



EMIL WOLF

EDITOR



# PROGRESS IN OPTICS

VOLUME 46

## CONTRIBUTORS

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E. Wolf

*University of Rochester, N.Y., U.S.A.*

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First edition 2004

Library of Congress Catalog Card Number: 61-19297

ISBN: 0 444 51468 6

ISSN: 0079-6638

♾️The paper used in this publication meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper).

Printed in The Netherlands.

# PROGRESS IN OPTICS

VOLUME 46

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## Preface

This volume presents five review articles of areas of current research interest in several branches of modern optics.

The first article, by U. Keller, discusses the progress which has been made in recent years in ultrafast pulse generation, using solid-state lasers. In the last decade, the performance of compact ultrafast solid-state lasers has been improved by several orders of magnitude in pulse duration, in average power, in pulse energies and in pulse repetition rates. In this article these and other breakthroughs are discussed. The article provides both the expert and the non-expert with an overview of this rapidly advancing field.

The second article, by A.V. Shchegrov, A.A. Maradudin and E.R. Méndez, reviews research on the scattering of electromagnetic waves from randomly rough surfaces. Unlike earlier investigations in this field, the article covers the more difficult subject of multiple scattering from such surfaces and discusses more recently discovered effects such as enhanced backscattering and enhanced transmission.

In the next article, by Y. Ishii, an interesting advance in interferometry is described, namely a phase-measuring technique which uses direct frequency modulation of a laser diode source by changing the current. This technique has been implemented in holographic interferometry and in phase conjugate interferometry, for example.

The fourth article, by J. Gea-Banacloche, reviews the theory of quantum teleportation and the ways in which this intriguing quantum phenomenon has been experimentally demonstrated in optical systems. Among the topics covered are the relationship between teleportation of discrete and continuous variables, entanglement and teleportation, the difficulty of Bell measurements, and schemes for near-deterministic teleportation with linear optics. The limitations of current experiments and some questions of interpretation are also discussed.

The concluding article, by H.J. Carmichael, G.T. Foster, L.A. Orozco, J.E. Reiner and P.R. Rice, uses intensity-field correlation functions of the electromagnetic field as a tool for studying quantum fluctuations of light. The relationship between the correlation functions and quadrature squeezing is noted and conditions are developed to distinguish between classical and non-classical field fluctuations. The

theoretical analysis is illustrated by examples such as the optical parametric oscillator, a cavity QED system and the composite system of a single atom coupled to an optical parametric oscillator. The results of experimental measurements on a cavity QED system are also reviewed.

Emil Wolf

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February 2004

# Contents

Preface . . . . .	v
-------------------	---

<b>Chapter 1. Ultrafast solid-state lasers, Ursula Keller</b> (Zürich, Switzerland) . . . . .	<b>1</b>
--	----------

List of symbols . . . . .	3
§ 1. Introduction . . . . .	7
§ 2. Definition of Q-switching and mode locking . . . . .	10
2.1. Q-switching . . . . .	10
2.2. Mode locking . . . . .	11
§ 3. Overview of ultrafast solid-state lasers . . . . .	15
3.1. Overview of solid-state laser materials . . . . .	15
3.2. Design guidelines of diode-pumped solid-state lasers . . . . .	39
§ 4. Loss modulation . . . . .	43
4.1. Optical modulators: acousto-optic and electrooptic modulators . . . . .	43
4.2. Saturable absorber: self-amplitude modulation (SAM) . . . . .	44
4.3. Semiconductor saturable absorbers . . . . .	49
4.4. Effective saturable absorbers using the Kerr effect . . . . .	52
§ 5. Pulse propagation in dispersive media . . . . .	54
5.1. Dispersive pulse broadening . . . . .	54
5.2. Dispersion compensation . . . . .	56
§ 6. Mode-locking techniques . . . . .	65
6.1. Overview . . . . .	65
6.2. Haus's master equations . . . . .	66
6.3. Active mode locking . . . . .	70
6.4. Passive mode locking with a slow saturable absorber and dynamic gain saturation . . . . .	74
6.5. Passive mode locking with a fast saturable absorber . . . . .	77
6.6. Passive mode locking with a slow saturable absorber without gain saturation and soliton formation . . . . .	80
6.7. Soliton mode locking . . . . .	81
6.8. Design guidelines to prevent Q-switching instability . . . . .	87
6.9. External pulse compression . . . . .	89
§ 7. Pulse characterization . . . . .	90
7.1. Electronic techniques . . . . .	90
7.2. Optical autocorrelation . . . . .	91
7.3. FROG and SPIDER . . . . .	92
§ 8. Carrier envelope offset (CEO) . . . . .	93
§ 9. Outlook . . . . .	95
References . . . . .	98



