

Springer Series in Optical Sciences Volume 64

Editor: A.E. Siegman

Springer-Verlag Berlin Heidelberg GmbH

Springer Series in Optical Sciences

Editorial Board: A. L. Schawlow A. E. Siegman T. Tamir

Managing Editor: H. K. V. Lotsch

- 42 **Principles of Phase Conjugation**
By B. Ya. Zel'dovich, N. F. Pilipetsky,
and V. V. Shkunov
- 43 **X-Ray Microscopy**
Editors: G. Schmahl and D. Rudolph
- 44 **Introduction to Laser Physics**
By K. Shimoda 2nd Edition
- 45 **Scanning Electron Microscopy**
Physics of Image Formation and Microanalysis
By L. Reimer
- 46 **Holography and Deformation Analysis**
By W. Schumann, J.-P. Zürcher, and D. Cuche
- 47 **Tunable Solid State Lasers**
Editors: P. Hammerling, A. B. Budgor,
and A. Pinto
- 48 **Integrated Optics**
Editors: H. P. Nolting and R. Ulrich
- 49 **Laser Spectroscopy VII**
Editors: T. W. Hänsch and Y. R. Shen
- 50 **Laser-Induced Dynamic Gratings**
By H. J. Eichler, P. Günter, and D. W. Pohl
- 51 **Tunable Solid State Lasers for Remote Sensing** Editors: R. L. Byer, E. K. Gustafson,
and R. Trebino
- 52 **Tunable Solid-State Lasers II**
Editors: A. B. Budgor, L. Esterowitz,
and L. G. DeShazer
- 53 **The CO₂ Laser** By W. J. Witteman
- 54 **Lasers, Spectroscopy and New Ideas**
A Tribute to Arthur L. Schawlow
Editors: W. M. Yen and M. D. Levenson
- 55 **Laser Spectroscopy VIII**
Editors: W. Persson and S. Svanberg
- 56 **X-Ray Microscopy II**
Editors: D. Sayre, M. Howells, J. Kirz,
and H. Rarback
- 57 **Single-Mode Fibers** Fundamentals
By E.-G. Neumann
- 58 **Photoacoustic and Photothermal Phenomena**
Editors: P. Hess and J. Pelzl
- 59 **Photorefractive Crystals
in Coherent Optical Systems**
By M. P. Petrov, S. I. Stepanov,
and A. V. Khomenko
- 60 **Holographic Interferometry
in Experimental Mechanics**
By Yu. I. Ostrovsky, V. P. Shchepinov,
and V. V. Yakovlev
- 61 **Millimetre and Submillimetre Wavelength
Lasers** A Handbook of cw Measurements
By N. G. Douglas
- 62 **Photoacoustic and Photothermal Phenomena II**
Editors: J. C. Murphy, J. W. MacLachlan Spicer,
L. C. Aamodt, and B. S. H. Royce
- 63 **Electron Energy Loss Spectrometers**
The Technology of High Performance
By H. Ibach
- 64 **Handbook of Nonlinear Optical Crystals**
By V. G. Dmitriev, G. G. Gurzadyan,
and D. N. Nikogosyan 2nd Edition
- 65 **High-Power Dye Lasers**
Editor: F. J. Duarte
- 66 **Silver Halide Recording Materials
for Holography and Their Processing**
By H. I. Bjelkhagen 2nd Edition
- 67 **X-Ray Microscopy III**
Editors: A. G. Michette, G. R. Morrison,
and C. J. Buckley
- 68 **Holographic Interferometry**
Principles and Methods
Editor: P. K. Rastogi
- 69 **Photoacoustic and Photothermal Phenomena III**
Editor: D. Bičanić
- 70 **Electron Holography**
By A. Tonomura
- 71 **Energy-Filtering Transmission
Electron Microscopy**
Editor: L. Reimer

V.G. Dmitriev G.G. Gurzadyan
D.N. Nikogosyan

Handbook of Nonlinear Optical Crystals

Second, Revised and Updated Edition

With 39 Figures



Springer

Professor VALENTIN G. DMITRIEV, Ph.D.

