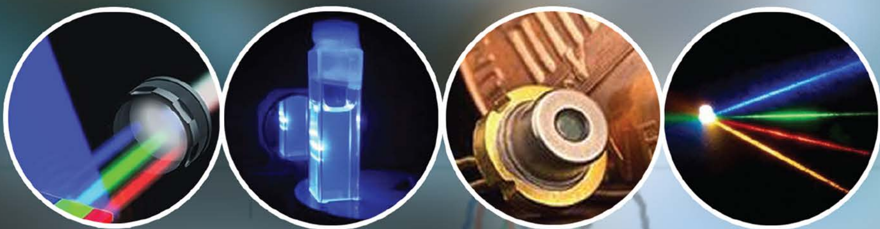
UNCONVENTIONAL LASERS– DESIGN AND TECHNICAL ANALYSIS



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Unconventional Lasers – Design and Technical Analysis

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Foreword

It is a matter of great pleasure for me to express that Dr Kamal Nain Chopra, has made a tremendous and commendable effort in writing this monograph on unconventional lasers, a topic, on which the availability of literature, especially at one place, is the need of the hour for the DRDO scientists in particular, and the researchers and academicians in general. Practically, all types of lasers in this category have been discussed in detail in this monograph, thereby making it very useful indeed for the scientific community both in India and abroad. Prior to this, very few attempts seem to have been made in presenting the different aspects of the subject at one place, and therefore, this effort will certainly bridge the gaps between the various types of research papers and literature on unconventional lasers available at different places. The monograph should especially be useful for the designers and engineers of such lasers, as the design aspects for the efficiency optimisation have been presented and discussed at length. In addition, the monograph is expected to be of immense utility for the budding researchers and scientists in the field, since the monograph provides a large number of theoretical and experimental results available in the literature, for them to have a clear understanding of the subject, and also to choose the direction in which to move for carrying out research in this fascinating field. It is my sincere wish that this monograph serves the researchers in enhancing their inputs on the subject, and also their interest in making more concentrated efforts in carrying out research in this briskly evolving field.

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Preface

A lot of literature, especially books on the conventional lasers like solid state lasers, gas lasers, and semiconductor lasers is available. However, not many efforts seem to have been made on writing books on unconventional lasers. This monograph is a small but sincere effort of the author to make available very useful information on this topic, especially from the research point of view. In addition, the technical analysis of the theoretical aspects of these lasers along with the modelling and designing considerations for maximising the efficiency of these lasers have been presented in this monograph. Apart from discussing the theoretical modelling and designing of these lasers, some related experimental results available in the literature have been presented to make the presentation clear and meaningful. Nearly all types of unconventional lasers including x-ray FELs (XFELs), GaSb-based type-I diode lasers, photonic crystal-based lasers, phase conjugated lasers, quantum cascade lasers (QCLs), and diode pumped fiber lasers, have been covered.

All these types of lasers are having many useful applications in various fields like industry, surgery, biology, and novel imaging techniques, apart from their usage in practical research applications in most of the scientific and engineering topics. In the field of medicine, these lasers are applied in several areas, including dermatology, in which they are used to skin tone more even. Vascular skin lesions are known to contain oxygenated hemoglobin, which has the characteristic of strongly absorbing the visible light at 418 nm, 542 nm and 577 nm, and the pigmented skin lesions contain melanin, which has a wide range of absorption in the visible and IR wavelength regions. The phase conjugated lasers are very useful for certain applications like–nullifying the optical distortion, and also achieving some novel characteristics of the lasers. The fiber laser along with the Raman converter module is capable of the efficient spectral conversion of its unique combined ultra-short radiation pulses into longer-wavelength spectral domain of 1150 to 1550 nm. Tourmaline Ytterbius-1100 has many applications like–time-resolved spectroscopy, Raman spectroscopy, micro- and nano-photonics, supercontinuum generation, fluorescence-lifetime imaging microscopy, and optical DNA sensing technology.

