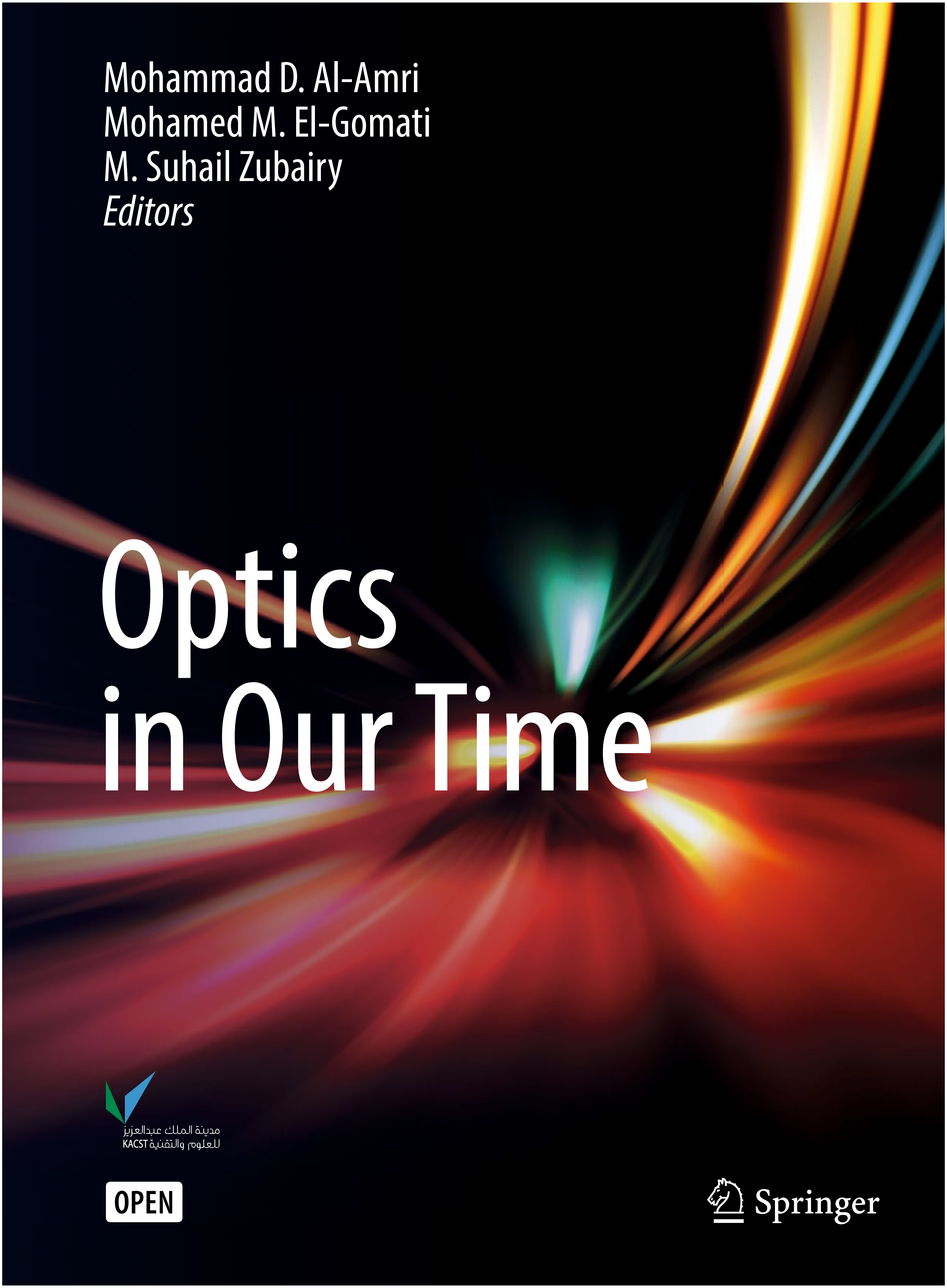

Mohammad D. Al-Amri
Mohamed M. El-Gomati
M. Suhail Zubairy
Editors

Optics in Our Time

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KACST للعلوم والتقنية

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Foreword

Light has occupied a position of importance in our attempt to understand the world around us. The earliest studies going back to the dawn of civilization related to our attempts to understand vision and the properties of optical materials. The modern era in optics is rooted in the great work of Ibn al-Haytham whose work on the nature of light and its applications had a long-lasting impact. In our generation, the discovery of laser has opened up not only new areas of research but also had great impact on a number of technologies. Lasers have revolutionized the fields of communication, medicine, and biotechnology. It has influenced the art, architecture, and printing. It is therefore befitting that United Nations has declared 2015 as the International Year of Light and Light-Based Technologies to celebrate these great achievements. Saudi Arabia is one of the sponsors of this initiative that has ignited a number of activities all around the world. This volume, which covers the history of light and its applications to many diverse branches of science, contains articles by some of the leading scientists who have played a key role in advancing the frontiers in our own times.

Turki S.M. Al-Saud
King Abdulaziz City for Science and Technology,
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Preface

Light and light-based technologies have played an important role in transforming our lives via scientific contributions spanned over thousands of years. In this book, we present a vast collection of articles on various aspects of light and its applications in the contemporary world at a popular or semi-popular level. These chapters are written by the world authorities in their respective fields. This is therefore a rare volume where the world experts have come together to present the developments in this most important field of science in an almost pedagogical manner.

This volume covers five aspects related to light. The first presents two articles, one on the history of the nature of light and the other on the scientific achievements of Ibn al-Haitham (Alhazen), who is broadly considered the father of modern optics. These are then followed by an article on ultrafast phenomena and the invisible world. The third part includes papers on specific sources of light, the discoveries of which have revolutionized optical technologies in our lifetime. They discuss the nature and the characteristics of lasers, solid-state lighting based on the light emitting diode (LED) technology, and finally modern electron optics and its relationship to the Muslim golden age in science. The book's fourth part discusses various applications of optics and light in today's world, including biophotonics, art, optical communication, nanotechnology, the eye as an optical instrument, remote sensing, and optics in medicine. In turn, the last part focuses on quantum optics, a modern field that grew out of the interaction of light and matter. Topics addressed include atom optics, slow, stored and stationary light, optical tests of the foundation of physics, quantum mechanical properties of light fields carrying orbital angular momentum, quantum communication, and wave-particle dualism in action.

We are grateful to many individuals and organizations whose contributions and cooperation were invaluable in compiling this book. First and foremost, we are grateful to all the authors who took their time in writing these articles for the general audience. We are very grateful to the leadership and the staff at *King Abdulaziz City for Science and Technology* (KACST) for their generous support in the completion of this project. Khalid Al Zahrani ought to be thanked with whom the idea of this book was triggered over a cup of tea.

We have however one deep regret: one of the authors, Nobel Laureate Ahmed Zewail, who enthusiastically supported this volume and contributed an important chapter passed away on August 2, 2016, before the publication of this book.

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York, UK

M. Suhail Zubairy
College Station, TX, USA

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About the Editors and Authors

Mohammad D. Al-Amri

received his MSc in physics with distinction from Sussex University, UK, in 2001. He went on and got his PhD from York University and was the recipient of the Stott Prize in Physics for the best PhD thesis in 2004. He then joined the National Center for Applied Physics (NCAP) at King Abdulaziz City for Science and Technology, where he has been working as a professor.

He was the recipient of the CO/ICTP Gallieno Denardo Award Winner (2013) and the senior membership of the Optical Society of America (2012). He has been working on different areas of research related to quantum optics and quantum informatics, where the focus is on quantum optical lithography and microscopy, weak measurement, and direct quantum communication. He has published around 55 journal papers, within about 35 published in the Journal of PRL and PRA, and has got 5 patents. Some of Dr. AlAmri's research work has been highlighted in semipopular press. He has given many lectures, seminars, and invited talks at universities and international conferences.

Mohamed M. El-Gomati

is professor of electronics at the University of York, UK. His research interests are in the fields of surface science and electron optics with particular emphasis on the development of novel instrumentation for nanostructure analysis. He is the author and co-author of more than 200 articles and patents in these fields. He is a fellow of the Institute of Physics (IoP) and the Royal Microscopical Society (RMS). His interests extend to history of physics with particular emphasis on history of optics within Muslim civilization. He is the chairman of the Foundation for Science, Technology and Civilisation (UK) and a trustee of the educational charity, Curriculum Enrichment for the Future, and is an advisor to a number of UK and overseas universities. He was awarded the UKESCA Award (1993), the Cosslett Award by the Microbeam Society of America (2008), the Fazlur Rahman Prize for Science and Engineering (2009), and the British Muslims Award for Science (2013). In 2012, Professor El-Gomati was awarded an OBE for his services to science.

M. Suhail Zubairy

is a university distinguished professor of physics and the holder of the Munnerlyn-Heep Chair in Quantum Optics at the Texas A&M University. He received his PhD from the University of Rochester in 1978. He served as professor of electronics and the founding chairman of the Department of Electronics at the Quaid-i-Azam University before joining Texas A&M University in 2000. Prof. Zubairy's research interests include quantum optics and laser physics. He has published over 300 research papers on topics such as precision microscopy and lithography, quantum computing, noise-free amplification, and atomic coherence effects. He is the co-author of two books, one on quantum optics and the other on quantum computing devices. He has received many honors including the Willis E. Lamb Award for Laser Science and Quantum Optics, Alexander von Humboldt Research Prize, the Outstanding Physicist Award from the Organization of Islamic Countries, the Abdus Salam Prize in Physics, the International Khwarizmi Award from the president of Iran, the Orders of Hilal-e-Imtiaz and Sitara-e-Imtiaz from the president of Pakistan, and the George H. W. Bush Award for Excellence in International Research. He is an elected member of the Pakistan Academy of Sciences and a fellow of the American Physical Society and the Optical Society of America.

