

2nd
Edition

K. Thyagarajan • Ajoy Ghatak



LASERS

Fundamentals
and Applications

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Fundamentals and Applications

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SECOND EDITION

K. Thyagarajan
Ajoy Ghatak

Indian Institute of Technology
New Delhi, India





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Preface to the Second Edition

It is exactly 50 years since the first laser was realized. Lasers emit coherent electromagnetic radiation and ever since their invention, they have assumed tremendous importance in the fields of science, engineering and technology because of their impact in both basic research as well as in various technological applications. Lasers are ubiquitous and can be found in consumer goods such as music players, laser printers, scanners for product identification, in industries like metal cutting, welding, hole drilling, marking etc., in medical applications in surgery and in scientific applications like in spectroscopy, interferometry, testing of foundations of quantum mechanics etc. The scientific and technological advances have enabled lasers spanning time scales from continuous operation up to as short as a hundred attoseconds, wavelengths spanning almost the entire electromagnetic spectrum up to the X-ray region, power levels into the terawatt region and sizes ranging from tiny few tens of nanometers to lasers having a length of 270 km. The range of available power, pulse widths and wavelengths is extremely wide and one can almost always find a laser that can fit into a desired application be it material processing, medical application or in scientific or engineering discipline. Laser being the fundamental source with such a range of properties and such wide applications, a course on the fundamentals and applications of lasers to both scientists and engineers has become imperative.

The present book attempts to provide a coherent presentation of the basic physics behind the working of the laser along with some of their most important applications and has grown out of the lectures given by the authors to senior undergraduate and graduate students at the Indian Institute of Technology Delhi.

In the first part of the book, after covering basic optics and basic quantum mechanics, the book goes on to discuss the basic physics behind laser operation, some important laser types and the special properties of laser beams. Fiber lasers and semiconductor lasers which are two of the most important laser types today are discussed in greater detail and so is the parametric oscillator which uses optical nonlinearity for optical amplification and oscillation and is one of the most important tunable lasers. The coverage is from first principles so that the book can also be used for self study. The tutorial coverage of fiber lasers given in the book is unique and should serve as a very good introduction to the subject of fiber amplifiers and lasers. Towards the end of the first part of the book we discuss quantization of electromagnetic field and develop the concept of photons, which forms the basic foundation of the field of quantum optics.

The second part of the book discusses some of the most important applications of lasers in spatial frequency filtering, holography, laser induced fusion, lightwave communications, and in science and in industry. Although there are many more applications that are not included in the book, we feel that we have covered some of the most important applications.

We believe that the reader should have some sense of perspective of the history of the development of the laser. One obvious way to go about would be to introduce the reader to some of the original papers; unfortunately these papers are usually not easy to read and involve considerable mathematical complexity. We felt that the Nobel lectures of Charles H Townes, Nicolai G Basov and A M Prokhorov would convey the development of the subject in a manner that could not possibly be matched and therefore in the third part of the book we reproduce these Nobel Lectures. We have also reproduced the Nobel lecture of Theodor W Hansch who in 2005 was jointly awarded the Nobel Prize for developing an optical “*frequency comb synthesizer*”, which makes it possible, for the first time, to measure with extreme precision the number of light oscillations per second. The frequency comb techniques described in the lecture are also offering powerful new tools for ultrafast physics.

Numerical examples are scattered throughout the book for helping the student to have a better appreciation of the concepts and the problems at the end of each chapter should provide the student with gaining a better understanding of the basics and help in applying the concepts to practical situations. Some of the problems are expected to help the reader to get a feel for numbers, some of them will use the basic concepts developed in the chapter to enhance the understanding and a few of the problems should be challenging to the student to bring out new features or applications leading perhaps to further reading in case the reader is interested. This book could serve as a text in a course at a senior undergraduate or a first year graduate course on lasers and their applications for students majoring in various disciplines such as Physics, Chemistry and Electrical Engineering.

The first edition of this book (entitled LASERS: Theory & Applications) appeared in 1981. The basic structure of the present book remains the same except that we have added many more topics like Erbium Doped Fiber Lasers and Amplifier, Optical Parametric Oscillators, etc. In addition we now have a new chapter on Semiconductor Lasers. A number of problems have now been included in the book which should be very useful in further understanding the concepts of lasers. We have also added the Nobel Lecture of Theodor Hansch. Nevertheless, the reader may find some of the references dated because they have been taken from the first edition.

