

# Room-Temperature Color Center Lasers

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(Invited Paper)

**Abstract**—A survey of results is presented on the development of room temperature tunable lasers using color centers in ionic crystals and on using color center crystals as nonlinear filters and passive Q-switches for neodymium lasers.

## I. INTRODUCTION

**L**ASERS using color centers (CC's) in ionic crystals, developed over the last 10 years, have become a new class of sources of coherent radiation with smoothly tunable wavelengths [1]–[12]. They possess an array of unique characteristics, such as 1) the practically important wavelength tuning region ranging from 0.5 to 4  $\mu\text{m}$ , 2) high wavelength stability, and 3) an extremely narrow output spectral width, achievable virtually without power loss while preserving a continuous wide region of tuning (up to 2500  $\text{cm}^{-1}$ ) due to quasi-homogeneous broadening of their gain transitions.

The superb characteristics obtained by available and simple laser techniques, and the capability of color-center lasers (CCL's) to operate efficiently in all the known temporal modes (continuous to subpicosecond pulse) make them most promising tools for experimental physics. They confidently compete with semiconductor lasers, notable for their high resolution in the near IR region, and essentially surpass them in peak and average power, low radiation divergence, and region of continuous wavelength tuning. Color-center lasers also do not yield to parametric light oscillators in output power in nano- and picosecond operating modes and surpass them in quasi-continuous and CW regimes. Due to their high gain, the CCL features a considerably narrower oscillation spectrum, as well as a low sensitivity to the quality of the cavity optical elements and to the spatial-angular and spectral characteristics of the pump radiation.

The aim of this paper is to give a review of the present status of research in the field of development and application of room temperature CCL's.

The idea of making lasers using electron-vibrational transitions of color centers was first discussed as far back as 1961, soon after the first laser was demonstrated. B. Fritz and E. Menke [13] were the first in 1965 to attain oscillation with a color center using a pulsed flashlamp to pump a KCL-Li crystal with  $F_2(\text{H})$  centers, cooled to

liquid nitrogen temperature. In the following decade, CCL's virtually fell outside active research interests. Considerable effort was devoted during this period to the development of tunable lasers using solutions of organic dyes. The availability of dyes, and the simplicity of creating an active volume, prompted a wide range of tunable dye laser research efforts. However, as early as the mid-1970's, when new application opportunities and requirements arose, and the merits and shortcomings of the dye lasers were clearly determined, an interest in tunable CCL's was renewed. Also by that time, the major techniques for narrowing laser radiation and for wavelength tuning across broad-electron-vibrational amplification bands using different types of dispersive cavities had been elaborated.

One of the first among those returning to the problem of making CCL's was a Bell Telephone group (U.S.A.). In 1974 they demonstrated [1], [6], [12] high monochromaticity and a wide tuning range of a KCL-Li laser with an  $F_2(\text{H})$  CC, operating at nitrogen temperature (77 K) and laser pumped [14], [15]. This group [1], [6], [12] engaged in a search for new CCL media and the achievement of different operating modes of cryogenic CCL's.

Later on, another group [16]–[18] from the Institute of Thermo-Physics of the U.S.S.R. Academy of Sciences achieved room temperature oscillation on new quasi-molecular aggregate CC ( $F_2^-$ ,  $F_2^+$ , and  $F_2^0$ ) in LiF and NaF crystals and showed them to be promising for producing tunable radiation in the spectral range 0.7–1.4  $\mu\text{m}$ .

A group [19], [20] from the Hannover Technological University (West Germany) was the first to make a cryogenic ( $T = 77$  K)  $F_2(\text{H})$  CCL. They developed the techniques for attaining super stable narrow-band CC oscillation.

Scientists from the Irkutsk State University (U.S.S.R.) proposed the technique of optical stabilization of thermally unstable  $F_2^+$  centers by doping the crystals with different impurities, and obtained oscillation using these impurity-vacancy centers at room temperature [2], [21], [22].

Oscillation on impurity-vacancy ( $F_2$ )<sub>4</sub> CC's in Na-doped CaF and SrF<sub>2</sub> was attained at  $T = 300$  K by researchers [23], [24] at the State Optical Institute (U.S.S.R.).