Govind P. Agrawal

received the MS and PhD degrees from the Indian Institute of Technology, New Delhi, in 1971 and 1974, respectively. After holding positions at the Ecole Polytechnique, France, the City University of New York, and AT&T Bell Laboratories, Dr. Agrawal joined in 1989 the faculty of the Institute of Optics at University of Rochester, where he is currently James C. Wyant Professor of Optics. His research interests focus on optical communications, nonlinear photonics, and laser physics. He is an author or co-author of more than 400 research papers and eight books. His books on nonlinear fiber optics (Academic Press, 5th ed., 2013) and fiber-optic communication systems (Wiley, 4th ed., 2010) are used worldwide for research and teaching. Since 2014, he is serving as editor-in-chief of the journal *Advances in Optics and Photonics*.

Prof. Agrawal is a fellow of the IEEE and OSA (the Optical Society) and a life fellow of the Optical Society of India. In 2012, the IEEE Photonics Society honored him with its prestigious Quantum Electronics Award. He received in 2013 the Riker University Award for Excellence in Graduate Teaching. More recently, he was awarded the 2015 Esther Hoffman Beller Medal of the Optical Society.

Pablo Artal

is a full professor of optics at the University of Murcia, Spain. He spent several periods doing collaborative research in laboratories in Europe, Australia, and the USA. He is a fellow member of the OSA, ARVO, and EOS. He received the prestigious 2013 Edwin H. Land Medal Award, and he is the recipient of the exclusive "ERC advanced grant" in 2013. He received the "Rey Jaime I" Award for Applied Research in 2015. He has published more than 180 reviewed papers that received 7000 citations (h-index: 43) and presented more than 150 invited talks in international meetings and is also a co-inventor of 20 international patents. He has pioneered a number of highly innovative advances in the methods for studying the optics of the eye and has contributed substantially to our understanding of the factors that limit human visual resolution. Dr. Artal is the founder of Voptica SL, a spin-off company developing the concept he invented of adaptive optics vision analyzers. He has been the mentor of many graduate and postdoctoral students. His personal science blog is followed by readers, mostly graduate students and fellow researchers, from around the world. He has been editor of the *Journal of the Optical Society of America A* and the *Journal of Vision*.

Robert W. Boyd

was born in Buffalo, New York. He received the BS degree in physics from MIT and the PhD degree in physics from the University of California at Berkeley. His PhD thesis was supervised by Charles Townes and involves the use of nonlinear optical techniques in infrared detection for astronomy. Professor Boyd joined the faculty of the University of Rochester in 1977 and in 2001 became the M. Parker Givens Professor of Optics and Professor of Physics. In 2010, he became professor of physics and Canada Excellence Research Chair in Quantum Nonlinear Optics at the University of Ottawa. His research interests include studies of "slow" and "fast" light propagation, quantum imaging techniques, nonlinear optical interactions, studies of the nonlinear optical properties of materials, and the development of photonic devices including photonic biosensors. Professor Boyd has written two books, co-edited two anthologies, published over 400 research papers ($\approx$29,000 citations, Google h-index 71), and been awarded nine patents. He is the 2009 recipient of the Willis E. Lamb Award for Laser Science and Quantum Optics, the 2010 recipient of a Humboldt Research Prize, and the 2014 recipient of the Quantum Electronics Award of the IEEE Photonics Society.

Charles M. Falco

has joint appointments as professor of optical sciences and professor of physics at the University of Arizona where he holds the UA Chair of Condensed Matter Physics. He is a fellow of four professional societies (the American Physical Society, the Institute of Electrical and Electronics Engineers (IEEE), the Optical Society of America, and the Society of Photo-optical Instrumentation Engineers (SPIE)), has published more than 275 scientific manuscripts, co-edited two books, has seven US patents, and has given over 400 invited talks at conferences, research institutions, and cultural organizations in 33 countries. In addition to his scientific research, he was co-curator of the Solomon R. Guggenheim museum's "The Art of the Motorcycle" which, with over 2 million visitors in New York, Chicago, Bilbao, and the Guggenheim Las Vegas, was by far the most successful exhibition of industrial design ever assembled. More recently, he and the world-renowned artist David Hockney found artists of such repute as van Eyck, Bellini, and Caravaggio who used optical projections in creating portions of their work. Three international conferences have been organized around these discoveries, and recognition for them includes the 2008 Ziegfeld Lecture Award from the National Art Education Association.

Michael Fleischhauer

is professor of theoretical physics at the University of Kaiserslautern, Germany. He made his PhD in physics at the University of Friedrich-Schiller University Jena on the theory of nonclassical light and his Habilitation on Electromagnetically Induced Transparency (EIT) and its applications at the Ludwig Maximilian University (LMU) of Munich, both in Germany. His interests are in quantum optics and many-body physics of ultracold quantum gases. He is an expert in numerical methods for strongly interacting systems in low dimensions, and his research interests include topological systems. Among other things, he has developed the method of light storage using EIT, which is by now one of the main techniques for quantum memories for light and key for photon-based quantum networks. He served as department head of the selection committee of the Alexander von Humboldt Foundation and at the boards of several physics journals and is currently a member of the editorial board of *Physical Review Letters*. Michael Fleischhauer is member of the executive board of the German Physical Society where he has been the spokesperson of the division of quantum optics and photonics. He is a member of the senate of the German Research Foundation and has been elected to the Academy of Sciences and Literature in Mainz.

Edward S. Fry

distinguished professor and former head of the Department of Physics and Astronomy at Texas A&M University, holds the George P. Mitchell Chair in Experimental Physics and has been with Texas A&M since 1969. He is past chair of the Texas Section of the American Physical Society and is a fellow of both the American Physical Society and the Optical Society of America. He received the Association of Former Students Distinguished Faculty Teaching Award (1993), the Texas A&M Distinguished Scientist Award of Sigma Xi (2001), and the Association of Former Students Distinguished Faculty Achievement Award (2012).

Dr. Fry's research interests cover the gamut from basic research to applied research. Some notable achievements include (i) one of the first, and definitive, Bell inequality tests of the foundations of quantum mechanics, addressing questions first raised by Einstein; (ii) the first observations of lasing without (population) inversion (LWI); (iii) a new integrating cavity technique for the measurement of optical absorption in the presence of even severe scattering, leading to what are now widely considered the standard reference data for pure water absorption; and (iv) a new diffuse reflector whose reflectivity is so high that ring-down spectroscopy in an integrating cavity is now possible.

Colin J. Humphreys

is professor of materials science and director of research in the Department of Materials Science and Metallurgy, University of Cambridge, and a fellow of Selwyn College, Cambridge. He is a fellow of the Royal Society and a fellow of the Royal Academy of Engineering. He founded and directs the Cambridge Centre for Gallium Nitride (GaN). He founded two spin-off companies to exploit the research of his group on low-cost LEDs for home and office lighting. The companies were acquired in February 2012 by Plessey, which is now manufacturing LEDs based on this technology at their factory in Plymouth, UK. He also founded and directs the Cambridge/Rolls-Royce Centre for Advanced Materials for Aerospace.

Gediminas Juzeliūnas

is a director of the Institute of Theoretical Physics and Astronomy of Vilnius University, Lithuania. He is also a principal researcher (research professor) at the institute. Dr. Juzeliunas completed a PhD in 1986 in theoretical condensed matter physics at Vilnius University, studying optical properties of excitons in confined geometries. Subsequently he held a two-year postdoctoral appointment at the University of East Anglia, England, shifting his research area toward quantum optics. Dr. Juzeliunas was a Humboldt research fellow at the University of Ulm, Germany (1997–1998), and a Fulbright scholar at the University of Oregon in the USA (2000–2001). Dr. Juzeliunas received a National State Prize for Science of Lithuania in 2008, a Vilnius University Rector's Award in 2010, and a Jucys Prize for Theoretical Physics of the Lithuanian Academy of Science in 2013. His current research focuses on ultracold atomic gases, slow light, and metamaterials. In particular, this includes a pioneering theoretical work on light-induced gauge potential for ultracold atoms.

Olga Kocharovskaya

is the distinguished professor in the Department of Physics and Astronomy, Texas A&M University. She joined the Texas A&M faculty in 1998 after 12 years at the Institute of Applied Physics of the Russian Academy of Sciences. She made a number of contributions to laser science and quantum optics.

These include the predictions of the phenomena of electromagnetically induced transparency and lasing without inversion as well as suggestion and experimental realization of the various schemes for coherent control of gamma-ray nuclear transitions. A fellow of both the American Physical Society and Optical Society of America, she has earned the Willis E. Lamb Medal for Laser Physics and Quantum Electronics, the Sigma Xi Distinguished Scientist Award, the Texas A&M Association of Former Students Distinguished Achievement Award in Research, and the Texas A&M University Distinguished Professor Award.

Mario Krenn

is a PhD student since 2012 in the group of Anton Zeilinger at the University of Vienna and Institute for Quantum Optics and Quantum Information (IQOQI) of the Austrian Academy of Sciences. He is investigating quantum properties of spatial structures of photons and high-dimensional Hilbert spaces. This involves the certification and long-distance transmission of spatial mode entanglement. In connection with complex high-dimensional multipartite quantum states, he is interested in automated computer-designed quantum experiments. In his free time, he enjoys playing table soccer and fantasizing about artificial general intelligence.