R&D Institute "Polyus", Vvedenskogo St. 3
Moscow, 117342, Russia

GAGIK G. GURZADYAN, Ph.D.

Yerevan State University
Yerevan, Armenia

Professor DAVID N. NIKOGOSYAN, Ph.D.

Institute of Spectroscopy
Russian Academy of Sciences
Troitzk, Moscow Region, 142092, Russia

Editorial Board

ARTHUR L. SCHAWLOW, Ph.D.

Department of Physics, Stanford University
Stanford, CA 94305-4060, USA

THEODOR TAMIR, Ph.D.

Department of Electrical Engineering
Polytechnic University, 333 Jay Street
Brooklyn, NY 11201, USA

Professor ANTHONY E. SIEGMAN, Ph.D.

Electrical Engineering
E.L. Ginzton Laboratory, Stanford University
Stanford, CA 94305-4085, USA

Managing Editor: Dr.-Ing. HELMUT K.V. LOTSCH

Springer-Verlag, Tiergartenstrasse 17, D-69121 Heidelberg, Germany

ISSN 0342-4111

ISBN 978-3-662-14102-1

Library of Congress Cataloging-in-Publication Data. Gurzadian, G.G. (Gagik Grigor 'evich), 1957- [Nelineino-opticheskie kristally. English] Handbook of nonlinear optical crystals/V.G. Dmitriev, G.G. Gurzadyan, D.N. Nikogosyan. p. cm. – (Springer series in optical sciences; v. 64) Gurzadian's name appears first on earlier edition. Includes bibliographical references and index.

ISBN 978-3-662-14102-1 ISBN 978-3-540-68392-6 (eBook)

DOI 10.1007/978-3-540-68392-6

1. Laser

materials – Handbooks, manuals, etc. 2. Optical materials – Handbooks, manuals, etc. 3. Crystals – Handbooks, manuals, etc. 4. Nonlinear optics – Handbooks, manuals, etc. I. Dmitriev, V.G. (Valentin Georgievich) II. Nikogosyan, D.N., 1946- . III. Title. IV. Series. QC374.G8713 1997 621.36'6-dc20 97-23159

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer-Verlag Berlin Heidelberg GmbH. Violations are liable for prosecution under the German Copyright Law.

© Springer-Verlag Berlin Heidelberg 1991, 1997

Originally published by Springer-Verlag Berlin Heidelberg New York in 1997

Softcover reprint of the hardcover 2nd edition 1997

The use of general registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Cover design: Design & Production GmbH, Heidelberg

Typesetting: Scientific Publishing Services (P) Ltd, Madras

SPIN: 10480587

54/3144/SPS – 5 4 3 2 1 0 – Printed on acid-free paper

To our Parents

Preface

Four years ago when we had finished our work on the first edition of our Handbook we didn't even suppose that three years later it would become necessary to greatly revise and update the material. It happened because of the following developments.

1. The invention and tremendous development of modern nonlinear optical crystals such as BBO, LBO, KTP, ZnGeP_2 , etc.
2. Rapid progress in laser techniques (femtosecond CPM laser, Ti: sapphire laser, diode-pumped solid-state lasers, etc.).
3. The appearance of numerous organic crystals which can be synthesized with predictable properties.
4. Progress in the theory of nonlinear frequency conversion utilizing biaxial crystals, femtosecond pulses, etc.
5. Accumulation of new data on the properties of nonlinear optical crystals.

In accordance with the above, we have made many changes in the text. The first chapter was revised by D.N. Nikogosyan, the second one by V.G. Dmitriev and D.N. Nikogosyan, and the fourth one by G.G. Gurzadyan. The third chapter, containing the main reference material on 77 nonlinear optical crystals was completely rewritten and updated by D.N. Nikogosyan. The Appendix containing the list of most commonly used laser wavelengths was compiled by D.N. Nikogosyan. We would appreciate any valuable comments and recommendations that will allow us to further improve the Handbook.

