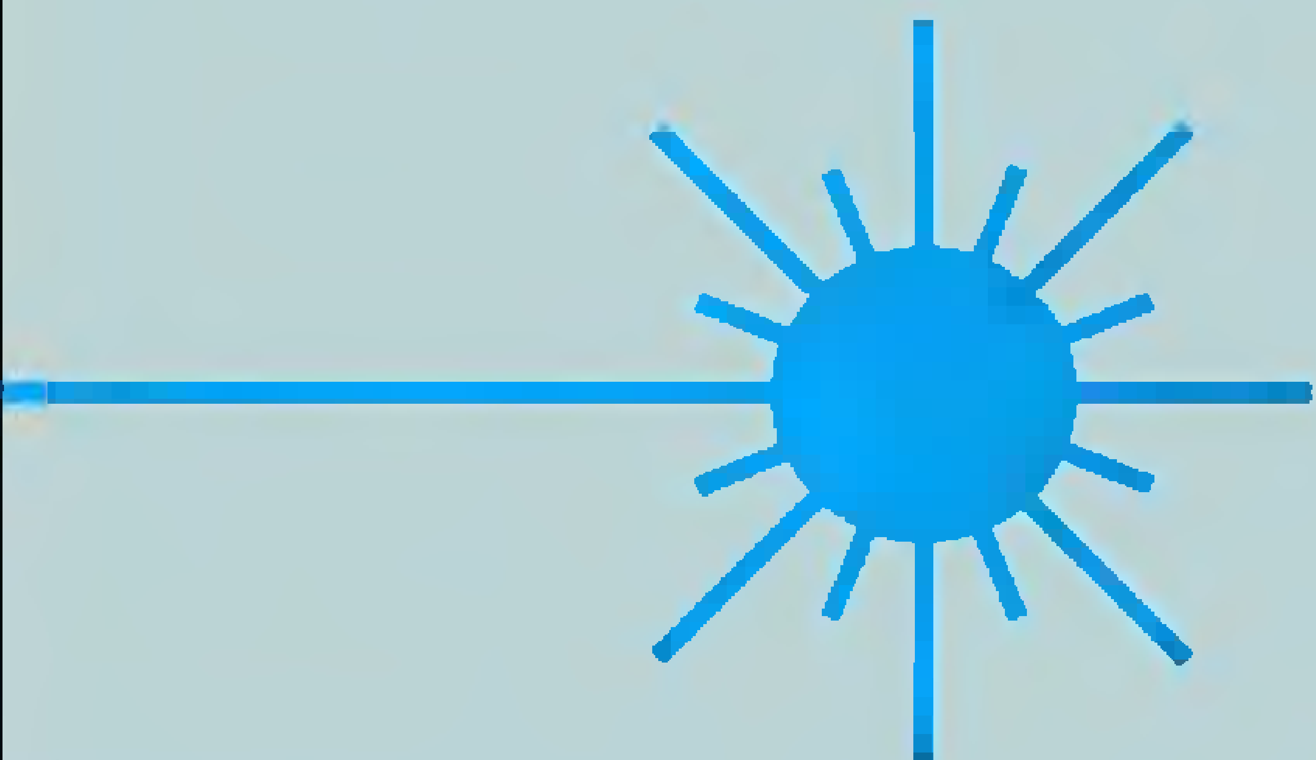
Cambridge Studies in Modern Optics

Compact Sources of Ultrashort Pulses

Edited by IRL N. DULING, III



Recent advances in materials and processing techniques have led to a revolution in the generation of ultrashort laser pulses. From novel fiber lasers to short pulse and high power diode lasers, development in this field has been very rapid. This comprehensive volume provides a survey of these innovations, and reviews the state of the art in compact, modelocked laser systems, discussing both their operational principles and potential applications.

The theory of short optical pulse generation by modelocking is covered in the first chapter, after which specific systems are discussed. These include passively modelocked solid state lasers, modelocked diode-pumped lasers, modelocked fiber lasers, nonlinear polarization evolution, modelocked surface emitting semiconductor lasers, ultrafast pulse generation by means of external cavity semiconductor lasers, hybrid soliton pulse sources, and monolithic colliding pulse modelocked diode lasers.

Presenting both theoretical and experimental aspects throughout, this book will be invaluable to anyone interested in short pulse laser systems, and particularly to researchers involved in high speed communications or the investigation of ultrafast phenomena.