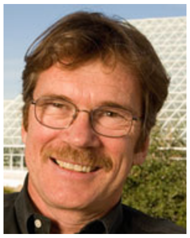
Mehul Malik

is a Marie Curie postdoctoral fellow in the group of Professor Anton Zeilinger at the Institute for Quantum Optics and Quantum Information in Vienna, Austria. Originally from New Delhi, India, Mehul received his PhD in optics in 2013 from the University of Rochester under the supervision of Professor Robert Boyd and a bachelor of arts in 2006 from Colgate University. He is currently working on creating the first multi-photon entangled states in high dimensions using the orbital angular momentum property of light. His broader research interests lie in the fields of fundamental quantum optics, quantum imaging, and quantum information. Mehul has published 19 papers in internationally recognized journals such as *Reviews of Modern Physics*, *Nature Communications*, and *Physical Review Letters*. He has delivered talks on his research in 11 different countries, including 5 invited talks at international conferences. Outside the laboratory, Mehul is an avid skier, loves to cook, and enjoys dancing salsa.

Alexis Méndez

received a PhD degree in electrical engineering from Brown University, USA, in 1992. He is president of MCH Engineering LLC—a consulting firm specializing in optical fiber sensing technology. Dr. Mendez was the former group leader of the Fiber Optic Sensors Lab within ABB Corporate Research (USA) where he led R&D activities for the development of fiber sensors for use in industrial plant, oil and gas, and high-voltage electric power applications. He has written 60 technical publications, taught several short courses on fiber sensors, holds 5 US patents, and is a recipient of an R&D100 award.

Dr. Mendez is a member of the OFS International Steering Committee, is a fellow of SPIE, and was past chairman of the 2006 International Optical Fiber Sensors Conference (OFS-18) and past technical chair of the 2nd Workshop on Specialty Optical Fibers and Their Applications (WSOF-2). He is also a member of the International Society for Health Monitoring of Intelligent Infrastructure (ISHMII) Committee. He is co-editor of the *Specialty Optical Fibers Handbook* and co-author of SPIE's *Fiber Optical Sensors Book: Fundamentals and Applications, 4th Ed.*



Pierre Meystre

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Munir H. Nayfeh

nanotechnology pioneer, Islamic Academy of Science fellow, and physics professor at the University of Illinois, received his BSc from the American University of Beirut and PhD from Stanford University in atomic laser spectroscopy. He was a researcher at Oak Ridge National Laboratory, lecturer at Yale University, and consultant at Argonne National Laboratory. He is chairman of the advisory board at center of excellence in nanotechnology (King Fahd University), ex-vice-chairman of the International Science Council at King Abdullah Institute for Nanotechnology, and advisor at the Nanotechnology Center at An-Najah University and Saigon Hi-Tech Park, Vietnam. He served on panels for King Abdullah University (KAUST) and

Royal Commission, Jubail. Nayfeh co-authored *Electricity and Magnetism* (translated into Farsi) and co-edited three laser books. He presents nanotechnology science fiction using the trademark "Dr. Nano." He holds the largest number of patents in nanosilicon worldwide (22 US-European, 18 issued) and is a founder of nanotechnology companies: NanoSi Advanced Technologies, Nano Silicon Solar, and Parasat-Nanosi (Kazakhstan). Professor Nayfeh developed a process for creating highly luminescent ultrasmall silicon nanoparticles with electronics, photonics, and biomedicine applications, a process for combining lasers with high electric fields of scanning electron microscopes to pin/write atoms on surfaces with atomic resolution, and a process using strong laser light to detect single atoms.

Roshdi Rashed
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Bahaa Saleh
has been dean of CREOL, the College of Optics and Photonics at the University of Central Florida, since 2009. He was born in Cairo, Egypt, and received the PhD degree from Johns Hopkins University in 1971. He held positions at the University of Santa Catarina in Brazil; Kuwait University; Max Planck Institute in Germany; University of California-Berkeley; European Molecular Biology Laboratory; Columbia University; University of Wisconsin-Madison, where he was chair of electrical and computer engineering (1990–1994); and Boston University, where he was chair of electrical and computer engineering (1994–2008). He has made significant contributions to coherence and statistical optics, nonlinear optics, quantum optics, and image science, and his publications include more than 600 journal and conference papers and 3 books: *Photoelectron Statistics* (Springer, 1978), *Fundamentals of Photonics* (Wiley, 2007, with M. C. Teich), and *Subsurface Imaging* (Cambridge, 2011). He served as editor-in-chief of the *Journal of the Optical Society of America A* (1991–1997) and founding editor of OSA's *Advances in Optics and Photonics* (2008–2013). He is a fellow of the IEEE, OSA, SPIE, APS, and Guggenheim Foundation and a recipient of the OSA Beller Award, OSA Meese Medal, OSA Distinguished Service Award, SPIE BACUS award, and Kuwait Prize.

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Wolfgang P. Schleich

is engaged in research on quantum optics ranging from the foundations of quantum physics via general relativity to number theory. He was educated at the Ludwig Maximilian University (LMU) of Munich and studied with Marlan O. Scully at the University of New Mexico, Albuquerque, and the Max Planck Institute for Quantum Optics, Garching. Moreover, he was also a postdoctoral fellow with John Archibald Wheeler at the University of Texas at Austin. Professor Schleich is a member of several national and international academies and has received numerous prizes and honors for his scientific work such as the Gottfried Wilhelm Leibniz Prize, the Max Planck Research Award, and the Willis E. Lamb Award for Laser Science and Quantum Optics. He is also a distinguished adjunct professor at the University of North Texas and a faculty fellow at Texas A&M University Institute for Advanced Study. His textbook, *Quantum Optics in Phase Space*, has been translated into Russian, and a Chinese edition was published in 2010.

Marlan O. Scully

(Baylor, Princeton, and Texas A&M) has worked on a variety of problems in laser physics and quantum optics including the first quantum theory of the laser with Lamb, the laser phase transition analogy and its applications to the Bose condensate, experimental demonstrations of lasing without inversion, and ultraslow light in hot gases via quantum coherence. His introduction of entanglement interferometry to quantum optics has shed light on the foundations of quantum mechanics, e.g., the quantum eraser. Recently, he and his colleagues have applied quantum coherence to remote sensing of anthrax and probing through turbid medium such as skin and plant tissue. Scully is currently a distinguished university professor at Texas A&M University and also holds positions at Princeton and Baylor Universities. He has been elected to the US National Academy of Sciences and the Max Planck Society. He has recently been awarded the OSA Frederic Ives Medal/Quinn Prize, the DPG/OSA Herbert Walther Award, and the Commemorative Silver Medal of the Senate of the Czech Republic (by K. Chapin).

Yanhua H. Shih

professor of physics at the University of Maryland, Baltimore Campus (UMBC), received his PhD in 1987 from the University of Maryland at College Park, USA. He started the Quantum Optics Laboratory at UMBC in the fall of 1989. His laboratory has been recognized as one of the leading groups in the field of quantum optics that attempts to probe the foundations of quantum theory. In the past 10 years, he published more than 100 papers in leading refereed journals and given more than 100 invited presentations in national and international professional conferences and workshops. His book *An Introduction to Quantum Optics: Photon and Biphoton Physics*, published in 2011, is a good summary of his theoretical and experimental research. Yanhua Shih is a winner of the 2002 Willis E. Lamb Medal for pioneering contributions to quantum electronics and especially the study of spatial coherence effects of multi-photon entangled states.

Alexei V. Sokolov

obtained a master's diploma from Moscow Institute of Physics and Technology (1994) and a physics PhD from Stanford University (2001). Currently at Texas A&M University, Sokolov holds a professor position in physics and astronomy and a Stephen Harris Professorship in Quantum Optics. His overall expertise is in the field of laser physics, nonlinear optics, ultrafast science, and spectroscopy. His research interests center around applications of molecular coherence to quantum optics, ultrafast laser science and technology including generation of sub-cycle optical pulses with prescribed temporal shapes, and studies of ultrafast atomic, molecular, and nuclear processes, as well as applications of quantum coherence in biological and defense-oriented areas. Sokolov is an OSA fellow; his awards include the Lomb Medal (OSA, 2003), the Hyer Award (TX section APS, 2007), and the Treat Award (Texas A&M Research Foundation, 2011).

Rupert Ursin
is a group leader and senior scientist at the IQOQI. His main field of research is to develop quantum communication and quantum information processing technologies, mainly for free-space but also for fiber-based systems. The scope of his work ranges from near-term engineering solutions for secure key sharing (quantum cryptography) to more speculative research (de-coherence of entangled states in gravitational fields). Experiments on quantum communication and teleportation using entangled photon pairs are also among his interests, with the long-term goal of a future global quantum network based on quantum repeaters. He has published more than 49 papers in peer-reviewed scientific journals such as *Science and Nature*. He has been experimentally active in numerous international collaborations in Germany, Italy, Spain, and the USA, as well as in Japan. To date, several of his publications were selected as yearly highlights by the British PhysicsWeb and others. In 2008, he received the Award for the Telecommunications Advancement Research Fellowship (National Institute of Information and Communications Technology (NICT), Tokyo, Japan) and in 2010, the Christian Doppler Prize. He has presented invited talks on original scientific results at more than 60 prestigious international conferences. He currently holds a guest professorship at the University of Science and Technology (USTC) in Shanghai, China.

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Thomas Walther
studied physics at the Ludwig Maximilian University (LMU) of Munich. After receiving his PhD from the University of Zürich in physical chemistry in 1994, he joined the Physics Department of Texas A&M University, College Station, TX, as a research assistant scientist, where he became an assistant professor in 1998. In 2002, he moved to the TU Darmstadt, Germany, as a full professor. His research interests include basic research in quantum optics as well as lasers and their applications.

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He has published some 600 articles and 14 books and is known for his effective public lectures and writings, not only on science but also in global affairs. For his leadership role in these world affairs, he received, among others, the "Top American Leaders Award" from *The Washington Post* and Harvard University. In 2009, President Barack Obama appointed him to the Council of Advisors on Science and Technology, and in the same year, he was named the first US Science Envoy to the Middle East. Subsequently, the Secretary General of the United Nations Ban Ki-moon invited Dr. Zewail to join the UN Scientific Advisory Board. In Egypt, he serves in the Council of Advisors to the President. Following the 2011 Egyptian revolution, the government established "Zewail City of Science and Technology" as the national project for scientific renaissance, and Dr. Zewail became its first chairman of the board of trustees.