We would like to thank H.K.V. Lotsch for fruitful and long-lasting cooperation.

Moscow, Yerevan, Troitzk
Russia, Armenia
December 1995

*V. G. Dmitriev
G. G. Gurzadyan
D. N. Nikogosyan*

Preface to the First Edition

Since the invention of the first laser 30 years ago, the frequency conversion of laser radiation in nonlinear optical crystals has become an important technique widely used in quantum electronics and laser physics for solving various scientific and engineering problems. The fundamental physics of three-wave light interactions in nonlinear optical crystals is now well understood. This has enabled the production of various harmonic generators, sum- and difference-frequency generators, and optical parametric oscillators based on nonlinear optical crystals that are now commercially available. At the same time, scientists continue an active search for novel, highly efficient nonlinear optical materials.

Therefore, in our opinion, there is a great need for a handbook of nonlinear optical crystals, intended for specialists and practitioners with an engineering background. This book contains a complete description of the properties and applications of all nonlinear optical crystals of practical importance reported in the literature up to the beginning of 1990. In addition, it contains the most important equations for calculating the main parameters (such as phase-matching direction, effective nonlinearity, and conversion efficiency) of nonlinear frequency converters.

Dolgoprudnyi, Yerevan, Troitzk
USSR
October 1990

*V. G. Dmitriev
G. G. Gurzadyan
D. N. Nikogosyan*

Contents

1 Introduction	1
2 Optics of Nonlinear Crystals	3
2.1 Three- and Four-Wave (Three- and Four-Frequency) Interactions in Nonlinear Media	3
2.2 Phase-Matching Conditions	5
2.3 Optics of Uniaxial Crystals	6
2.4 Types of Phase Matching in Uniaxial Crystals	10
2.5 Calculation of Phase-Matching Angles in Uniaxial Crystals	13
2.6 Reflection and Refraction of Light Waves at the Surfaces of Uniaxial Crystals	14
2.7 Optics of Biaxial Crystals	16
2.8 Types of Phase Matching in Biaxial Crystals	18
2.9 Calculation of Phase-Matching Angles in Biaxial Crystals	19
2.10 Crystal Symmetry and Effective Nonlinearity: Uniaxial Crystals ..	23
2.11 Crystal Symmetry and Effective Nonlinearity: Biaxial Crystals ..	25
2.12 Theory of Nonlinear Frequency-Conversion Efficiency	32
2.13 Wave Mismatch and Phase-Matching Bandwidth	40
2.14 Calculation of Nonlinear Frequency-Conversion Efficiency in Some Special Cases	48
2.14.1 Plane-Wave Fixed-Field Approximation	49
2.14.2 Fundamental Wave Depletion (“Nonlinear Regime”) ..	52
2.14.3 SHG of a Divergent Fundamental Radiation Beam in the Fixed-Field Approximation	54
2.14.4 SHG of a Divergent Fundamental Radiation Beam in the Nonlinear Regime	55
2.14.5 Fixed-Intensity Approximation	57
2.14.6 Frequency Conversion of Ultrashort Laser Pulses	59
2.14.7 Frequency Conversion of Laser Beams with Limited Aperture in the Stationary Regime	61
2.14.8 Linear Absorption	65
2.15 Additional Comments	65