Scientists [25]–[29] of the General Physics Institute of the U.S.S.R. Academy of Sciences proposed new schemes for attaining tunable radiation using thermo- and photo-unstable CC's at room temperature, developed the tech-

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# Room Temperature Tunable Color Center Lasers

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## **Room Temperature Tunable Color Center Lasers:**

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*Handbook of Laser Wavelengths* Marvin J. Weber, 2018-10-08 This volume represents the most complete up to date compilation of wavelengths of lasers in all media Divided by type solid liquid and gas and listed in order of increasing wavelength Handbook of Laser Wavelengths includes crystalline paramagnetic ion lasers glass lasers color center lasers semiconductor lasers polymer lasers liquid and solid state dye lasers rare earth liquid lasers neutral atom ion and molecular gas lasers extreme ultraviolet and soft X ray lasers free electron lasers nuclear pumped lasers lasers in nature lasers without inversion Brief descriptions of each type of laser are presented followed by tables listing the laser wavelength lasing element or medium host transition and primary literature citations A special section on commercial lasers is an added featured Handbook of Laser Wavelengths singularly serves as the essential reference for scientists and engineers searching for laser sources for specific applications as well as a survey of the developments that have occurred since the advent of the laser

Selected Papers on Color-center Lasers Kenneth James Teegarden, 2003 A collection of papers dealing with the colour center laser The first section deals with fundamental research that preceded the colour center laser the second covers the discovery and development of several types of laser and the final section contains examples of applications of the laser

Solid-State Mid-Infrared Laser Sources Irina T. Sorokina, Konstantin L. Vodopyanov, 2003-07-10 The book describes the most advanced techniques for generating coherent light in the mid infrared region of the spectrum These techniques represent diverse areas of photonics and include heterojunction semiconductor lasers quantum cascade lasers tunable crystalline lasers fiber lasers Raman lasers and optical parametric laser sources Offering authoritative reviews by internationally recognized experts the book provides a wealth of information on the essential principles and methods of the generation of coherent mid infrared light and on some of its applications The instructive nature of the book makes it an

excellent text for physicists and practicing engineers who want to use mid infrared laser sources in spectroscopy medicine remote sensing and other fields and for researchers in various disciplines requiring a broad introduction to the subject

*Handbook of Laser Technology and Applications* Colin Webb, Julian D.C. Jones, 2020-09-29 The invention of the laser was one of the towering achievements of the twentieth century At the opening of the twenty first century we are witnessing the burgeoning of the myriad technical innovations to which that invention has led The Handbook of Laser Technology and Applications is a practical and long lasting reference source for scientists and engineers who work with lasers The Handbook provides a comprehensive guide to the current status of lasers and laser systems it is accessible to science or engineering graduates needing no more than standard undergraduate knowledge of optics Whilst being a self contained reference work the Handbook provides extensive references to contemporary work and is a basis for studying the professional journal literature on the subject It covers applications through detailed case studies and is therefore well suited to readers who wish to use it to solve specific problems of their own The first of the three volumes comprises an introduction to the basic scientific principles of lasers laser beams and non linear optics The second volume describes the mechanisms and operating characteristics of specific types of laser including crystalline solid state lasers semiconductor diode lasers fibre lasers gas lasers chemical lasers dye lasers and many others as well as detailing the optical and electronic components which tailor the laser s performance and beam delivery systems The third volume is devoted to case studies of applications in a wide range of subjects including materials processing optical measurement techniques medicine telecommunications data storage spectroscopy earth sciences and astronomy and plasma fusion research This vast compendium of knowledge on laser science and technology is the work of over 130 international experts many of whom are recognised as the world leaders in their respective fields Whether the reader is engaged in the science technology industrial or medical applications of lasers or is researching the subject as a manager or investor in technical enterprises they cannot fail to be informed and enlightened by the wide range of information the Handbook supplies **Laser Induced Damage in Optical Materials** ,1996

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telecommunications and data storage to medicine optical measurement defense and security nanomaterials processing and characterization