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15

Slow, Stored and Stationary Light

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15.1 Introduction

Since the experiments of Michelson and Morely and their brilliant explanation by Albert Einstein more than 100 years ago which have laid the foundation for the theory of relativity, we know that light propagates in empty space with the largest possible velocity. This speed of about 300,000 km/s is so fast that we can have a phone conversation around the globe without noticing that an electromagnetic signal has to be transmitted for every bit of information. When we look through a window or a prism of quartz we see that light gets refracted. Refraction is due to the fact that light propagates in a transparent medium at a slightly lower speed than allowed by the universal traffic laws of nature. This speed, called phase velocity depends on the color of light and the variation of the phase velocity in media, is what causes the beauty of a rainbow or the bright fan of colors produced by a prism. Yet the change of the velocity of light in water, in glass or even in diamond is small, it is typically less than a factor of 2. But what if this factor is 10^7, a ten with 6 extra zeros, i.e. 10,000,000? Such light can truly be called ultra slow. As opposed to propagation faster than the vacuum speed of light, this is not forbidden by Einstein's theory of relativity, but for a long time did not seem feasible. It did so until the late 1980s and early 1990s, when Steve Harris from Stanford University pointed out that an effect he termed electromagnetically induced transparency (EIT) [1, 2] can lead to a massive reduction of the effective speed of pulsed light [3]. When we talk about 'slow' light we talk about the speed of *pulses* of light, called group velocity, which needs to be distinguished from the phase velocity mentioned above.

Although a number of experiments have seen evidence of velocity reduction in EIT media, it took until 1999 [4–6] that slow light received a great deal of attention. In 1998 the group of Lene Hau at the Rowland Institute for Science together with Steve Harris managed to decelerate the propagation of light in an atomic gas to 17 m/s, i.e. almost 20 million times slower than in vacuum. The cover page of the journal Nature (Fig. 15.1), where this experiment was

Fig. 15.1 *Slow light:* Cover page of the 18th February 1999 issue of the journal Nature illustrating an experiment on slow light by the group of Lene Hau at the Rowland Institute for Science. Using an ultracold gas of atoms the physicists managed to slow down a pulse of light to a velocity of 17 m/s (Reproduced with permission of the journal Nature)

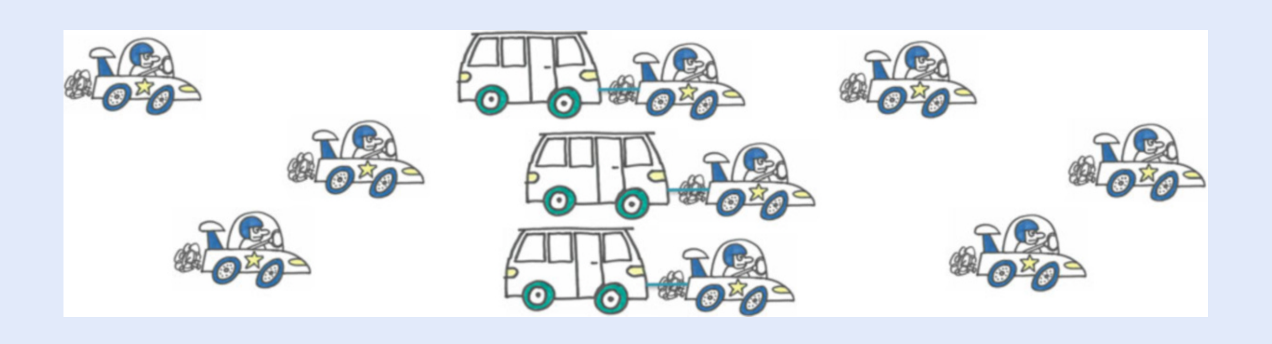
published in 1999, illustrates the achievement showing that a trained cyclist could even outrace such a light pulse. This is of course only a figurative way to demonstrate how slow the light was compared to the usual. Actually there was no cyclist involved in the experiment. The light was propagating in a tiny cloud of ultracold atoms contained in a vacuum chamber over a very small distance, as one can see by closer inspection of the figure. This spectacular result then triggered a rapidly growing activity in the field leading to many fascinating applications.

So, what is slow light and what is it good for? How can we understand the physics of it and how can we practically make light go so slow? These are the questions we want to answer in the following using simple pictures, on the one hand, and supplementing them with a little bit of details, on the other hand, for those who want to go slightly deeper. Yet we will avoid math as much as possible and refer those who seek more detailed information to the specialized literature [7–11].

15.2 Slow Light, Stopped Light and Stationary Light: A Simple Picture

How can one slow down light to such extremely low velocities? Imagine a fast racing car (▣ Fig. 15.2). If a heavy trailer is attached to the car, its engine has now also to pull the trailer. This slows down the car considerably. Something similar happens with light in a specially arranged atomic medium used in EIT experiments. Light is composed of photons—tiny particles which are very fast, so one can visualize them as fast racing cars. When entering the atomic medium, most of the photons are converted into a special kind of atomic excitations (which we here call spin excitations) which cannot move on their own, and thus behave like heavy trailers. The atomic excitations generated in this way are coupled to the small number of remaining photons which have to pull a vast number of immobile spin excitations while travelling in the medium. In this way, the propagation of the whole pulse of light is slowed down dramatically. The possibility to convert ‘fast cars’ into ‘immobile trailers’ is a small, but important difference to usual cars and trailers we encounter in real life. When the crawling light pulse reaches the end of the medium, the atomic excitations (trailers) are converted back to photons (fast cars), so the light exiting the medium becomes fast again.

Now imagine that the number of photons converted into atomic excitations (i.e. fast cars converted into trailers) can somehow be increased at will. This means there is an even lesser number of remaining cars to pull the whole bunch of trailers.



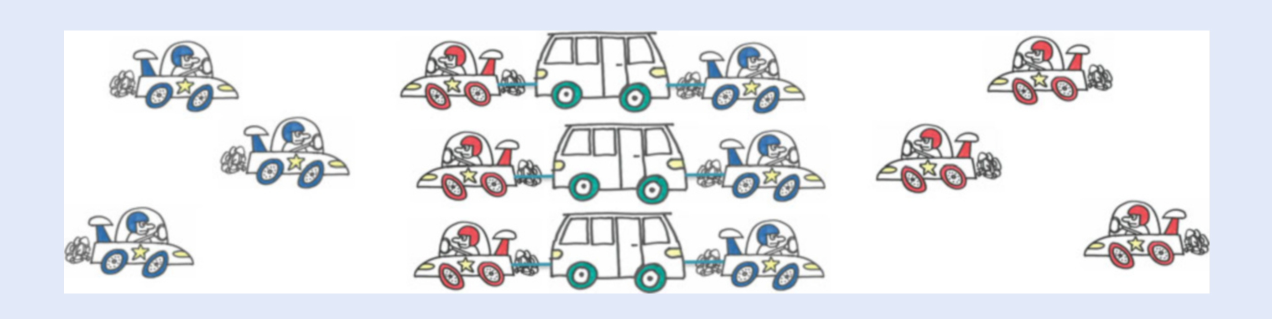
▣ **Fig. 15.2** *A simple picture of slow light:* Imagine a bunch of racing cars that enter a parking lot where heavy trailers get attached to them. Since the racing cars have to pull the trailers, they get slowed down considerably. When they reach the end of the parking lot, the trailers get detached, and the cars can move on with their full speed. Slow light is almost like this, except that cars get partially converted into trailers at the entrance to the parking lot and converted back at the end

And now imagine further that the conversion between cars and trailers can be changed while the fast cars are going through the trailer park. What if all of them are converted and no racing car is left to pull? The pulse would stop! This is the essence of stopped, or more precisely stored light, theoretically predicted in [12] and soon after experimentally verified in [13, 14]. The important difference of this kind of light storing and using a black piece of paper, which just absorbs the light, is that here the information carried by the photons is still present in the medium, in our analogy in the form of heavy trailers. Thus in principle all information about the original photons stored in the atomic excitations (trailers) can be converted back into photons (fast cars) either completely or in part. When the slow-light pulse reaches the end of the medium, the atomic excitations can no longer be dragged along and are fully converted back into light. In this way the stored light pulse can be fully retrieved.

Light storage is of particular interest in information technology especially in quantum information science. Light is an ideal carrier of information be it classical information which we use in every-day life or be it quantum information which may encounter at some day in a quantum network. Yet in the second case it is rather difficult to store information without loosing the quantum character, referred to as quantum coherence. Here light storage is an extremely useful method to build what is called a quantum memory for light. In fact first proof-of-principle demonstrations of quantum memories for photons based on light storage have already been made in a number of labs [15, 16].

It is noteworthy that by storing a light pulse all its photons (i.e. all the racing cars) are converted into immobile atomic excitations (trailers). Yet there is another way to make photons immobile where the photons are still present in the medium. This is called stationary light. It is formed when two counter-propagating pulses of light are driving the *same* spin excitations of a properly prepared atomic medium [17–21]. This corresponds to having two types of racing cars, one going from the left to the right, and another one from the right to the left. Both types of cars are trying to pull the same immobile trailers in opposite directions, as illustrated in ■ Fig. 15.3. The forces compensate, so the cars and the trailers remain at rest. More precisely stationary light behaves like massive quantum particles with zero average velocity. Note that in the quantum world physical quantities such as the particle velocity fluctuate and thus we need to talk about averages here.