3 Properties of Nonlinear Optical Crystals	67
3.1 Basic Nonlinear Optical Crystals	68
3.1.1 LiB_3O_5 , Lithium Triborate (LBO)	68
3.1.2 KH_2PO_4 , Potassium Dihydrogen Phosphate (KDP)	78
3.1.3 KD_2PO_4 , Deuterated Potassium Dihydrogen Phosphate (DKDP)	85
3.1.4 $\text{NH}_4\text{H}_2\text{PO}_4$, Ammonium Dihydrogen Phosphate (ADP)	90
3.1.5 $\beta\text{-BaB}_2\text{O}_4$, Beta-Barium Borate (BBO)	96
3.1.6 LiIO_3 , Lithium Iodate	103
3.1.7 KTiOPO_4 , Potassium Titanyl Phosphate (KTP)	107
3.1.8 LiNbO_3 , Lithium Niobate	119
3.1.9 KNbO_3 , Potassium Niobate	126
3.1.10 AgGaS_2 , Silver Thiogallate	132
3.1.11 ZnGeP_2 , Zinc Germanium Phosphide	136
3.2 Frequently Used Nonlinear Optical Crystals	142
3.2.1 $\text{KB}_5\text{O}_8 \cdot 4\text{H}_2\text{O}$, Potassium Pentaborate Tetrahydrate (KB5)	142
3.2.2 $\text{CO}(\text{NH}_2)_2$, Urea	146
3.2.3 CsH_2AsO_4 , Cesium Dihydrogen Arsenate (CDA)	149
3.2.4 CsD_2AsO_4 , Deuterated Cesium Dihydrogen Arsenate (DCDA)	152
3.2.5 KTiOAsO_4 , Potassium Titanyl Arsenate (KTA)	156
3.2.6 $\text{MgO} : \text{LiNbO}_3$, Magnesium-Oxide-Doped Lithium Niobate	159
3.2.7 Ag_3AsS_3 , Proustite	162
3.2.8 GaSe , Gallium Selenide	166
3.2.9 AgGaSe_2 , Silver Gallium Selenide	169
3.2.10 CdSe , Cadmium Selenide	173
3.2.11 CdGeAs_2 , Cadmium Germanium Arsenide	176
3.3 Other Inorganic Nonlinear Optical Crystals	179
3.3.1 $\text{KB}_5\text{O}_8 \cdot 4\text{D}_2\text{O}$, Deuterated Potassium Pentaborate Tetrahydrate (DKB5)	179
3.3.2 CsB_3O_5 , Cesium Triborate (CBO)	180
3.3.3 $\text{BeSO}_4 \cdot 4\text{H}_2\text{O}$, Beryllium Sulfate	182
3.3.4 MgBaF_4 , Magnesium Barium Fluoride	184
3.3.5 $\text{NH}_4\text{D}_2\text{PO}_4$, Deuterated Ammonium Dihydrogen Phosphate (DADP)	186
3.3.6 RbH_2PO_4 , Rubidium Dihydrogen Phosphate (RDP)	188
3.3.7 RbD_2PO_4 , Deuterated Rubidium Dihydrogen Phosphate (DRDP)	192
3.3.8 KH_2AsO_4 , Potassium Dihydrogen Arsenate (KDA)	192
3.3.9 KD_2AsO_4 , Deuterated Potassium Dihydrogen Arsenate (DKDA)	195