We hope that the book will be of use to scientists and engineers who plan to study or teach the basic physics behind the operation of lasers along with their important applications.

New Delhi, India

K. Thyagarajan
Ajoy Ghatak

Preface to the First Edition

Since their invention in 1960, lasers have assumed tremendous importance in the fields of science and engineering because of their use both in basic research and in various technological applications. The present book is an attempt at a coherent presentation of the basic physics behind the working of lasers along with some of their important applications.

A major portion of the book evolved from lectures given by the authors to senior undergraduate and graduate students at the Indian Institute of Technology, New Delhi. A part of the book has also been used in a few summer/winter schools organized by the Institute.

In the first part of the book, an attempt is made to present, in a coherent fashion, the basic theory behind laser operation. The topics are introduced from first principles so that the book can be used for self-study. We do not discuss the maser principle; however, the Nobel lecture of Townes gives a nice discussion of this and is reproduced in Part III of this book. The fully quantum mechanical theory is also not given as it is beyond the scope of the present book.

In the second part of the book, we discuss, in reasonable detail, some of the important applications of lasers, including topics such as spatial frequency filtering, holography, laser-induced fusion, light wave communications, and applications of lasers in pure sciences and in industry. Although there are many more applications which are not included in this book, we feel that we have covered the most important applications. It was not possible to go into the details of the various applications because for each of the applications separate books could be (and have been) written.

We feel that the reader should have some sense of perspective of the history of the development of the laser. One obvious way would be to introduce the reader to some of the original papers; unfortunately these papers are usually not easy to read and involve considerable mathematical complexity. We felt that the Nobel lectures of Townes, Basov, and Prochorov¹ would convey the development of the subject in a manner that could not possibly be matched, and therefore, in the third part of the book, we reproduce these Nobel lectures. We also reproduce the Nobel lecture of Gabor² because in it Gabor has beautifully distilled the physics and the important applications of holography.

We hope that the book will be of use to scientists and engineers who plan to study or teach the basic physics behind the operation of lasers along with their important applications.

We will be most grateful for comments from readers.

New Delhi, India

K. Thyagarajan
Ajoy Ghatak

¹ Townes, Basov, and Prochorov were jointly awarded the 1964 Noble Prize for Physics for "fundamental work relating to the maser-laser principle.

² Dennis Gabor was awarded the 1971 Noble Prize for Physics for the invention of holography.

Acknowledgements

At IIT Delhi we have quite a few courses related to Photonics and this book has evolved from the lectures delivered in various courses ranging from *Basics of Lasers* to *Quantum Electronics* and our interaction with students and faculty have contributed a great deal in putting the book in this form. Our special thanks to Professor M.R. Shenoy (at IIT Delhi) for going through very carefully the chapter on Semiconductor Lasers and making valuable suggestions and to Dr Brahmanand Upadhyaya (at RRCAT, Indore) for going through the chapter on Fiber Lasers and for his valuable suggestions. We are grateful to our colleagues Professor B.D. Gupta, Professor Ajit Kumar, Professor Arun Kumar, Professor Bishnu Pal, Professor Anurag Sharma, Professor Enakshi Sharma and Dr Ravi Varshney for continuous collaboration and discussions. Our thanks to Dr S.V. Lawande (of Bhabha Atomic Research Center in Mumbai) for writing the section on laser isotope separation.

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**K. Thyagarajan
Ajoy Ghatak**

Contents

<i>Preface to the Second Edition</i>	v
<i>Preface to the First Edition</i>	vii
<i>Acknowledgements</i>	ix
<i>Milestones in the Development of Lasers and Their Applications</i>	xix

PART I ***Fundamentals of Lasers***

1 INTRODUCTION	3—7
2 BASIC OPTICS	8—30
2.1 Introduction	8
2.2 The Wave Equation	8
2.3 Linearly Polarized Waves	12
2.4 Circularly and Elliptically Polarized Waves	14
2.5 The Diffraction Integral	16
2.6 Diffraction of a Gaussian Beam	18
2.7 Intensity Distribution at the Back Focal Plane of a Lens	21
2.8 Two Beam Interference	22
2.9 Multiple Reflections from a Plane Parallel Film	23
2.10 Modes of the Fabry-Perot Cavity	27
<i>Problems</i>	28
<i>Solution</i>	29
3 ELEMENTS OF QUANTUM MECHANICS	31—59
3.1 Introduction	31
3.2 The One-Dimensional Schrödinger Equation	31
3.3 The Three-dimensional Schrödinger Equation	41
3.4 Physical Interpretation of ψ and its Normalization	42
3.4.1 Density of States	45