CAMBRIDGE STUDIES IN MODERN OPTICS

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Acronyms and abbreviations

A-FPSA	antiresonant Fabry–Perot saturable absorber
AFSA	artificial fast saturable absorber
AM	amplitude modulated
AOM	acousto-optic modulator
APM	additive pulse modelocking
AR	antireflection
ASE	amplified spontaneous emission
BER	bit error rate
BH	buried heterostructure
BITS	building integrated timing supply
BW	bandwidth
CCM	coupled cavity modelocking
CPM	colliding pulse modelocking
CTM	carrier-type modelocking
CW	continuous wave
DBR	distributed Bragg reflector
DC	direct current
DDF	dispersion decreasing fiber
DDL	dispersive delay line
DEMUX	demultiplexer
DFB	distributed feedback
DH	double heterojunction
ECL	emitter coupled logic
EDFA	erbium-doped fiber amplifier
e-hh	electron-heavy hole
EOT	electro-optic tuner
F8L	figure eight laser
FM	frequency modulated
FP	Fabry–Perot
FR	Faraday rotator
FRM	Faraday rotator mirror
FSF	frequency shifted feedback
FWHM	full width at half-maximum

GDD	group delay dispersion
GRIN-SCH	graded index separate confinement heterostructure
GVD	group velocity dispersion
HR	high reflector
HSPS	hybrid soliton pulse source
IMPATT	impact ionization avalanche transit time
IR	infrared
I-V	current versus voltage
KLM	Kerr lens modelocking
KSM	Kerr shift modelocking
LBO	lithium triborate
LD	laser diode
LDPSSL	laser diode pumped solid state laser
L-I	light versus current
ML	modelocked
MQW	multiple quantum well
MUX	multiplex, multiplexer
MZ	Mach–Zehnder
NALM	nonlinear amplifying loop mirror
NLSE	nonlinear Schrödinger equation
NOLM	nonlinear optical loop mirror
OC	output coupler
OE	opto-electronic
OEIC	opto-electronic integrated circuit
OMVPE	organometallic vapor phase epitaxy
OPO	optical parametric oscillator
OSA	optical spectrum analyzer
PM	polarization maintaining
Pr	praesedymium
PZT	piezo-electric transducer
RBW	resolution bandwidth
RF	radio frequency
RIN	relative intensity noise
RSS	Raman self-scattering
RWA	rotating wave approximation
SAM	self-amplitude modulation
SDA	saturable diode amplifier
SF10, SF18, SF57	Corning glass types
SH	second harmonic
SHG	second harmonic generation
SIOB	silicon optical bench
SMSR	side-mode suppression ratio
SP	synchronous pumped
SP-APM	stretched pulse-additive pulse modelocking
SPM	self-phase modulation
SQW	single quantum well
SRD	step recovery diode

SWP	sweep time
TDM	time division multiplexed
TE	transverse electric
TEM_{00}	lowest order transverse electric mode
TM	transverse magnetic
TOD	third-order dispersion
TWA	traveling-wave (laser) amplifier
UV	ultraviolet
VBW	video bandwidth
VCSEL	vertical cavity surface emitting laser
WDM	wavelength division multiplexing
WP	wave plate
WPS	weak pulse shaping
XPM	cross-phase modulation
YAG	yttrium aluminum garnet
YLF	yttrium lithium fluoride

Preface

Since the development of the first diode lasers and the recent proliferation of fiber amplifiers, the dream of researchers for a compact, efficient, turn-key source of ultrashort pulses has come closer to reality. A number of candidates for this ultimate source have been proposed and researched and a large body of information has been produced. To date there has not been a compilation of this valuable information in one place. It is the intent of this work to present the state of the art in the development of these sources. It is the added intention to provide a basis for the future research of others attempting to enter this still very active field.

In 1983, when the technique of electro-optic sampling was developed, the dream was that the sampler could be combined with a compact ultrashort pulse source to produce a subpicosecond resolution oscilloscope. This technology has languished due to the missing source. In 1988 the development of high efficiency low temperature GaAs photoconductive switches has produced similar high promise, but there is still no suitable low cost compact ultrashort pulse source. It is hoped that this book will show that much progress has been made since the early 80s and the groundwork has been laid for a new class of instrumentation, where a laser is included for optical processing and may not ever leave the instrument.

By producing compact and hopefully low cost sources of ultrashort pulses, probing of materials for characterization becomes more practical and optical ranging becomes more precise. Techniques such as surface harmonic generation and two photon absorption, both of which rely on the intensity of the light, can benefit from these sources. In fact the shortness of the pulse is not the issue any more, but it may be a distinct advantage in that the thermal loading on the sample is less while the peak intensity is the same. This may allow biological samples to be probed without damage.

A number of sensors have been developed which utilize short pulse sources. Modelocked gyroscopes may prove superior to their CW counterparts. Short pulses can be used to distinguish the signals from distributed sensors in detector arrays or smart structures. Even the modelocking process itself can be used for this purpose, turning the entire sensor into a modelocked laser.

As the applications multiply for compact short pulse sources it is necessary for the researchers developing these systems to have a full knowledge of the state of the art and a clear understanding of the limitations of the different modelocking techniques. It is the intent of this book to bring together the leading edge research in this field presented in such a way that it is useful to both the experienced researcher and to that person wishing to enter the field.