3.3.10	$\text{NH}_4\text{H}_2\text{AsO}_4$, Ammonium Dihydrogen Arsenate (ADA)	196
3.3.11	$\text{NH}_4\text{D}_2\text{AsO}_4$, Deuterated Ammonium Dihydrogen Arsenate (DADA)	198
3.3.12	RbH_2AsO_4 , Rubidium Dihydrogen Arsenate (RDA)	199
3.3.13	RbD_2AsO_4 , Deuterated Rubidium Dihydrogen Arsenate (DRDA)	202
3.3.14	$\text{LiCOOH} \cdot \text{H}_2\text{O}$, Lithium Formate Monohydrate (LFM)	204
3.3.15	NaCOOH , Sodium Formate	207
3.3.16	$\text{Ba}(\text{COOH})_2$, Barium Formate	209
3.3.17	$\text{Sr}(\text{COOH})_2$, Strontium Formate	210
3.3.18	$\text{Sr}(\text{COOH})_2 \cdot 2\text{H}_2\text{O}$, Strontium Formate Dihydrate	211
3.3.19	LiGaO_2 , Lithium Gallium Oxide	213
3.3.20	$\alpha\text{-HIO}_3$, α -Iodic Acid	214
3.3.21	$\text{K}_2\text{La}(\text{NO}_3)_5 \cdot 2\text{H}_2\text{O}$, Potassium Lanthanum Nitrate Dihydrate (KLN)	217
3.3.22	CsTiOAsO_4 , Cesium Titanyl Arsenate (CTA)	220
3.3.23	NaNO_2 , Sodium Nitrite	221
3.3.24	$\text{Ba}_2\text{NaNb}_5\text{O}_{15}$, Barium Sodium Niobate (“Banana”)	224
3.3.25	$\text{K}_2\text{Ce}(\text{NO}_3)_5 \cdot 2\text{H}_2\text{O}$, Potassium Cerium Nitrate Dihydrate (KCN)	227
3.3.26	$\text{K}_3\text{Li}_2\text{Nb}_5\text{O}_{15}$, Potassium Lithium Niobate	229
3.3.27	HgGa_2S_4 , Mercury Thiogallate	231
3.3.28	HgS , Cinnibar	233
3.3.29	Ag_3SbS_3 , Pyrargyrite	235
3.3.30	Se, Selenium	236
3.3.31	Tl_3AsS_3 , Thallium Arsenic Selenide (TAS)	238
3.3.32	Te, Tellurium	240
3.4	Other Organic Nonlinear Optical Crystals	243
3.4.1	$\text{C}_{12}\text{H}_{22}\text{O}_{11}$, Sucrose (Saccharose)	243
3.4.2	L-Arginine Phosphate Monohydrate (LAP)	245
3.4.3	Deuterated L-Arginine Phosphate Monohydrate (DLAP)	247
3.4.4	L-Pyrrolidone-2-carboxylic Acid (L-PCA)	250
3.4.5	$\text{CaC}_4\text{H}_4\text{O}_6 \cdot 4\text{H}_2\text{O}$, Calcium Tartrate Tetrahydrate (L-CTT)	251
3.4.6	$(\text{NH}_4)_2\text{C}_2\text{O}_4 \cdot \text{H}_2\text{O}$, Ammonium Oxalate (AO)	253
3.4.7	m-Bis(aminomethyl)benzene (BAMB)	254
3.4.8	3-Methoxy-4-hydroxy-benzaldehyde (MHBA)	256
3.4.9	2-Furyl Methacrylic Anhydride (FMA)	258
3.4.10	3-Methyl-4-nitropyridine-1-oxide (POM)	259
3.4.11	Thienylchalcone (T-17)	261
3.4.12	5-Nitouracil (5NU)	263
3.4.13	2-(N-Prolinol)-5-nitropyridine (PNP)	265