The unconventional lasers based on photonic crystals are very useful for certain applications like–data storage, biomedical applications, and display technologies. GaSb-based type-I diode lasers operating in the optical spectral region ≥3μm are very useful for a variety of applications including trace gas sensing, free-space optical communications, and infrared countermeasures. The field of QCLs has recently grown fast due to the fact that these lasers are having great advantages over the other semiconductor lasers, and consequently have found newer applications. Higher powers from femtosecond fiber lasers have become very useful for a variety of applications including laser processing, medical bio-optics, and opto-electronics The studies on the Cr: Colquiriite lasers–Cr: LiSaF and Cr: LiCaF lasers, have also drawn the attention of various researchers , because of their main advantage, that they can be pumped by diodes (GaInP/AlGaInP QW), and therefore, are quite compact and inexpensive. Ti: Sapphire lasers are popular and important because of the fact that they: (i) are tunable lasers, capable of emitting red and near-IR radiations in the spectral region 650 nm to 1100 nm, and (ii) generate ultra short pulses. Because of these characteristics, they have become very handy for carrying out scientific research. As is well known, the Random lasers have also been drawing the attention of various researchers because of their unique theory, fabrication, and properties. It has now been well understood that this novel laser produces random mid-infrared light, and because of the great advantage of its capability of removing speckling, has important applications in the systems requiring high image quality, e.g., airport security. Raman lasers, spin lasers, and ultrafast mid-IR lasers are also useful in research and other upcoming fields. The amasingly high intensities of x-ray free-electron lasers–108-1010 times greater than the ordinary laboratory sources, have led to their great application in the very highly specialised areas of scientific research.

A number of important academic institutes like IITs, IISc and universities, and scientific laboratories including National Physical Laboratory, other CSIR laboratories, ISRO, and DRDO (in which LASTEC and IRDE have been quite active), are engaged deeply in this subject. Keeping these points into consideration, a monograph on this topic is really needed, which will undoubtedly serve the purpose of understanding the complexities of such systems for the scientists of NPL, DRDO, and CSIR. Apart from being useful to these scientists and technologists, this monograph will serve as the motivating force for the researchers entering the field of such complicated laser systems.

KN Chopra

Acknowledgements

The author is really grateful to DRDO in general and LASTEC in particular for providing an opportunity to work for many years with a number of scientists working on lasers, and the systems based on lasers. A large number of presentations and discussions on the complexities and technicalities of some of these unconventional lasers, including the very recent venture on fibre lasers have been immensely helpful in the writing of this monograph; and most importantly the urge to undertake this project was ignited during these meetings. My sincere thanks are due to Dr Haribabu, Director, LASTEC for project review meetings on fibre lasers, which provided me an opportunity to interact with various experts in the fields of high power lasers, including Dr MN Reddy, Scientist G, LASTEC, and Dr Chandrasekaran Natarajan, Scientist G, DGECS, DRDO, Bangaluru, and the discussions with them, and other scientists present in the meetings helped me in giving final touches to this interesting field. Thanks are due to Dr Rambabu Kammili, Director, RCI, Hyderabad, for giving me opportunities to give invited talks, and attend review meetings on laser coatings and ring laser gyroscopes, thereby providing me the chances to interact with the scientists of DRDO laboratories of Hyderabad, and also academicians of the Indian Institute of Science, Bangalore, the discussions with whom helped me in the final refinements of the monograph. Finally, the author is grateful to Prof Vipin Kumar Tripathi of Lasers and Plasmas Group, Department of Physics, Indian Institute of Technology, Delhi, for various suggestions and encouragement during the course of writing this monograph, which helped in greatly improving the contents and more importantly the presentation and readability of the monograph. Thanks are also due to the DESIDOC scientists Ms Alka Bansal, Scientist F and Ms Kavita Narwal, Scientist D, DESIDOC, but for whose guidance and cooperation, it would not have been possible to prepare the monograph in the present form. Finally, the author wishes to thank two anonymous learned reviewers, whose valuable comments and suggestions have helped in substantially improving the presentation and contents of the monograph.