It is also important that the engineer who is designing applications based on these sources be presented with the strong points of each so that he can choose the optimal source for the given application. He should also get a clear understanding of the required conditions to make the laser operate as necessary for the given application. It is our hope that this book can fulfill all of these goals. Some of the criteria which must be addressed and which will vary from source to source are the output power, the shortest duration necessary for the application, the repetition rate required, the wavelength at which the system must operate, amplitude and phase noise, and allowed cost of the system. At a workshop on 'Real World Sources' at the 1994 Ultrafast Phenomena Conference in Dana Point, CA, the consensus was that the market applications for ultrashort pulse sources would open up if the cost could be brought below $10 000. At this point none of the sources can meet that criterion, but it is expected that in the next few years there will be more than one technology meeting that threshold.

With the current emphasis being placed on the national information infrastructure and the best way to increase the bandwidth of the current installed fiber, it hardly needs to be said that a major motivation for working in this area is to produce viable sources for high speed telecommunications. A large portion of the work being done on optical fiber sources operates in the anomalous dispersion regime where solitons can be formed. Soliton communications systems are already planned for installation in the transoceanic links. Time division multiplexed communication has been carried out at 100 Gb/s and will soon reach 160 Gb/s and beyond. The importance of reliable sources of clean stable solitons cannot be avoided.

Chapter 1 treats the theory of the generation of short optical pulses by modelocking. This discussion will cover the effects of dispersion and nonlinearity within the fiber laser for a generalized switching mechanism, concentrating on the APM type of nonlinear switching. The analysis will present the master equation for the laser dynamics and its consequences for various laser configurations.

The pulse shaping dynamics of solitary solid state lasers utilizing modelocking techniques exploiting the Kerr nonlinearity of solids is the subject of Chapter 2. Specifically the pulse buildup in passively mode-locked solid state lasers and the new phenomena associated with solitary modelocking (modelocking when soliton-like pulse shaping is occurring in the cavity) is examined.

The recent developments in the modelocking of diode pumped solid state lasers is covered in Chapter 3. It includes a practical review of standard modelocking and pulse measurement techniques with a strong emphasis on active modelocking.

Chapter 4 is a review of the modelocking of fiber lasers. With the exception of nonlinear polarization rotation modelocking, which is treated in Chapter 5, the passive, active and hybrid techniques of modelocking fiber lasers is covered with a comparison between them. A detailed discussion of cavity dispersion is presented, with its effect on pulse formation.

The phenomenon of nonlinear polarization evolution and its use for modelocking is covered in Chapter 5. The implementation of this technique in both bulk and fiber lasers is addressed, and analysis with and without dispersion in the cavity based on the soliton and solitary laser models is included.

After a review of the modelocking in edge-emitting diode lasers, Chapter 6 covers the modelocking of surface emitting semiconductor lasers. The analysis includes chirp analysis and carrier transport effects and their relationship to pulse formation.

Ultrafast optical pulse generation techniques utilizing external cavity semiconductor lasers are described in Chapter 7. Active modelocking, passive modelocking, hybrid modelocking and chirp compensation techniques are examined. The pulses from these lasers are used to study the ultrafast amplification characteristics of semiconductor lasers. The chapter covers the nature of the effects which dominate the pulse shaping mechanisms in external cavity hybrid modelocked diode lasers. These systems are applied to providing synchronous timing signals for clock distribution, photonic network synchronization, and all-optical clock recovery.

An alternative solution to the extended cavity semiconductor laser is to integrate the extended cavity in semiconductor material or fiber. These options are treated in Chapter 8. The development of this source, elimination of instabilities and optimization of pulse length and chirp are covered. The final results on a packaged device are also presented. With the use of a two-section laser diode high power pulses are generated.

The final chapter of the book covers what are probably the most compact of the lasers presented here. The monolithic colliding pulse modelocked diode lasers incorporate the modelocking mechanism into the diode laser cavity providing a high repetition rate source of ultrashort optical pulses. The stability criterion and the different modelocking techniques for these unique lasers are addressed.

1

Short pulse generation

H. A. HAUS

Introduction

Optical frequencies are so high that a small relative bandwidth is a very large bandwidth in absolute terms. This fact is behind the success of optical short pulse generation. The first successful generation of short optical pulses via modelocking started in the 60s with Nd:glass. Figure 1.1 gives the history of the advances in short pulse generation. Steady progress in generating shorter and shorter pulses was achieved with dye lasers, principally because these were CW lasers that had much more predictable modelocking behavior than Q-switched lasers. After subpicosecond pulse generation was achieved with dye lasers, it was soon realized that the short pulses produced by the lasers were much shorter than the relaxation times of the dyes used for the gain and absorption media. It was recognized that the pulses were generated through combined action of the saturable absorber dye that, by saturating, opened the 'shutter' for the transmission of the pulse, and the gain, by saturating, closed the 'shutter.' This was an important discovery since there exist very few saturable absorbers with subpicosecond relaxation times appropriate for intracavity operation. The shortest pulses achieved were 27 fs in duration, and after spectral spreading in a fiber and subsequent compression 6 fs was achieved[1], still the record today.

In 1978 the first modelocking of semiconductor lasers was achieved[2]. They are of prime importance in communications applications and are limited to about 100 fs pulse duration, a pulse width adequate for communications for many years to come. Color center lasers operating around 1.5 micron wavelength were pioneered by Mollenauer and

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