One can also produce a situation where two counter-propagating pulses of light drive *different* spin excitations of the atomic medium. If the two types of spin excitations are coupled to each other in the right way, two-component slow light is formed which has a more complex structure resembling what is known in quantum physics as a particle with a spin degree of freedom [22–25]. This is like having two types of racing cars going in opposite directions, each pulling different types of



■ **Fig. 15.3** *The principle of stationary light:* Imagine racing cars entering a parking lot with heavy trailers from opposite sides. When attaching trailers to the cars they are pulled in opposite directions with equal forces and thus don't move at all. In this way the racing cars can be brought to halt even without converting them completely into trailers as is the case for light storage

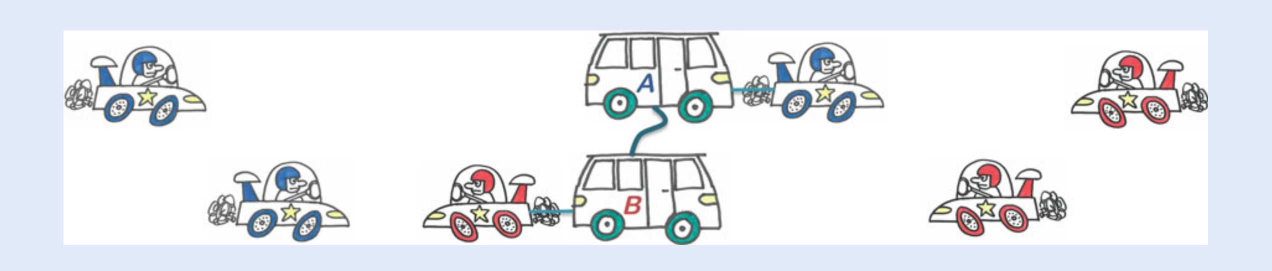


Fig. 15.4 *Multi-component slow light:* When racing cares moving in opposite directions pull different types of trailers, both types of cars would slow down independently of each other. However, when coupling the trailers together in a proper way a situation is created that corresponds in physics to quantum particles with an internal degree of freedom

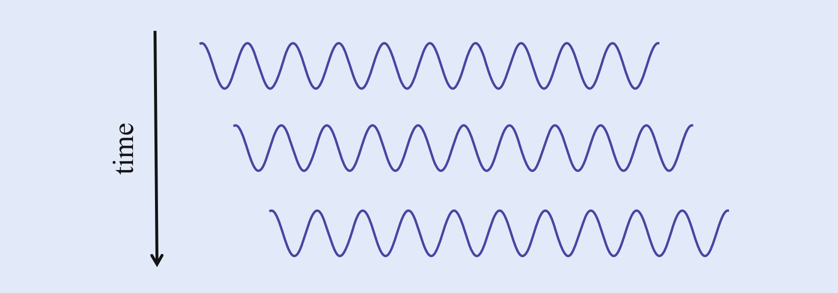


Fig. 15.5 *Light waves:* Light are waves of the electric field oscillating in space with a certain period, the wavelength λ. The 'hills' and 'valleys' of the wave, i.e. the points of maximum and minimum wave amplitude propagate in space with phase velocity *c*, such that at a fixed point in space the electric field oscillates in time with frequency $\omega = 2\pi c/\lambda$

trailers, as shown in Fig. 15.4. If the trailers were not coupled to each other, the two types of cars would slowly move in opposite directions pulling their respective trailers independently from each other. Yet if there is a coupling between the two sorts of trailers, the oppositely moving cars and trailers influence each other, making a more complex dynamics, resembling that of a relativistic quantum particle.

15.3 A Microscopic Picture of Light Propagation in a Medium

In order to understand the mechanism behind slow light we first have to talk about the microscopic physics of light propagation in a medium. In particular we will discuss what the physical origin of absorption and refraction is, two phenomena which we are familiar with in every-day life.

15.3.1 Absorption, Emission and Refraction

Light is nothing else than an electromagnetic wave build up from oscillating electric and magnetic fields. The color of light is determined by the oscillation frequency $\omega = 2\pi/T$, given by the inverse of the temporal period T of oscillations. The electric field of a plane wave propagating along say the x axis of some coordinate system has a sinusoidal form depicted in Fig. 15.5. It is characterized by the frequency ω, and a corresponding wavelength λ, which is the spatial period of the wave. This can be written in the following form:

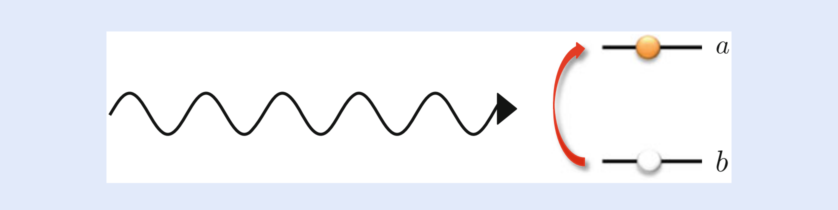


Fig. 15.6 *Absorption:* When an atom absorbs a photon it changes its quantum state from a low-energy state to a high-energy one

$$E = E_0 \sin(\omega t - 2\pi x/\lambda) = E_0 \sin(\phi), \tag{15.1}$$

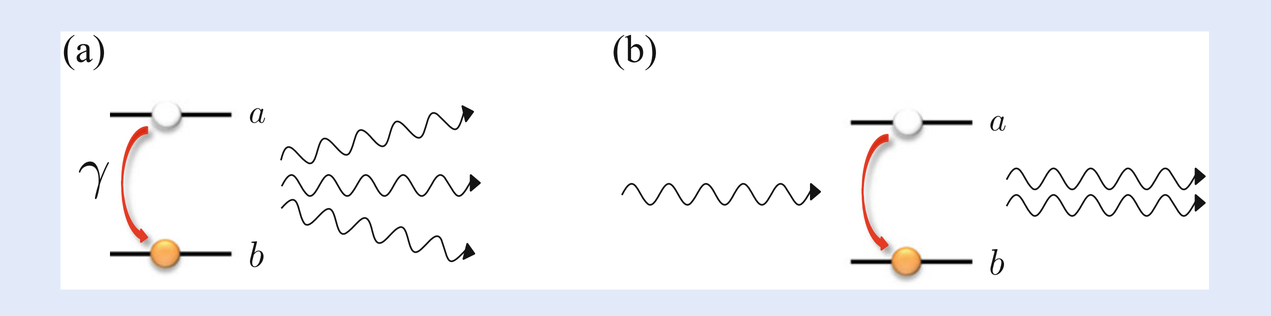
where we have introduced the phase ϕ. The propagation velocity of such a wave can be found by asking: What is the position change Δx in a time Δt for a fixed value of the phase ϕ? One finds: $c = \Delta x/\Delta t = \omega\lambda/2\pi$, which is called the phase velocity.

Light carries energy, which, as figured out first by Max Planck in 1900, comes in quantized units. So a beam of light is composed of particles called photons. The amount of energy E contained in each of these photons is proportional to the oscillation frequency ω, i.e. it depends on the color, $E = \hbar\omega$, where the constant $\hbar$ entering here is the famous Planck constant. High-frequency photons, such as those of ultra-violet light or even X-rays, are very energetic, while low-frequency photons such as infrared light or microwaves, which we cannot see with our eyes, do contain much less energy per photon.

Matter, on the other hand, consists of atoms, which according to the laws of quantum mechanics have a number of states characterized by discrete energies. Very often it is sufficient to consider only two or three most relevant states. Atoms are also small quantum oscillators which can 'vibrate' at different frequencies corresponding to the energy differences between quantum states $\omega_{ab} = (E_a - E_b)/\hbar$. Many (but not all) of these 'vibration' modes are associated with an oscillating electric dipole. In this way an atom can absorb or emit radiation just like an antenna of a mobile phone. As we shall see later on, photons play the role of the fast racing cars described in the introductory section, whereas properly prepared atoms absorbing the photons play the role of the heavy trailers. When an atom absorbs a photon it changes its quantum state from the low-energy state to the high-energy state (see Fig. 15.6) and vice versa if it emits a photon.

There are actually two types of emission of an excited atom. The most common is spontaneous emission, where a photon is emitted in a random direction leading to the loss of information on the state, the propagation direction and the polarization of the photon that excited the atom in the first place, see Fig. 15.7a. The other one is stimulated emission which takes place in the presence of other identical photons and is pointed into the direction determined by these photons, see Fig. 15.7b. In addition to spontaneous emission there are a number of other relaxation processes for excited states in atoms. As a consequence of these processes and due to spontaneous emission, excited atomic states decay with some rate γ. Thus when light shines on a cloud of atoms or atoms arranged in a crystal, it can be absorbed by exciting some of the atoms into high-energy states which subsequently decay. Clearly how much a medium absorbs depends on the density of atoms, which in a gas is much less than, e.g., in a solid.

Still, why is it that some solids like diamond are transparent to visible light and others like coal are pitch black? Both are just slightly different forms of carbon and their density does not differ significantly. The reason is simple: In order for a photon to be efficiently absorbed, its frequency has to be close to the frequency of the atomic oscillator, i.e. the frequency should correspond more or less to the



■ **Fig. 15.7** *Spontaneous and stimulated emission:* An excited atom can loose its excitation energy either by spontaneously emitting a photon in an arbitrary direction (**a**) or stimulated by an incoming photon (**b**) in which case the emitted photon has the same direction than the incident one. In both cases the atom changes its quantum state from the high-energy to the low-energy one

energy difference between some lower and higher state $\omega_{ab} = (E_a - E_b)/\hbar$. When this is the case, one talks about resonance. If the photon frequency is very different from any of the vibration frequencies of the atomic oscillator, i.e. if the light is off-resonant, not much can happen. It is like if you are trying to make a bridge vibrate by jumping up and down but are doing it at the wrong pace. Only a tiny bit of the photon energy is transferred to the atom, stored there for a very little moment and then is reemitted into the stream of photons. In this process the atom is actually not completely transferred from the lower-energy state to the higher-energy state, as in ■ Fig. 15.6, and the subsequent emission process is a bit different from the stimulated process shown in ■ Fig. 15.7b, but in essence it is like this. A word of caution is needed here: This picture of absorption is a bit of an oversimplification if applied to solids rather than to sparse atomic gases. The quantum states and energies in a solid are not the same than those of isolated atoms as they are affected by atom–atom interactions. Also even off-resonant transitions can eventually lead to sizable absorption if there are very many of them.