List of Acronyms

AM	Amplitude Modulation
ASU	Arizona State University
CEO	Carrier Envelope Offset
CL	Classical Laser
CLC	Cholesteric Liquid Crystal
CNT	Carbon Nanotube
CVD	Chemical Vapour Deposition
CW	Continuous Wave
CXDI	Coherent X-ray Diffraction Imaging
DBR	Distributed Bragg Reflectors
DFB	Distributed Feedback
DOS	Density of Optical States
DPSSL	Diode Pumped Solid State Laser
EPDL	Explosively Pumped Photo Dissociation Iodine Laser
Er	Erbium
FDTD	Finite Difference Time Domain
FEL	Free Electron Laser
FOD	Fourth Order Dispersion
fs	Femtosecond
GD	Group Delay
GDD	Group Delay Dispersion
GNLSE	Generalised Non Linear Schrödinger Equation
GVM	Group Velocity Mismatch
hh	Heavy Hole
LCLS	Linac Coherent Light Source

LCP	Lipidic Cubic Phase
LDs	Laser Diodes
LEDs	Light Emitting Diodes
LL	Light-in/Light-out
LPCM	Loop Phase Conjugate Mirror
LSPR	Localised Surface Plasmon Resonances
MBE	Molecular Beam Epitaxy
MIM	Metal Insulator Metal
MSM	metal Semiconductor Metal
MSSI	Mid Span Spectral Inversion
OISLs	Optical Inter Satellite Links
OPC	Optical Phase Conjugation
PBEs	Photonic Band Edges
PBG	Photonic Band Gap
PC	Photonic Crystals
PCF	Photonic Crystal Fiber
PCL	Photonic Crystal Laser
PCM	Phase Conjugate Mirror
PC- MOPA	Phase Conjugate Master Oscillator Power Amplifier
PM	Polarisation Modulation
ps	Picosecond
QB	Quasi Bound
QCLs	Quantum Cascade Lasers
QD	Quantum Dot
QW	Quantum Well
QWL	Quantum Well Laser
SBS	Stimulated Brillouin Scattering
SERS	Surface Enhanced Raman Scattering
SFM	Spin Flip Model
SHG	Second Harmonic Generation
SML	Metal-cavity Submonolayer
SPM	Self Phase Modulation
SPOPO	Synchronously Pumped Optical Parametric Oscillator
OSNR	High Optical Signal-to-Noise Ratio
TDLAS	Tunable Diode Laser Absorption Spectroscopy

TE	Transverse Electric
THG	Third Harmonic Generation
TM	Transverse Magnetic
TOD	Third Order Dispersion
TPA	Two Photon Absorption
VBG	Volume Bragg Grating
XDL	Times Diffraction Limited
XFEL	X-ray Free-electron Laser
Yb	Ytterbium

CHAPTER 1

Modeling and Optimisation of the Efficiency of Spin Lasers

1.1 INTRODUCTION

After a stupendous development in the conventional lasers of various forms and with increased output power, researchers have started making parallel efforts on studying the unconventional lasers, e.g., phase conjugated lasers; diode pumped Er fiber lasers, lasers based on photonic crystals, GaSb-based type-I diode lasers operating in the optical spectral region around 3μm, and quantum cascade lasers, which have been the subject of interest[1-5] in the recent past. A new addition to this list is the Raman laser, as it is a specific type of laser with the fundamental light-amplification mechanism being the stimulated Raman scattering, unlike the stimulated electronic transitions for amplifying light in the conventional lasers, which qualifies it to be considered as closer to the class of random lasers[6].

It has also been observed in the recent past, that the studies and phenomena based on the interaction of spin of electrons have led to great progress in the development of the field of spintronics, which is in fact the combination of the fields of the spin of electrons and the modern electronics. A number of studies[7-15] on this interesting and important subject have been made in the recent past. It is natural that the successful applications of the spin of electrons to the field of electronics, and the evolution of the field of unconventional lasers, has led to the development of spin lasers, which is in fact the amalgamation of the spin of electrons, and unconventional lasers. It has been observed that the spin-polarised light sources are a new class of devices in which the radiative recombination of spin-polarised carriers results in luminescence along with exhibiting a net circular polarisation. A number of important studies[16-20] have been carried out in this upcoming field.