3.5	Expectation Values of Dynamical Quantities	46
3.6	The Commutator	47
3.7	Orthogonality of Wave Functions	48
3.8	Spherically Symmetric Potentials	49
3.9	The Two-body Problem	51
3.9.1	The Hydrogen-like Atom Problem	52
	<i>Problems</i>	57
4.	EINSTEIN COEFFICIENTS AND LIGHT AMPLIFICATION	60–93
4.1	Introduction	60
4.2	The Einstein Coefficients	60
4.2.1	Absorption and Emission Cross Sections	65
4.3	Light Amplification	66
4.4	The Threshold Condition	69
4.5	Line Broadening Mechanisms	72
4.5.1	Natural Broadening	72
4.5.2	Collision Broadening	74
4.5.3	Doppler Broadening	77
4.6	Saturation Behaviour of Homogeneously and Inhomogeneously Broadened Transitions	79
4.7	Quantum Theory for the Evaluation of Transition Rates and Einstein Coefficients	81
4.7.1	Interaction with Radiation having a Broad Spectrum	84
4.7.2	Interaction of a Near Monochromatic Wave with an Atom Having a Broad Frequency Response	88
4.8	More Accurate Solution for the Two-level System	88
	<i>Additional Problems</i>	92
5.	LASER RATE EQUATIONS	94–117
5.1	Introduction	94
5.2	The Two-level System	95
5.3	The Three-level Laser System	97
5.4	The Four-level Laser System	102
5.5	Variation of Laser Power Around Threshold	107
5.6	Optimum Output Coupling	114
	<i>Problems</i>	116
6.	SEMICLASSICAL THEORY OF LASER	118–138
6.1	Introduction	118
6.2	Cavity Modes	119
6.3	Polarization of the Cavity Medium	124
6.3.1	First-order Theory	128
6.3.2	Higher-order Theory	133

7. OPTICAL RESONATORS	139–193
7.1 Introduction	139
7.2 Modes of a Rectangular Cavity and the Open Planar Resonator	140
7.3 Spherical Mirror Resonators	147
7.4 The Quality Factor	149
7.5 The Ultimate Linewidth of a Laser	151
7.6 Mode Selection	154
7.6.1 Transverse Mode Selection	154
7.6.2 Longitudinal Mode Selection	155
7.7 Pulsed Operation of Lasers	160
7.7.1 Q-switching	160
7.7.2 Techniques for Q-switching	166
7.7.3 Mode Locking	168
7.8 Modes of Confocal Resonator System	177
7.9 Modes of a General Spherical Resonator	184
<i>Problems</i>	187
8. VECTOR SPACES AND LINEAR OPERATIONS: DIRAC NOTATION	194–215
8.1 Introduction	194
8.2 The BRA and KET Notation	194
8.3 Linear Operators	195
8.4 The Eigenvalue Equation	197
8.5 Observables	198
8.6 The Harmonic Oscillator Problem	199
8.6.1 The Number Operator	203
8.6.2 The Uncertainty Product	204
8.6.3 Coherent States	205
8.7 Time Development of States	207
8.8 The Density Operator	209
8.9 The Schrödinger and Heisenberg Pictures	212
<i>Problems</i>	215
9. QUANTUM THEORY OF INTERACTION OF RADIATION FIELD WITH MATTER	216–250
9.1 Introduction	216
9.2 Quantization of the Electromagnetic Field	217
9.3 The Eigenkets of the Hamiltonian	224
9.4 The Coherent States	229
9.5 Squeezed States of Light	232
9.6 Transition Rates	235
9.7 The Phase Operator	240
9.8 Photons Incident on a Beam Splitter	243
<i>Problems</i>	248