As we have mentioned before, waves are characterized by a wavelength λ, which gives the spatial period of a wave and is directly related to the frequency. In vacuum the relation between the two is $\lambda_0 = 2\pi c_0/\omega$. Here c_0 is the vacuum speed of light, i.e. the fastest velocity allowed by the laws of nature. In a medium this relation is changed, however. The short moment for which the photon is stored in the atom causes a delay. The effect of the very many, tiny delays at every atom in the medium makes light appear to propagate with a modified phase velocity

$$c(\omega) = c_0/n(\omega). \tag{15.2}$$

Here $n(\omega)$ is called the refractive index. In vacuum the refractive index is unity. The name 'refractive index' stems from the fact that it characterizes the refraction of light beams at an interface between say air and a piece of glass, as illustrated in ■ Fig. 15.8. Refraction comes about since along with the change of the phase velocity of a plane wave at frequency ω comes a change of the wavelength $\lambda = \lambda_0/n(\omega)$. This is because the frequency of the wave remains the same in the medium, giving $\omega = 2\pi c_0/\lambda_0 = 2\pi c/\lambda$.

The influence of a medium on the propagation of light is characterized by the susceptibility χ. In ■ Fig. 15.9 we have plotted both the absorption strength (red line) represented by the imaginary part of the susceptibility $Im[\chi] = \chi''(\omega)$ together with its real part $Re[\chi] = \chi'(\omega)$ (blue line) as function of the frequency in the vicinity of an atomic resonance frequency ω_{ab}. The latter χ' describes the deviation of the index of refraction from unity, $n = 1 + \chi'/2$. One recognizes that the absorption peaks on resonance and falls off quickly with increasing frequency mismatch $\Delta = \omega - \omega_{ab}$, called detuning. The refractive index has a bit more

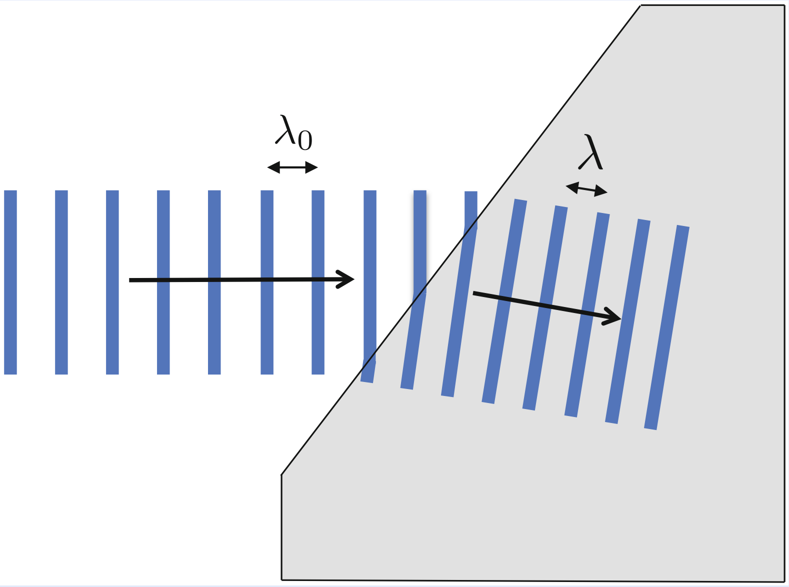


Fig. 15.8 *Refraction of a wave:* When a wave hits the surface of a medium with a different phase velocity, the wavelength has to change as the electric field oscillates in time always with the same frequency. This causes a change in the propagation direction of the wave

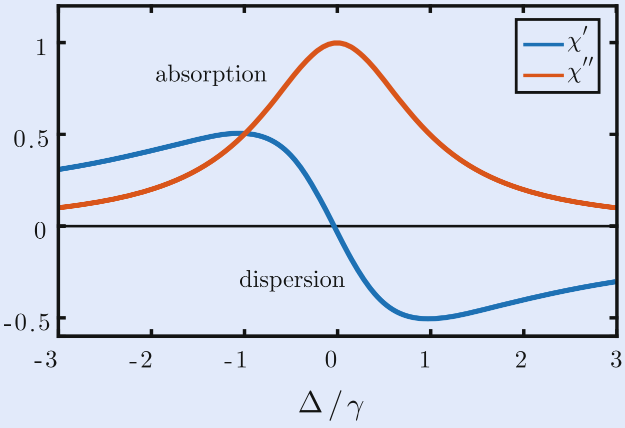


Fig. 15.9 *Absorption and dispersion of a two-level atom:* An atomic oscillator described by a two-level quantum systems leads to a strong absorption of light close to its resonance frequency. This is shown by the *red curve*, representing the imaginary part $\chi''(\omega)$ of the susceptibility as function of frequency ω. The refractive index $n(\omega) = 1 + \chi'(\omega)/2$, determined by the real part of the susceptibility $\chi'(\omega)$, is shown as the *blue curve*

complicated anti-symmetric shape. For frequencies above the resonance, $\omega > \omega_{ab}$, the medium leads to a reduction of the refractive index with respect to the background value, while below resonance, $\omega < \omega_{ab}$, the refractive index is enhanced. One notices the following from the figure: For large values of $|\Delta|$ the refractive index falls off much slower than the absorption, so for far off-resonant light only refractive effects of the medium matter. This is why even transparent media can still have a strong effect on the propagation of light. One of these effects

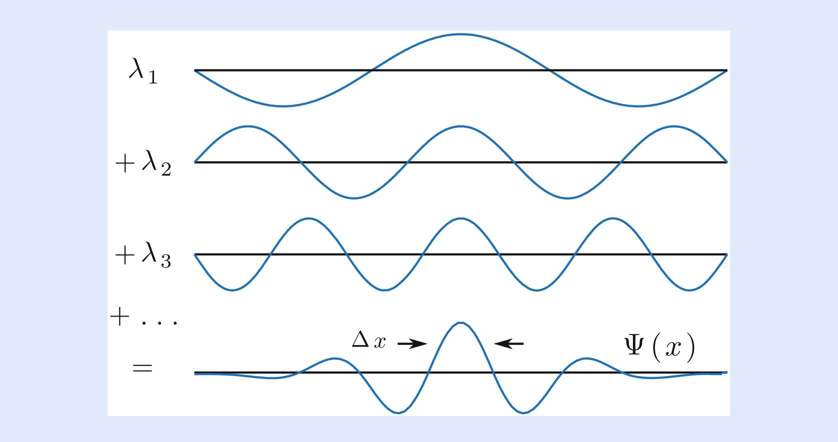


Fig. 15.10 *Wavepackets:* In order to create pulses of light with a finite spatial length, one needs to superimpose plane waves with slightly different wavelength in a proper way. In a medium the phase velocity of these components can differ. As a consequence the effective speed of the wavepacket is not given by the phase velocity but by the group velocity defined in Eq. (15.3)

is the refraction of a light beam at an interface between two media with different refractive indices. Another one is the modification of the propagation velocity of pulses, discussed in the following subsection.

15.3.2 Group Velocity

We have seen that the dependence of the refractive index on the frequency leads to different wavelength of light in a transparent medium as compared to free space. This dependence has another equally important effect, it determines the effective propagation speed of photon *wavepackets*. As illustrated in Fig. 15.10, one needs to superpose light waves with slightly different wavelength in order to create a wavepacket, i.e. a light pulse of finite length. In some sense we can envision photons as such wavepackets.

What is the propagation speed of such a wavepacket which consists of plane waves of different frequencies? In vacuum all frequency components propagate at the fundamental speed of light c_0, so wavepackets made of plane waves also propagate at this speed. But what about a medium, where each component has a different phase velocity $c(\omega) = c_0/n(\omega)$? It turns out that the slightly different phase velocities of each constituting plane wave cause the envelope of the pulse to move at the so-called group velocity v_{gr} which can be very different from the phase velocity $c = c_0/n(\omega)$. It is given by

$$v_{\mathrm{gr}} = \frac{c_0}{n(\omega_0) + \left(\frac{\Delta n}{\Delta\omega}\omega_0\right)} \qquad \textbf{(15.3)}$$

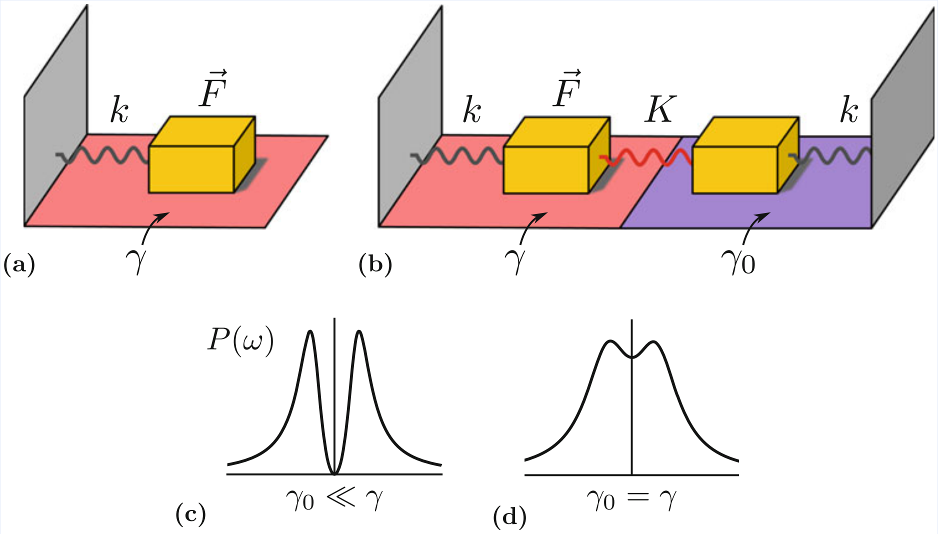
where ω_0 is the average frequency of the different components. The group velocity determines the effective speed of photons in a medium. When we talk about slow light, what we mean is light with a very small group velocity compared to c_0.