The basis of the theory and working of the spin lasers is entirely different from that of the theory and working of a traditional laser. Whereas, in the case of a traditional laser, electrons radiate photons (energy in the form of electromagnetic waves) by changing position in space from higher energy orbital to lower energy orbital, a spin wave laser is based on the emission of energy in the form of electromagnetic waves by electrons with axial and orbital spin undergoing transition from the higher energy spin states to the lower energy spin state.

The spin lasing is possible in certain magnetic materials, which is understood in a simple manner, in terms of the potential energy stored in the difference of spin orientation and the associated magnetic dipole. In case of a magnetic material, if each spin orientation and the associated magnetic dipole are not aligned with an external magnetic field, then there is some amount of potential energy stored in that difference of orientation. It is clear that the case when each individual magnetic dipole orientation aligns itself with the external magnetic field is the one corresponding to a lower energy state. The energy propagating away through direct spin-lattice coupling is generally lost as heat in a magnetic material where lasing is not occurring. However, this energy lost can be made to radiate away as electromagnetic waves, which is done in spin laser by creating a population inversion having a large number of spins in a metastable spin state, in which there is a natural tendency of the individual spins to reorient themselves to a direction corresponding to the lower energy state, but the event is initiated only when they first receive some stimulus. It is obvious that this is related to the hysteresis characteristics of the particular magnetic material used as the lasing medium. The underlying principle is simple in that whereas normally, when a magnetic material is remagnetised in some new direction the process occurs as disorganised avalanches of more and more magnetic domains till the whole sample is remagnetised in some new orientation; in case of a spin wave laser this process is based on a very ordered avalanche of spins transitioning to lower spin states.

The working principle is simple. For a spin wave laser with a population inversion of spin states, the individual spins precess resulting in the stimulus to drop to a lower energy spin state, in the form of electromagnetic waves, matching the frequency of precession–the larmor frequency. Interestingly, the spins are stimulated to emit electromagnetic waves, which are in phase with the stimulating electromagnetic waves. However, there is a glaring dissimilarity of the process of the spin laser from that of the traditional laser. Unlike the traditional laser, the phase of the simulating electromagnetic waves is a problem, when the electromagnetic waves interact with all the spins of all the individual magnetic domains with spins which are in the metastable states. The explanation for this is easy: whereas in a traditional laser, the wavelength is very small in comparison to the distances between electrons in metastable states, in case of a spin wave laser the frequencies are lower and in addition, there is more electromagnetic coupling between the metastable spins. Hence, a spin wave laser is designed in such a manner that the

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About the Book

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About the Author

Dr Kamal Nain Chopra has done BSc (University of Delhi), MSc (Physics - IIT, Delhi), MTech (Opto-Electronics - IIT, Delhi), and PhD (Applied Physics - IIT, Delhi). He has served DRDO for a period of 33 years and superannuated as Scientist G, from Laser Science and Technology Centre (LASTEC), Delhi, in 2005. Subsequently, he has also served as Professor (Physics) in NSIT, University of Delhi, and as Project Scientist in IIT, Delhi, in various Projects.

He has about 225 publications including 150 in international journals (UK, USA, France, Germany, and Italy) on various topics including thin films optics, lasers and laser components, holography, and modern optics; 12 invited talks; 14 technical reports; and 21 papers in conference proceedings. He has co-authored a monograph titled 'Thin Films and their Applications in Military and Civil Sectors', DRDO, Ministry of Defence, 2010. He has undertaken visits to foreign universities and industries including (i) School of Thin Film Coatings, Department of Physics, St. Jerome University, Marseille, France [5 months (1984-85)]; (ii) Department of Physics, Innsbruck Univ., Austria, including five days in M/s. Balzers, Switzerland [10 days (1995)]; and (iii) M/s. Elettrorava, Torino, Italy [15 days (2000)]. He has vast experience of serving the recruitment and assessment boards of DRDO as Chairman as well as Expert Board Member.

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