**Solid-State Lasers and Applications** Alphan Sennaroglu, 2017-12-19 Because of the favorable characteristics of solid state lasers they have become the preferred candidates for a wide range of applications in science and technology including spectroscopy atmospheric monitoring micromachining and precision metrology Presenting the most recent developments in the field Solid State Lasers and Applications focuses on the design and applications of solid state laser systems With contributions from leading international experts the book explores the latest research results and applications of solid state lasers as well as various laser systems The beginning chapters discuss current developments and applications of new solid state gain media in different wavelength regions including cerium doped lasers in the ultraviolet range ytterbium lasers near 1  $\mu$ m rare earth ion doped lasers in the eye safe region and tunable Cr<sup>2+</sup>/ZnSe lasers in the mid infrared range The remaining chapters study specific modes of operation of solid state laser systems such as pulsed microchip lasers high power neodymium lasers ultrafast solid state lasers amplification of femtosecond pulses with optical parametric amplifiers and noise characteristics of solid state lasers Solid State Lasers and Applications covers the most important aspects of the field to provide current comprehensive coverage of solid state lasers

*Laser/Optoelektronik in der Technik / Laser/Optoelectronics in Engineering* W. Waidelich, 2012-12-06

**Nonlinear Optics and Solid-State Lasers** Jianquan Yao, Yuyue Wang, 2012-01-14 This book covers the complete spectrum of nonlinear optics and all solid state lasers The book integrates theory calculations and practical design technology experimental schemes and applications With the expansion and further development of Laser technology the wavelength spectrum of Lasers had to be enlarged even to be tunable which requires the use of nonlinear optical and Laser tunable technology It systematically summarizes and integrates the analysis of international achievements within the last 20 years in this field It will be helpful for university teachers graduate students as well as engineers

**Laser Beam Shaping Applications** Fred M. Dickey, Todd E. Lizotte, Scott C. Holswade, David L. Shealy, 2018-10-03 The practice of shaping the irradiance profile of laser beams goes back more than three decades and the applications of beam shaping are as diverse as they are numerous However until Dickey and Holswade's groundbreaking and highly popular Laser Beam Shaping Theory and Techniques was published there was no single detailed treatment available on the underlying theory and basic techniques of beam shaping Building on the foundations of this previous work these esteemed editors have teamed with recognized expert David L. Shealy to produce the first in depth account of beam shaping applications and design Laser Beam Shaping Applications details the important features of beam shaping and exposes the subtleties of the theory and techniques that are best demonstrated through proven applications In chapters contributed by prominent active leaders in their respective specialties the book discusses applications in lithography laser printing optical data storage stable isotope separation adaptive mirrors and spatially dispersive lasers The contributors share major insights knowledge and experience reveal the advantages of the technologies and include extensive

references to the literature The book concludes with a summary of beam shaping theory and techniques as well as the history of the field Providing practical expertise Laser Beam Shaping Applications is an extremely helpful guide to improving current laser processes optimizing application specific technologies and advancing future development in the field

**Advance Elements of Laser Circuits and Systems** Ofer Aluf, 2021-03-09 This book on Advance Elements of Laser circuits and systems Nonlinearity applications in engineering addresses two separate engineering and scientific areas and presents advanced analysis methods for Laser circuits and systems that cover a broad range of engineering and scientific applications The book analyzed Laser circuits and systems as linear and nonlinear dynamical systems and there limit cycles bifurcation and limit cycle stability by using nonlinear dynamic theory Further it discussed a broad range of bifurcations related to Laser systems and circuits starting from laser system differential equations and their bifurcations delay differential equations DDEs are a function of time delays delay dependent parameters followed by phase plane analysis limit cycles and their bifurcations chaos iterated maps period doubling It combines graphical information with analytical analysis to effectively study the local stability of Laser systems models involving delay dependent parameters Specifically the stability of a given steady state is determined by the graphs of some functions of which can be expressed explicitly The Laser circuits and systems are Laser diode circuits MRI system Laser diode circuitry Electron photon exchanges into VCSEL Ti Sapphire laser systems Ion channel and long wavelength lasers Solid state lasers Solid state laser controlled by semiconductor devices microchip solid state laser Q switched diode pumped solid state laser Nd YAG Mid Infrared and Q switched microchip lasers Gas laser systems copper vapor laser CVL circuitry Dual wavelength laser systems Dual wavelength operation of a Ti sapphire laser Diode pumped Q switched Nd YVO4 yellow laser Asymmetric dual quantum well lasers Tm3 doped silica fibre lasers Terahertz dual wavelength quantum cascade laser The Book address also the additional areas Laser X guiding system Plasma diagnostics Laser Beam shaping Jitter and crosstalk Plasma mirror systems and High power Laser Target diagnostic system optical elements The book is unique in its emphasis on practical and innovative engineering and scientific applications All conceptual Laser circuits are innovative and can be broadly implemented in many engineering applications The dynamics of Laser circuits and systems provides several ways to use them in a variety of applications covering wide areas This book is aimed at electrical and electronics engineers students and researchers in physics as well It is also aimed for research institutes in lasers and plasma physics and gives good comprehensive in laser and plasma systems In each chapter the concept is developed from basic assumptions up to the final engineering and scientific outcomes The scientific background is explained at basic and advance levels and closely integrated with mathematical theory Many examples are presented in this book and it is also ideal for intermediate level courses at graduate level studies It is also ideal for engineer who has not had formal instruction in nonlinear dynamics but who now desires to fill the gap between innovative Laser circuits systems and advance mathematical analysis methods

