfactory to the expert reader. |
| **Correctness and appropriate description of the physics** | Incorrect or inappropriate use of physics in most areas. | Mostly correct and appropriate use of physics. But flawed in parts. | Correct and appropriate use of physics, with some clarity on assumptions, approximations, experimental techniques, and derivations. | Correct and appropriate use of physics, with assumptions, approximations, experimental techniques, and derivations that are accurate and detailed. | Correct and appropriate use of physics, with assumptions, approximations, experimental techniques, and derivations that are accurate and detailed. With further details of their limitation and how these could be improved. |
| **Development of Ideas** | Does not clearly introduce the topic. Does not establish or maintain focus on the topic. | Introduces the topic. Somewhat maintains focus on the topic, but lost in some parts. Development of some of the ideas. | Introduces the topic clearly. Maintains focus on the topic. Development of and/or connection between ideas are clear and correct. | Introduces the topic clearly and creatively. Maintains clear focus on the topic throughout. Development of and connection between ideas are clear and correct. | Introduces the topic clearly and creatively. Maintains clear focus on the topic throughout. Development of and connection between ideas are clear and correct. Gives detailed outlook on how ideas could be further developed in the future. |
| **Use of secondary material (references and citations)** | Improper and unclear citations and attribution of others' work in most part, and with major errors. | Partly proper and clear citations and attribution of others' work, with some errors. | Proper, accurate and clear citations and attribution of others' work in most parts. | Proper, accurate and clear citations and attribution of others' work throughout. | Proper, accurate and complete referencing and attribution of others' work in the field. |

***Graduate Attributes***

***What we want our graduates from Physics and Applied Physics to be able to do:***

Upon the successful completion of the PHY, APHY, PHME and PHMS programs, graduates should be able to:

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| ***Competency*** | 1 | demonstrate a rigorous understanding of the core theories and principles of physics involving (but not limited to) areas such as classical mechanics, electromagnetism, thermal physics and quantum mechanics<br><br>[PHMS only] demonstrate a rigorous understanding of the core theories and principles of mathematical sciences involving (but not limited to) areas such as analysis, algebra and statistical analysis |
| | 2 | read and understand undergraduate level physics content independently; |
| | 3 | make educated guesses / estimations of physical quantities in general; |
| | 4 | apply fundamental physics knowledge, logical reasoning, mathematical and computational skills to analyse, model and solve problems; |
| | 5 | develop theoretical descriptions of physical phenomena with an understanding of the underlying assumptions and limitations; |
| | 6 | critically evaluate and distinguish sources of scientific/non-scientific information and to recommend appropriate decisions and choices when needed; |
| | 7 | demonstrate the ability to design and conduct experiments in a Physics laboratory, to make measurements, analyse and interpret data to draw valid conclusions. |

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| ***Creativity*** | 1 | propose valid approaches to tackle open-ended problems in unexplored domains; |
| | 2 | offer valid alternative perspectives/approaches to a given situation or problem. |

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| ***Communication*** | 1 | describe physical phenomena with scientifically sound principles; |
| | 2 | communicate (in writing and speaking) scientific and non-scientific ideas effectively to professional scientists and to the general public; |
| | 3 | communicate effectively with team members when working in a group. |

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| ***Character*** | 1 | uphold absolute integrity when conducting scientific experiments, reporting and using the scientific results; |
| | 2 | readily pick up new skills, particularly technology related ones, to tackle new problems; |
| | 3 | contribute as a valued team member when working in a group. |

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| ***Civic Mindedness*** | 1 | put together the skills and knowledge into their work in an effective, responsible and ethical manner for the benefits of society. |