From Eq. (15.3) one recognizes that in addition to the refractive index itself, contained in the phase velocity $c = c_0/n(\omega)$, also the slope $\Delta n(\omega)/\Delta\omega$ enters at which the refractive index $n(\omega)$ changes by $\Delta n(\omega)$ when the frequency makes a small change $\Delta\omega$. As can be seen from Fig. 15.9 this slope is typically small far off resonance and the second term in the denominator of Eq. (15.3) is irrelevant. Thus in this frequency range the group velocity is essentially equal to the average phase velocity. One also recognizes that on either side of the resonance, provided one is sufficiently far away from the resonance point, the slope of $n(\omega)$ is positive, which is called 'normal' dispersion. Here the group velocity is slightly smaller than the phase velocity. In order to see a dramatic difference between group and phase velocity one has to go closer to resonance. We immediately notice the problem with that: Whenever we are closer to resonance, the absorption of the medium becomes large and light gets quickly absorbed. In the following section we will explain how one can overcome this problem in an elegant way making use of an effect called EIT.

But before we proceed with this let's make a little side remark here: One notices that the situation is completely different in a very narrow frequency range around resonance: Here $\Delta n(\omega)/\Delta\omega$ is negative and large and the group velocity can become larger than the phase velocity. In principle it can even become larger than the vacuum speed of light c_0! But don't worry, this does not violate Einstein's principle of relativity as proven already by Arnold Sommerfeld [26]. One notices, for example, that in the same spectral region there is large absorption. As a consequence no signal can actually propagate faster than c_0.

15.4 Electromagnetically Induced Transparency

How can we get around the problem that strong effects on the group velocity of light seem to be always associated with large losses? The answer came from an effect known as EIT [2, 27, 28]. To understand what EIT is all about let us start with an analogy from mechanics [29]: Consider a mass m which can slide on a surface and is attached to a wall with a spring, as shown in ◘ Fig. 15.11a. This system forms an oscillator with frequency $\omega_0 = \sqrt{k/m}$, where k is the spring constant. Now assume that there is some friction, e.g. due to a rough surface on which the mass slides. If the oscillator is excited by a periodic force with frequency



◘ **Fig. 15.11** *Coupled mechanical oscillators:* (**a**) A mechanical oscillator with resonance frequency $\omega_0 = \sqrt{k/m}$ driven by a periodic force **F** with frequency ω and subject to friction with energy loss rate γ generates a loss power spectrum similar to the absorption spectrum of a two-level system shown in Fig. 15.9. (**b**) If the mass is coupled to a second one with smaller friction (loss rate $\gamma_0 \ll \gamma$) a resonant periodic drive causes only the second mass to move and thus the power loss is dramatically reduced. (**c**) Loss power spectrum for $\gamma_0 \ll \gamma$. (**d**) If γ_0 equals γ, the total loss power spectrum is that of two independent absorption spectra slightly shifted in frequency (Adapted from [29])

ω close to the resonance frequency ω_0, energy is transferred to the oscillator and subsequently dissipated into heat due to the friction. The dissipated power $P(\omega)$ depends on the frequency mismatch between oscillator and drive frequency $\Delta = \omega - \omega_0$ and has a similar form as the absorption curve in ◘ Fig. 15.9.

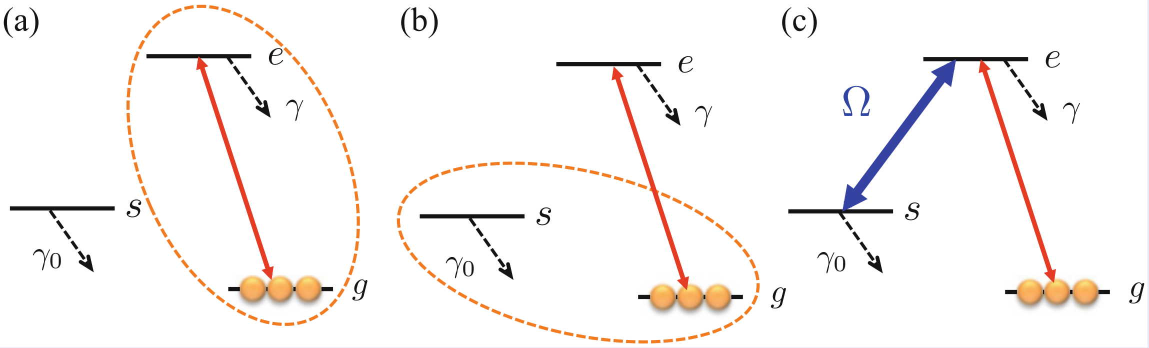
Now suppose we couple this oscillator to another mass oscillating with the same frequency ω_0 using an additional spring with spring constant K (◘ Fig. 15.11b). Let us assume next that the second oscillator has little or no friction. If we now drive the first mass with a periodic force something interesting happens: Looking at ◘ Fig. 15.11c, where we have plotted the dissipated power again as function of frequency, one notices that if the driving frequency ω matches exactly the oscillator resonance frequency ω_0 little or no energy gets dissipated!

The reason is that the first mass, i.e. the one with friction, does not move at all. Only the second mass, the one with little or no friction, oscillates. It does this in such a way that it produces a force on the first mass exactly opposite to the external force F. The two forces compensate each other, and so the first mass stands still. One can say that the system of oscillators is driven into a dark mode, i.e. a mode without dissipation in which the lossy oscillator is not excited. Consequently the effect of friction is reduced considerably and no or little energy is dissipated.

The situation changes if the second mass also experiences a substantial friction. In particular, if the loss rates of both oscillators are the same, i.e. $\gamma_0 = \gamma$, the loss power spectrum is just the addition of two simple loss curves slightly shifted in frequency relative to each other, as shown in ◘ Fig. 15.11d. As long as γ_0 is not too large, there are two maxima corresponding to the two eigenfrequencies of the coupled oscillators. The splitting increases with $\sqrt{K}$, i.e. with the strength of the coupling. Most importantly if γ_0 vanishes or is very small, one can make the coupling very weak and still the dissipation essentially disappears when driving the first mass. This creates a situation where one can be close to resonance while there is almost no loss.

This principle can be translated to atomic oscillators. What is needed are two oscillators, one of them almost lossless, another one lossy, and the two oscillators need to be coupled by a ‘spring’. This can be realized in a 3-level Λ-type system shown in ◘ Fig. 15.12. The atom-light coupling scheme is called Λ-type scheme because of the resemblance to the Greek letter Λ.

The first oscillator corresponds to the transition between the initially populated ground state g and the excited state e, as shown in ◘ Fig. 15.12a. This oscillator dissipates energy because of decay of the excited state e with rate γ, e.g. due to



◘ **Fig. 15.12** *Principle of electromagnetically induced transparency:* (**a**) A lossy atomic oscillator consisting of the initially populated ground state g and an excited atomic state e is driven by a probe field (*red arrow*). (**b**) In a three-level Λ-type system there exists a second atomic oscillator between states g and s, which can be lossless or have very small losses, e.g. if s is a low-energy state. (**c**) Coupling the two oscillators by a control laser with a strength characterized by the Rabi frequency Ω produces a situation similar to that shown in ◘ Fig. 15.11b. Consequently the medium becomes (almost) transparent to the probe field

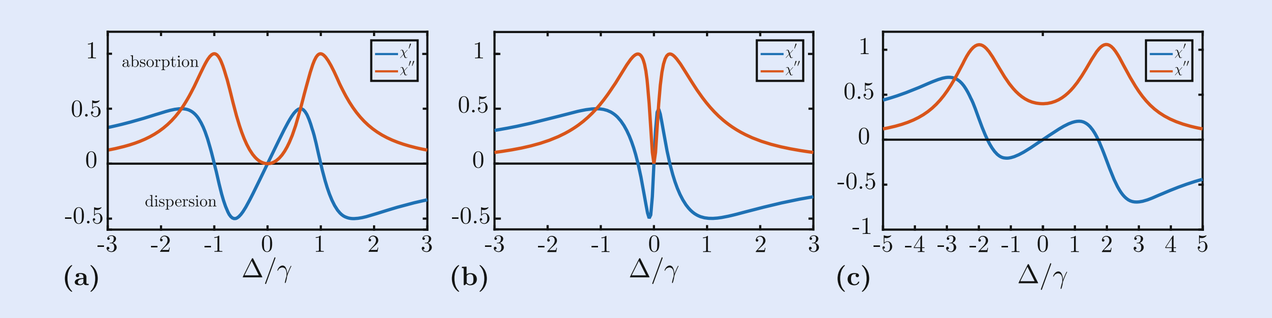


Fig. 15.13 *EIT versus two-level resonances:* (**a**) Real (χ') and imaginary (χ'') parts of the susceptibility of an EIT system characterizing the refraction and the absorption, respectively. Figure (**b**) shows the same with a smaller Rabi frequency of the drive field. For comparison we have shown in (**c**) the total susceptibility spectrum of two independent two-level systems with slightly shifted resonance frequencies. While χ', i.e. the index of refraction has a very similar shape in (**a**) and (**c**), there is an important difference in the absorption: In the EIT case it vanishes in between the two maxima, while for two two-level resonances it remains large

spontaneous emission. The oscillator is driven by the probe field (see Fig. 15.12a) corresponding to the external driving force in the mechanical picture from above. The ground state g together with another metastable ground state s forms the second oscillator (see Fig. 15.12b). The latter state s can be, e.g., a long-lived hyperfine spin state in the atomic ground state manifold, i.e. a low-energy state like g. Therefore the second oscillator is essentially lossless or has very small losses. Finally the role of the spring coupling the two oscillators is taken over by a coherent control laser field inducing transitions between the excited state e and state s (see Fig. 15.12c). The strength of this coupling is directly proportional to the amplitude of the electric field of the control laser, and the resulting splitting of the absorption peak (shown in Fig. 15.13) is denoted as Ω and is called Rabi frequency.