10. PROPERTIES OF LASERS	251–262
10.1 Introduction	251
10.2 Laser Beam Characteristics	251
10.3 Coherence Properties of Laser Light	257
10.3.1 Temporal Coherence	257
10.2.2 Spatial Coherence	259
<i>Problems</i>	261
11. SOME LASER SYSTEMS	263–274
11.1 Introduction	263
11.2 Ruby Laser	263
11.3 Neodymium-based Lasers	266
11.3.1 Nd:YAG Laser	266
11.3.2 Nd:glass Laser	267
11.4 Titanium Sapphire Laser	268
11.5 The He-Ne Laser	269
11.6 The Argon Ion Laser	270
11.7 The CO ₂ Laser	271
11.8 Dye Lasers	273
<i>Problems</i>	274
12. DOPED FIBER AMPLIFIERS AND LASERS	275–303
12.1 Introduction	275
12.2 The Fiber Laser	276
12.3 Basic Equations for Amplification in Erbium Doped Fiber	278
12.4 Fiber Lasers	287
12.5 Erbium Doped Fiber Amplifier	294
12.6 Mode Locking in Fiber Lasers	297
<i>Problems</i>	302
13. SEMICONDUCTOR LASERS	304–343
13.1 Introduction	304
13.2 Some Basics of Semiconductors	304
13.2.1 E vs. k	305
13.3 Optical Gain in Semiconductors	308
13.3.1 Density of States	308
13.3.2 Probability of Occupancy of States	309
13.3.3 Interaction with Light	310
13.3.4 Joint Density of States	312
13.3.5 Absorption and Emission Rates	314
13.3.6 Light Amplification	315
13.4 Gain Coefficient	317
13.4.1 Electron Hole Population and Quasi Fermi Levels	321
13.4.2 Gain in a Forward Biased <i>p-n</i> Junction	323

13.4.3	Laser Oscillation	326
13.4.4	Heterostructure Lasers	326
13.5	Quantum-well Lasers	330
13.5.1	Joint Density of States	334
13.6	Materials	337
13.7	Laser Diode Characteristics	337
13.8	Vertical Cavity Surface Emitting Lasers (VCSELs)	341
	<i>Problems</i>	342
14.	OPTICAL PARAMETRIC OSCILLATORS	344–366
14.1	Introduction	344
14.2	Nonlinearity	345
14.3	Parametric Amplification	350
14.4	Singly Resonant Oscillator	354
14.5	Doubly Resonant Oscillator	356
14.6	Frequency Tuning	359
14.7	Phase Matching	361
14.7.1	Birefringence Phase Matching	361
14.7.2	Quasi Phase Matching	361
	<i>Problems</i>	364
 PART II <i>Some Important Applications of Lasers</i> 		
15.	SPATIAL FREQUENCY FILTERING AND HOLOGRAPHY	367–381
15.1	Introduction	369
15.2	Spatial Frequency Filtering	369
15.3	Holography	374
	<i>Problems</i>	380
16.	LASER-INDUCED FUSION	382–393
16.1	Introduction	382
16.2	The Fusion Process	382
16.3	The Laser Energy Requirements	384
16.4	The Laser-induced Fusion Reactor	387
17.	LIGHTWAVE COMMUNICATIONS	394–371
17.1	Introduction	394
17.2	Carrier Wave Communication	394
17.2.1	Analog Modulation	395
17.2.2	Digital Modulation	398
17.3	Optical Fibers in Communication	403
17.4	The Optical Fiber	403

17.5	Why Glass Fibers?	405
17.6	Attenuation in Optical Fibers	405
17.7	Numerical Aperture in the Fiber	407
17.8	Multimode and Single Mode Fibers	408
17.9	Single Mode Fiber	410
17.10	Pulse Dispersion in Optical Fibers	411
	<i>Problems</i>	416
18.	LASERS IN SCIENCE	418-440
18.1	Introduction	418
18.2	Second Harmonic Generation	418
18.3	Stimulated Raman Emission	423
18.4	Intensity Dependent Refractive Index	428
18.5	Lasers in Chemistry	430
18.6	Lasers and Ether Drift	431
18.7	Lasers and Gravitational Waves	432
18.8	Rotation of the Earth	432
18.8	Photon Statistics	434
18.9	Lasers in Isotope Separation	436
	18.9.1 Separation Using Radiation Pressure	437
	18.9.2 Separation by Selective Photoionization or Photodissociation	438
	18.9.3 Photochemical Separation	439
	<i>Problems</i>	440
19.	LASERS IN INDUSTRY	441-472
19.1	Introduction	441
19.2	Applications in Material Processing	443
	19.2.1 Laser Welding	443
	19.2.2 Hole Drilling	445
	19.2.3 Laser Cutting	446
	19.2.4 Other Applications	448
19.3	Laser Tracking	448
19.4	Lidar	452
19.5	Lasers in Medicine	453
19.6	Precision Length Measurement	454
19.7	Laser Interferometry and Speckle Metrology	455
	19.7.1 Homodyne and Heterodyne Interferometry	456
	19.7.2 Holographic Interferometry	459
	19.7.3 Laser Interferometry Lithography	461
	19.7.4 Speckle Metrology	462
19.8	Velocity Measurement	467
	19.8.1 Lasers in Information System Storage	470
	19.8.2 Bar Code Scanner	471
	<i>Problems</i>	472