<b>Chapter 2. Multiple scattering of light from randomly rough surfaces,</b> <i>Andrei V. Shchegrov (Rochester, NY, USA), Alexei A. Maradudin (Irvine, CA, USA) and Eugenio R. Méndez (Ensenada, Mexico)</i> . . . . .	117
§ 1. Introduction . . . . .	119
§ 2. Characterization of randomly rough surfaces . . . . .	121
2.1. Two-dimensional random surfaces . . . . .	121
2.2. One-dimensional random surfaces . . . . .	125
§ 3. Equations for electromagnetic fields and observable quantities . . . . .	126
3.1. Physical quantities studied in rough surface scattering problems . . . . .	126
3.2. Rayleigh method . . . . .	129
3.3. Surface integral equations for electromagnetic fields . . . . .	131
§ 4. Weak localization effects in the multiple scattering of light from randomly rough surfaces, Enhanced backscattering . . . . .	133
4.1. The nature of enhanced backscattering effect . . . . .	133
4.2. Theoretical methods employed in the study of multiple-scattering phenomena . . . . .	137
4.3. Experimental techniques used in the study of multiple scattering effects, including the enhanced backscattering effect . . . . .	169
§ 5. Angular intensity correlation functions . . . . .	180
5.1. Memory and reciprocal memory effects: theory and experiment . . . . .	184
5.2. The correlation function $C^{(10)}(q, k q', k')$ : theory and experiment . . . . .	186
5.3. Correlations in film systems . . . . .	188
§ 6. Multiple-scattering effects in the scattering of light from complex media bounded by a rough surface . . . . .	189
6.1. Coherent effects associated with the interference of nonreciprocal optical paths . . . . .	189
6.2. Scattering from the random surface of an amplifying medium . . . . .	200
6.3. Scattering from a nonlinear medium bounded by a rough surface . . . . .	203
§ 7. Near-field effects: localization phenomena for surface waves . . . . .	217
§ 8. Spectral changes induced by multiple scattering . . . . .	221
§ 9. Conclusions . . . . .	229
Acknowledgements . . . . .	233
References . . . . .	233
 <b>Chapter 3. Laser-diode interferometry, Yukihiro Ishii</b> <i>(Sagamihara, Japan)</i> . . . . .	 243
§ 1. Introduction . . . . .	245
§ 2. Laser-diode operation . . . . .	246
2.1. Single-mode laser diodes . . . . .	247
2.2. Wavelength tunability in laser diodes . . . . .	248
§ 3. Modulation methods in laser-diode interferometers . . . . .	250
§ 4. Laser-diode phase-shifting interferometers . . . . .	251
4.1. Single-wavelength phase-shifting interferometry . . . . .	253
4.2. Phase-shift calibration . . . . .	260
4.3. Laser-diode Fizeau interferometry . . . . .	264
4.4. Phase-extraction algorithm insensitive to changes in LD power . . . . .	273
4.5. Two-wavelength phase-shifting interferometry . . . . .	277
§ 5. Sinusoidal phase-modulating interferometry . . . . .	283
§ 6. Feedback interferometry . . . . .	285

§ 7. Heterodyne interferometry . . . . .	286
7.1. Single-wavelength heterodyne interferometry . . . . .	287
7.2. Two-wavelength heterodyne interferometry . . . . .	294
§ 8. Optical coherence function synthesized by tunable LD . . . . .	299
§ 9. Holographic interferometer and phase-conjugate interferometer by tunable LD . . . . .	301
§ 10. Conclusions . . . . .	302
Acknowledgements . . . . .	303
References . . . . .	303