3.4.14	2-Cyclooctylamino-5-nitropyridine (COANP)	266
3.4.15	L-N-(5-Nitro-2-pyridyl)leucinol (NPLO)	268
3.4.16	C ₆ H ₄ (NO ₂) ₂ , m-Dinitrobenzene (MDNB)	270
3.4.17	4-(N,N-Dimethylamino)-3-acetamidonitrobenzene (DAN)	272
3.4.18	Methyl-(2,4-dinitrophenyl)-aminopropanoate (MAP)	274
3.4.19	m-Nitroaniline (MNA)	276
3.4.20	N-(4-Nitrophenyl)-N-methylaminoacetonitrile (NPAN)	278
3.4.21	N-(4-Nitrophenyl)-L-prolinol (NPP)	280
3.4.22	3-Methyl-4-methoxy-4'-nitrostilbene (MMONS)	281
3.5	Properties of Crystalline Quartz (α -SiO ₂)	283
3.6	New Developments	286
4	Applications of Nonlinear Crystals	289
4.1	Generation of Neodymium Laser Harmonics	289
4.1.1	Second-Harmonic Generation of Neodymium Laser Radiation in Inorganic Crystals	289
4.1.2	Second-Harmonic Generation of 1.064 μ m Radiation in Organic Crystals	294
4.1.3	Intracavity SHG	296
4.1.4	Third-Harmonic Generation	298
4.1.5	Fourth-Harmonic Generation	301
4.1.6	Fifth-Harmonic Generation	301
4.1.7	Harmonic Generation of 1.318 μ m Radiation	304
4.2	Harmonic Generation of High-Power Large-Aperture Neodymium Glass Laser Radiation	306
4.2.1	“Angle-Detuning” Scheme	306
4.2.2	“Polarization-Mismatch” Scheme	306
4.2.3	“Polarization-Bypass” Scheme	308
4.2.4	Comparison of Schemes	308
4.2.5	Experimental Results	308
4.2.6	“Quadrature” Scheme	310
4.3	Harmonic Generation for Other Laser Sources	311
4.3.1	Ruby Laser	311
4.3.2	Ti:sapphire Laser	312
4.3.3	Semiconductor Lasers	312
4.3.4	Dye Lasers	315
4.3.5	Gas Lasers	320
4.3.6	Iodine Laser	321
4.3.7	CO ₂ Laser	324
4.3.8	Other Lasers	324
4.3.9	Frequency Conversion of Femtosecond Pulses	326

4.4	Sum-Frequency Generation	327
4.4.1	Up-Conversion to the UV Region	328
4.4.2	Infrared Up-Conversion	333
4.4.3	Up-Conversion of CO ₂ Laser Radiation to the Near IR and Visible Regions	336
4.5	Difference-Frequency Generation	339
4.5.1	DFG in the Visible Region	339
4.5.2	DFG in the Mid IR Region	340
4.5.3	DFG in the Far IR Region	344
4.6	Optical Parametric Oscillation	345
4.6.1	OPO in the UV, Visible, and Near IR Spectral Regions	345
4.6.2	OPO in the Mid IR Region	359
4.6.3	Conversion of OPO Radiation to the UV Region	360
4.7	Stimulated Raman Scattering and Picosecond Continuum Generation in Crystals	362
References		367
Appendix: List of Commonly Used Laser Wavelengths		405
Subject Index		407

List of Abbreviations

a	Aperture
c	Cut
cont	Continuum
cr	Critical
cw	Continuous wave
DF	Difference frequency
DFG	Difference-frequency generation
dif	Diffraction
DROPO	Doubly-resonant optical parametric oscillation
ds, dis	Dispersive spreading
e	Extraordinary
eff	Effective
exp	Experimental
f	Fast
fcg	Free-carrier generation
FIHG	Fifth-harmonic generation
FOHG	Fourth-harmonic generation
ICSFG	Intracavity sum-frequency generation
ICSHG	Intracavity second-harmonic generation
int	Internal
IR	Infrared
L	Linear
NCPM	Non-critical phase matching
NL	Nonlinear
no pm	No phase matching
o	Ordinary
OPO	Optical parametric oscillation
OR	Optical rectification
p	Pulse
PM, pm	Phase matching
PL	Parametric luminescence
pr	Photorefraction
qs	Quasistatic
s	Slow
SF	Sum frequency

XVIII List of Abbreviations

SFG	Sum-frequency generation
SFM	Sum-frequency mixing
SH	Second harmonic
SHG	Second-harmonic generation
SIHG	Sixth-harmonic generation
SROPO	Singly-resonant optical parametric oscillation
SRS	Stimulated Raman scattering
theor	Theoretical
THG	Third-harmonic generation
thr	Threshold
tsa	Thermal self-action
TWOPO	Traveling-wave optical parametric oscillation
unc	Unconverted
UV	Ultraviolet