PART III
Nobel Lectures

1. PRODUCTION OF COHERENT RADIATION BY ATOMS AND MOLECULES	473–495
2. SEMICONDUCTOR LASERS	496–507
3. QUANTUM ELECTRONICS	508–512
4. PASSION FOR PRECISION	513–532
 APPENDIX	 533–565
A. Solution for the Harmonic Oscillator Equation	533
B. The Solution of the Radial Part of the Schrödinger Equation	536
C. The Fourier Transform	540
D. Planck's Law	549
E. The Density of States	552
F. Fourier Transforming Property of a Lens	555
G. The Natural Lineshape Function	559
H. Nonlinear Polarization in Optical Fibers	563
 REFERENCES AND SUGGESTED READING	 567–572
 INDEX	 573–577

Milestones in the Development of Lasers and Their Applications

1917: A Einstein postulated stimulated emission and laid the foundation for the invention of the laser by re-deriving Planck's law

1924: R Tolman observed that "molecules in the upper quantum state may return to the lower quantum state in such a way to reinforce the primary beam by *"negative absorption"* [Ref: Mario Bertolotti, The History of the Laser, IOP Pub., 2005]

1928: R W Landenberg confirmed the existence of stimulated emission and negative absorption through experiments conducted on gases.

1940: V A Fabrikant suggests method for producing population inversion in his PhD thesis and observed that *"if the number of molecules in the excited state could be made larger than that of molecules in the fundamental state, radiation amplification could occur"*.

1947: W E Lamb and R C Retherford found apparent stimulated emission in hydrogen spectra.

1950: Alfred Kastler suggests a method of "optical pumping" for orientation of paramagnetic atoms or nuclei in the ground state. This was an important step on the way to the development of lasers for which Kastler received the 1966 Nobel Prize in Physics

1951: C H Townes, J Weber, A Prochorov and N G Basov invent the MASER

1951: E M Purcell and R V Pound: In an experiment using nuclear magnetic resonance, Purcell and Pound introduce the concept of negative temperature, to describe the inverted populations of states usually necessary for maser and laser action.

1954: J P Gordon, H J Zeiger and C H Townes and demonstrate first MASER operating as a very high resolution microwave spectrometer, a microwave amplifier or a very stable oscillator.

1956: N Bloembergen first proposal for a three level solid state MASER

1958: A Schawlow and C H Townes, extend the concept of MASER to the infrared and optical region, the concept of the laser.

1959: Gordon Gould introduces the term LASER

- 1960: T H Maiman realizes the first working laser: Ruby laser
- 1960 P P Sorokin and M J Stevenson Four level solid state laser (uranium doped calcium fluoride)
- 1960: A Javan W Bennet and D Herriott invent the He-Ne laser
- 1961: E Snitzer: First glass laser
- 1961: P Franken; observes optical second harmonic generation
- 1962: E Snitzer: First Nd:Glass laser
- 1962: R. Hall creates the first GaAs semiconductor laser
- 1962: R W Hellwarth invents Q-switching
- 1963: Mode locking achieved
- 1963: Z Alferov and H Kromer: Proposal of heterostructure diode lasers
- 1964: C K N Patel invents the CO₂ laser
- 1964: W Bridges: Realizes the first Argon ion laser
- 1964: Nobel Prize to C H Townes, N G Basov and A M Prochorov *"for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle"*
- 1964: J E Geusic, H M Marcos, L G Van Uiteit, B Thomas and L Johnson: First working Nd:YAG laser
- 1964: E Snitzer: First fiber laser
- 1965: CD player
- 1966: C K Kao and G Hockam Proposal for using optical fibers for communication. Kao was awarded the Nobel Prize in 2009 for this work.
- 1966: P Sorokin and J Lankard: First organic dye laser
- 1966: Nobel Prize to A Kastler *"for the discovery and development of optical methods for studying Hertzian resonances in atoms"*
- 1968: Laser in space
- 1969: CW chemical laser
- 1969: Pulsed dye laser
- 1970: Excimer laser
- 1970: Z Alferov and I Hayashi and M Panish: CW room temperature semiconductor laser
- 1970: Corning Glass Work scientists prepare the first batch of optical fiber, hundreds of yards long and are able to communicate over it with crystal clear clarity