## **Chapter 4. Optical realizations of quantum teleportation, *Julio Gea-Banacloche (Fayetteville, AR, USA)* . . . . . 311**

§ 1. A brief primer on quantum teleportation . . . . .	313
1.1. Introduction . . . . .	313
1.2. Teleportation of a two-state system (qubit) . . . . .	313
1.3. Generalization to an $N$ -state system . . . . .	317
1.4. Continuous-variable teleportation . . . . .	319
1.5. Imperfect teleportation . . . . .	321
1.6. Possible applications and extensions . . . . .	324
§ 2. Optical teleportation of discrete variables . . . . .	326
2.1. The difficulties of Bell-state measurements . . . . .	326
2.2. Teleportation using entanglement between different degrees of freedom of the same photon . . . . .	329
2.3. Teleportation with less than a full Bell-state measurement (conditional teleportation) . . . . .	332
2.4. Low-efficiency teleportation with complete Bell-state measurement . . . . .	336
2.5. Near-deterministic teleportation of photonic qubits using only linear optics . . . . .	337
§ 3. Optical teleportation of continuous variables . . . . .	342
3.1. Squeezed states as EPR states . . . . .	342
3.2. Teleportation fidelity for coherent states . . . . .	345
3.3. The role of “classical” fields, and the nature of laser fields . . . . .	347
§ 4. Conclusions . . . . .	350
References . . . . .	350

## **Chapter 5. Intensity-field correlations of non-classical light, *H.J. Carmichael (Auckland, New Zealand), G.T. Foster (New York, NY, USA), L.A. Orozco (Stony Brook, NY, USA), J.E. Reiner (Stony Brook, NY, USA) and P.R. Rice (Oxford, OH, USA)* . . . . . 355**

§ 1. Introduction . . . . .	357
§ 2. Theory . . . . .	359
2.1. The intensity-field correlation function $h_{\theta}(\tau)$ . . . . .	360
2.2. Classical bounds for $h_{\theta}(\tau)$ . . . . .	363
2.3. Time reversal properties of $h_{\theta}(\tau)$ . . . . .	364
2.4. Intensity-field correlations in classical optics . . . . .	365
§ 3. Examples . . . . .	366
3.1. Optical parametric oscillator . . . . .	369
3.2. Cavity QED . . . . .	372
3.3. Two-level atom in an optical parametric oscillator . . . . .	381

§ 4. Experiment in cavity QED . . . . .	385
4.1. Cavity QED apparatus . . . . .	385
4.2. Conditional homodyne detector . . . . .	386
4.3. Measurements . . . . .	388
§ 5. Equal-time cross- and auto-correlations . . . . .	393
5.1. Cross-correlations . . . . .	394
§ 6. Quantum measurements and quantum feedback . . . . .	396
6.1. Weak measurements . . . . .	397
6.2. Vacuum state squeezing versus squeezed classical noise . . . . .	398
6.3. Application of $h_{ij}(\tau)$ to quantum feedback . . . . .	400
§ 7. Conclusion and outlook . . . . .	402
Acknowledgements . . . . .	403
References . . . . .	403
 Author index for Volume 46 . . . . .	 405
Subject index for Volume 46 . . . . .	423
Contents of previous volumes . . . . .	427
Cumulative index – Volumes 1–46 . . . . .	437

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## **Chapter 1**

# **Ultrafast solid-state lasers**

*by*

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**Contents**

	Page
List of symbols . . . . .	3
§ 1. Introduction . . . . .	7
§ 2. Definition of Q-switching and mode locking . . . . .	10
§ 3. Overview of ultrafast solid-state lasers . . . . .	15
§ 4. Loss modulation . . . . .	43
§ 5. Pulse propagation in dispersive media . . . . .	54
§ 6. Mode-locking techniques . . . . .	65
§ 7. Pulse characterization . . . . .	90
§ 8. Carrier envelope offset (CEO) . . . . .	93
§ 9. Outlook . . . . .	95
References . . . . .	98