**Laser Spectroscopy** Wolfgang Demtröder, 2013-06-29 Laser Spectroscopy in

this second enlarged edition provides an introduction to modern techniques and instrumentation in laser spectroscopy The first part which discusses the basic concepts of absorption and emission of light the spectroscopic instrumentation for wavelength measurements and detection of light and the spectroscopic properties of lasers is a textbook for graduate students The second part gives a survey on different techniques of laser spectroscopy and their applications with ample references to the original literature This book helps close the gap between classical works on optics and spectroscopy and more specialized publications on modern research in this field It is addressed to graduate students in physics and chemistry as well as scientists just entering this field on research

*Laser Spectroscopy 1* Wolfgang Demtröder, 2014-05-07 Keeping abreast of the latest techniques and applications this new edition of the standard reference and graduate text on laser spectroscopy has been completely revised and expanded While the general concept is unchanged the new edition features a broad array of new material e g ultrafast lasers atto and femtosecond lasers and parametric oscillators coherent matter waves Doppler free Fourier spectroscopy with optical frequency combs interference spectroscopy quantum optics the interferometric detection of gravitational waves and still more applications in chemical analysis medical diagnostics and engineering

**Mid-Infrared Coherent Sources and Applications** Majid Ebrahim-Zadeh, Irina T. Sorokina, 2008-01-02 Covering fundamental principles and the state of the art this is a collection of reviews from experts in mid infrared mid IR coherent sources Among the sources covered are optical parametric oscillators difference frequency generators and the most recent broadband crystalline quantum cascade and fiber lasers The authors show how advances in mid IR science and technology make these sources indispensable for a variety of applications

*Proceedings of the Seventh International Symposium on Physics and Chemistry of Luminescent Materials* Charles W. Struck, Kailash C. Mishra, Baldassare Di Bartolo, 1999

*CLEO '96* Optical Society of America, 1996

**Laser Materials And Laser Spectroscopy: A Satellite Meeting Of Iqec '88** Zhijiang Wan, Zhiming Zhang, 1989-03-01 Contents Laser Site Spectroscopy of Transition Metal Ions in Glass Gan Fuxi Liu Huimin Pair Pumped Upconversion Solid State Lasers Stephen C Rand CW Upconversion Laser Action in Neodymium and Erbium Doped Solids R M Macfarlane et al A Critical Review of High Efficiency Crystals for Tunable Lasers J T Lin The Growth and Properties of BaTiO<sub>3</sub> Crystals Wu Xing et al Potassium Titanyl Phosphate KTP Properties and New Applications J D Bierlein Growth Spectroscopic Properties and Applications of Doped LiNbO<sub>3</sub> Crystals Liu Jiancheng Recent Advances in Photorefractive Nonlinear Optics Pochi Yeh Nonclassical Radiation From Single Atom Oscillators Herbert Walther Laser Spectroscopic Studies of Molecules in Highly Excited Vibrational State Tadao Shimizu et al Kinetic Processes in the Electron Beam Pumped KrF Laser H Takuma et al Sum Frequency Generation For Surface Vibrational Spectroscopy P Guyot Sionnest et al Optical Studies of Molecule Surface Interactions M M T Loy et al Femtosecond Photon Echoes C V Shank et al Laser Cooling and Trapping of Atoms Steven Chu et al Observation of the Motion of Slow Atoms in a Standing Wave Field Wang Yuzhu et al and others Readership Applied physicists

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