- 1970: TEA pressure CO₂ laser
- 1970: CW dye laser
- 1970: Optical tweezers
- 1971: Nobel Prize: D Gabor *"for his invention and development of the holographic method"*
- 1975: Barcode scanner
- 1975: Commercial CW semiconductor lasers
- 1976: Free electron laser
- 1977: Live fiber optic telephone traffic: General Telephone & Electronics send first live telephone traffic through fiber optics, 6 Mbit/s in Long Beach CA.
- 1979: Vertical Cavity Surface Emitting Laser (VCSEL)
- 1981: Nobel Prize to N Bloembergen and A L Schawlow *"for their contribution to the development of laser spectroscopy"*
- 1982: Ti:Sapphire laser
- 1983: Redefinition of the meter based on the speed of light
- 1985: Steven Chu, Claude Cohen-Tannoudji, and William D. Phillips develop methods to cool and trap atoms with laser light. Their research helps to study fundamental phenomena and measure important physical quantities with unprecedented precision. They are awarded the Nobel Prize in Physics in 1997.
- 1987: Laser eye surgery
- 1987: R.J.Mears, L.Reekie, I.M.Jauncey, and D.N.Payne: Demonstration of Erbium doped fiber amplifiers
- 1988: Transatlantic fiber cable
- 1988: Double clad fiber laser
- 1994: J Faist, F Capasso, D L. Sivco, C Sirtori, A L. Hutchinson, and A Y. Cho: Invention of quantum cascade lasers
- 1996: S Nakamura: First GaN laser
- 1997: Nobel Prize to S Chu, C Cohen Tannoudji and W D Philips *"for development of methods to cool and trap atoms with laser light"*
- 1997: W Ketterle: First demonstration of atom laser
- 1997: T Hansch proposes an octave-spanning self-referenced universal optical frequency comb synthesizer
- 1999: J Ranka, R Windeler and A Stentz demonstrate use of internally structured fiber for supercontinuum generation

2000: J Hall, S Cundiff J Ye and T Hansch: Demonstrate optical frequency comb and report first absolute optical frequency measurement

2000: Nobel Prize to Z I Alferov and H Kroemer “*for developing semiconductor heterostructures used in high-speed and opto-electronics*”

2001: Nobel Prize to E Cornell, W Ketterle and C E Wieman “*for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates*”

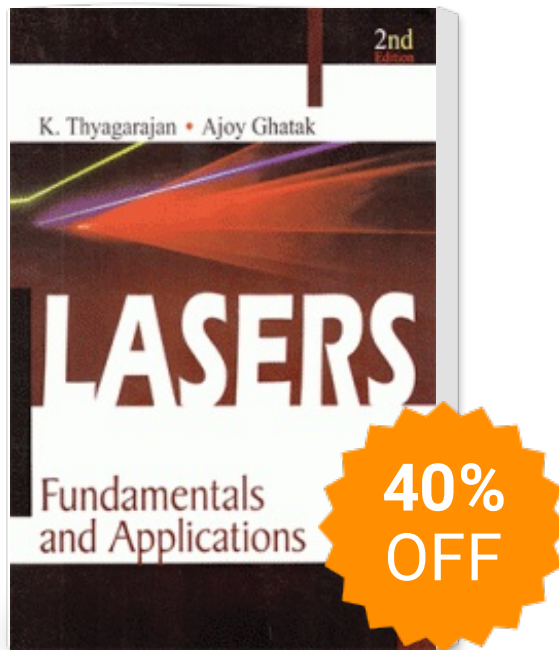
2005: H Rong, R Jones, A Liu, O Cohen, D Hak, A Fang and M Paniccia: First continuous wave Raman silicon laser

2005: Nobel Prize to R J Glauber “*for his contribution to the quantum theory of optical coherence*” and to J L Hall and T H Hansch “*for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique*”

2009: Nobel Prize to C K Kao “*for groundbreaking achievements concerning the transmission of light in fibers for optical communication*”

Ref: Many of the data given here has been taken from the URL for Laserfest: <http://www.laserfest.org/lasers/history/timeline.cfm>

Lasers Fundamentals And Applications



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