## List of symbols

$A$	pulse envelope normalized such that $ A(z, t) ^2 = P(z, t)$ (eq. (6.2))
$\tilde{A}$	$\tilde{A}$ is the Fourier transformation of $A$ , i.e. $\tilde{A} = \int A(t)e^{-i\omega t} dt$ (eqs. (6.8) and (6.9))
$A_A$	laser mode area on saturable absorber
$A_L$	laser mode area in laser gain media
$A_p$	pump mode area
$b$	depth of focus or confocal parameter of a Gaussian beam
$D$	dispersion parameter (eq. (6.18) and Table 7), i.e. half of the total group delay dispersion per cavity roundtrip
$D_g$	gain dispersion (eq. (6.10)) and Table 7)
$D_p$	width of the pump source (i.e. approximately the stripe width of a diode array or bar)
$DR(t)$	impulse response of a saturable absorber mirror measured with standard pump probe (fig. 4)
$E$	electric field of the electromagnetic wave
$\tilde{E}$	$\tilde{E}$ is the Fourier transformation of $E$ , i.e. $\tilde{E} = \int E(t)e^{-i\omega t} dt$ (eqs. (6.6) and (6.7))
$E_p$	intracavity pulse energy
$E_{p,\text{out}}$	output pulse energy
$E_{\text{sat},A}$	absorber saturation energy (Table 3)
$E_{\text{sat},L}$	laser saturation energy $E_{\text{sat},L} = F_{\text{sat},L} \cdot A_L$
$f(t)$	$f(t) = \frac{P(t)}{E_p}$ , with $\int f(t) dt = 1$ (eq. (4.7))
$f_{\text{rep}}$	pulse repetition frequency
$F$	fluence, $F = \int I(t) dt$ , in units of $\frac{\text{J}}{\text{cm}^2}$
$F_{\text{sat},A}$	absorber saturation fluence (Table 3)
$F_{\text{sat},L}$	laser saturation fluence (eqs. (3.1) and (3.2))
$F_{p,A}$	incident pulse fluence on saturable absorber (Table 3)
$g$	saturated amplitude laser gain coefficient
$g_0$	small signal amplitude laser gain

$h\nu$	photon energy
$I$	intensity
$I_A$	incident intensity on saturable absorber
$I_{\text{sat},A}$	absorber saturation intensity (Table 3)
$k$	vacuum wave number, i.e. $k = 2\pi/\lambda$
$k_n$	wave number in a dispersive media, i.e. $k_n = nk$
$l$	total saturated amplitude loss coefficient. $l$ includes the output coupler, all the residual cavity losses and the unsaturated loss of the saturable absorber
$l_{\text{out}}$	amplitude loss coefficient of output coupler
$l_s$	amplitude loss coefficient of soliton due to gain filtering and absorber saturation (eq. (6.53))
$L_a$	absorption length
$L_g$	length of laser gain material
$M$	modulation depth of loss modulator (eq. (6.11))
$M_s$	curvature of loss modulation (eq. (6.11) and Table 7)
$M^2$	$M^2$ factor defining the laser beam quality (eq. (3.3))
$M_{\text{slow}}^2$	$M^2$ factor in the “slow” axis, parallel to the pn junction of the diode laser
$M_{\text{fast}}^2$	$M^2$ factor in the “fast” axis, perpendicular to the pn junction of the diode laser
$n$	refractive index of a dispersive media
$n_2$	nonlinear refractive index (eq. (6.20))
$P$	power
$P_0$	peak power of pulse
$P_{\text{abs}}$	absorbed pump power
$P_{\text{av, out}}$	average output power
$q$	saturable amplitude loss coefficient (i.e. nonsaturable losses not included) (eq. (4.2))
$q_0$	unsaturated amplitude loss coefficient or maximal saturable amplitude loss coefficient (eq. (4.1))
$q_p$	total absorber loss coefficient which results from the fact that part of the excitation pulse needs to be absorbed to saturate the absorber
$q_s$	residual saturable absorber amplitude loss coefficient for a fully saturated ideal fast absorber with soliton pulses (eq. (6.46))
$R$	reflectivity for intensity
$S$	saturation parameter $S = \frac{F_{p,A}}{F_{\text{sat},A}}$ (Section 4.2.1)
$t$	time
$t_D$	time shift (eq. (6.37))
$T$	time that develops on a time scale of $T_R$ (eq. (6.1))

$T_{\text{out}}$	intensity transmission of the laser output coupler
$T_R$	cavity roundtrip time
$V_p$	pump volume
$W_{0,G}$	beam waist of a Gaussian beam (eq. (3.3))
$W_{0,\text{opt}}$	optimized beam waist for efficient diode pumping (eq. (3.5))
$x$	chirp parameter (eqs. (6.30) and (6.31))
$z$	pulse propagation distance
$z_0$	Rayleigh range of a Gaussian beam, i.e. $z_0 = \frac{\pi W_0^2}{\lambda}$
$\Delta A$	change in the pulse envelope
$\Delta R$	modulation depth of a saturable absorber mirror (fig. 5)
$\Delta R_{\text{ns}}$	nonsaturable reflection loss of saturable absorber mirror (fig. 5)
$\Delta T$	modulation depth of saturable absorber in transmission
$\Delta T_{\text{ns}}$	nonsaturable transmission loss of saturable absorber
$\Delta \lambda_g$	FWHM gain bandwidth
$\Delta \nu_g$	FWHM gain bandwidth, i.e. $\frac{\Delta \nu_g}{\nu_0} = \frac{\Delta \lambda_g}{\lambda_0}$
$\delta_L$	SPM coefficient (eq. (6.22) and Table 7)
$\phi$	phase shift, $\phi = k_n \cdot z$ , $z$ : propagation distance
$\phi_{\text{nl}}$	nonlinear phase shift per cavity roundtrip (eq. (6.33))
$\phi_s(z)$	phase shift of the soliton during propagation along the $z$ -axis (eq. (6.51))
$\phi_s$	phase shift of the soliton per cavity round trip (eq. (6.54))
$\phi_{\text{nl}}(z)$	nonlinear phase shift of a pulse with peak intensity $I_0$ during propagation through a Kerr media along the $z$ -axis, i.e. $\phi_{\text{nl}}(z) = kn_2 I_0 z$
$\psi$	phase shift (eq. (6.28))
$\gamma_A$	absorber coefficient (eq. (4.13) and Table 7)
$\lambda$	vacuum wavelength of light
$\lambda_0$	center vacuum wavelength
$\lambda_n$	wavelength in a dispersive media with refractive index $n$ , i.e. $\lambda_n = \lambda/n$
$\lambda_{\text{eff}}$	effective wavelength (eq. (3.4))
$\nu$	frequency
$\nu_{\text{pump}}$	pump photon frequency
$\omega$	radian frequency
$\omega_0$	center radian frequency
$\omega_m$	modulation frequency in radians/second
$\Omega_g$	half-width-half-maximum (HWHM) gain bandwidth of laser in radians/seconds, i.e. $\Omega_g = \pi \Delta \nu_g$ (eq. (6.3))
$\theta$	divergence angle of a pump source (i.e. the beam radius increases approximately linearly with propagation distance, defining a cone with half-angle $\theta$ )
$\theta_G$	divergence angle of a Gaussian beam, i.e. $\theta_G = \frac{\lambda}{\pi W_{0,G}}$ (eq. (3.3))



$\sigma_A$	absorber cross section
$\sigma_L$	gain cross section
$\sigma_L^{\text{abs}}$	absorption cross section
$\tau_A$	recovery time of saturable absorber
$\tau_{\text{Au}}$	FWHM of intensity autocorrelation pulse
$\tau_c$	photon cavity lifetime
$\tau_L$	upper state lifetime of laser gain material
$\tau_p$	FWHM intensity pulse duration
$\tau_{p,\text{min}}$	minimal $\tau_p$