The absorption as a function of the probe field frequency ω relative to the resonance, expressed by the detuning $\Delta = \omega - \omega_0$ is shown in Fig. 15.13a, b as red lines. It consists of two absorption peaks like the spectrum of two coupled mechanical oscillators in Fig. 15.11c. Similar to the mechanical analog, the absorption shown in Fig. 15.13a, b vanishes exactly on resonance for $\gamma_0 = 0$, or is insignificant for small γ_0. This is quite remarkable since this means that despite the fact that one is very close to the resonance frequencies of the coupled system, the absorption is vanishingly small! Since a non-absorbing medium is transparent and since this effect is induced by the coupling of the two atomic oscillators by the drive laser, this phenomenon was called electromagnetically induced transparency or in short EIT.

The phenomenon of EIT has a widespread application in atomic and molecular physics and in optics. It can be used, for example, to make nonlinear optical processes much more efficient as it allows to operate close to atomic resonance without suffering from absorption. Some of the interesting applications will be discussed in detail in the following section.

15.5 Slow Light, Stored Light and Dark-State Polaritons

15.5.1 Slow Light

As we have discussed in Sect. 15.3 the absorption spectrum is associated with the imaginary part of the susceptibility. Figure 15.13a, b show the absorption spectrum of the atomic medium at an EIT resonance. The spectrum consists of two lines separated by an amount proportional to the strength of the driving field (Ω)

and in between these two peaks the absorption goes to zero. Also shown is the real part of the susceptibility as a function of frequency, which is called dispersion. In ◘ Fig. 15.13c we have plotted the absorption and dispersion spectra of two uncoupled oscillators with slightly different frequencies. We notice that the dispersion curves look qualitatively very similar in ◘ Fig. 15.13a, c. In particular the real part of the susceptibility, i.e. the refractive index, has a positive slope around $\Delta = 0$. In the case of two uncoupled two-level systems this just results from superposing the below-resonance tail corresponding to one oscillator with the above-resonance tail of the other. The most important difference between the case of two uncoupled resonances and EIT is that in the former case the absorption does not vanish in between the two resonances.

The dispersion curve has a remarkable feature right on resonance. It has a linear slope that can become very steep. In fact the closer the two absorption peaks are, the steeper is the dispersion curve. From Eq. (15.3) we notice that a steep slope of the index of refraction leads to a very large denominator in the expression for the group velocity. This means close to resonance the medium is, on the one hand, transparent due to EIT and at the same time the group velocity can be extremely small. This is the origin of ultra-slow light in EIT.

The value of the group velocity in an EIT medium is determined by the general equation (15.3) with the second term in the denominator being much larger than the first one, giving

$$v_{\text{gr}} \approx \frac{c_0}{\omega_0 \frac{\Delta n}{\Delta \omega}} \sim \frac{\Omega^2}{\rho}, \tag{15.4}$$

where Ω is the Rabi frequency of the drive laser, and ρ is the density of atoms. By turning down the intensity of the drive laser, i.e. by reducing Ω, or alternatively by increasing the atom density ρ, one can reach very small values of the group velocity. This can also be seen from ◘ Fig. 15.13a, b: Reducing Ω the separation between the absorption maxima decreases making the dispersion curve steeper in the center and hence the group velocity smaller.

The first experiments measuring the group velocity reduction in EIT where done by Harris et al. [3] in an atomic vapor cell reaching $v_{\text{gr}} = c_0/170$. The smallest group velocities achieved so far in experiments are obtained using very cold and dense clouds of atoms such as in a Bose Einstein Condensate and are on the order of 10 m/s, i.e. $v_{\text{gr}} = c_0/30{,}000{,}000$ [4].

When a light pulse enters a medium with a small group velocity it will be transmitted if its central frequency is close enough to the resonance and if its spectral width, i.e. the spread of frequencies associated with any pulse of finite duration, is much less than the distance between the two peaks in the absorption spectrum shown in ◘ Fig. 15.13. The very steep slope of the refractive index has also a profound effect on the spatial shape of the pulse, as illustrated in ◘ Fig. 15.14. When the pulse just enters the medium its front end will propagate with the group velocity v_{gr}, while its back end still propagates with the vacuum speed of light. As a consequence the pulse will be dramatically compressed in length inside the medium. The compression ratio is given by

$$l/l_0 = v_{\text{gr}}/c_0. \tag{15.5}$$

This resembles a situation where a number of vehicles moving fast on a highway suddenly approaches the beginning of an area with restricted speed. At this point the bunch of cars is compressed since when the first cars have already entered the area of restricted velocity, the ones at the back still drive at full speed. If the velocity of the vehicles is reduced by half, the distance between them becomes twice

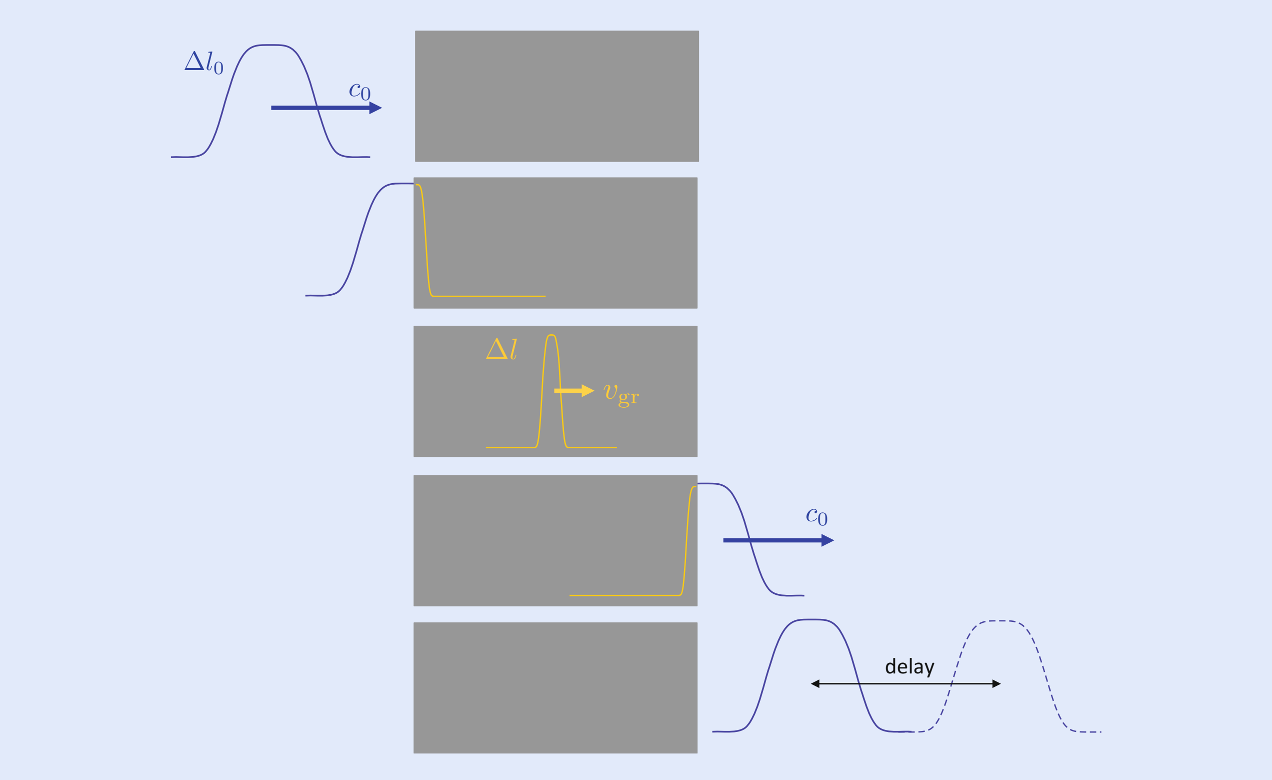


Fig. 15.14 *Pulse compression:* When a light pulse enters a medium with a reduced group velocity it becomes spatially compressed by the ratio v_{gr}/c_0. When the front end is already in the medium it propagates with v_{gr}, while the back end still moves with the much larger speed c_0. This causes the pulse to shrink in space. The opposite is happening when the pulse leaves the medium

smaller, so the compression factor is 1/2. Since in the atomic media the light can be slowed down to such extremely small velocities as $v_{gr} \approx c_0/30,000,000 = 10$ m/s, the incoming pulse of fast light with original length l_0 of about 1 km will be compressed to a pulse of length l of about 30 μm (!). In this way even very long pulses of light can be made to fit into a small-sized material, such as an elongated (cigar shape) Bose Einstein Condensate of sodium atoms used in the 1999 experiment by the group of Hau [4]. When the pulse leaves the medium the opposite effect happens. The leading edge travels fast since it is in free space and the back end lags behind as it is still inside the medium. At the end the outgoing pulse has the same length as the incoming one, at least under ideal conditions. This is again like the spatial decompression of a bunch of cars when leaving the area of restricted speed on the highway.

15.5.2 Stopped Light and Quantum Memories for Photons

As can be seen from Eq. (15.4) the group velocity of slow light can be controlled by the strength of the coupling laser or the density of the medium. So what would happen if we turn the coupling laser off while the probe pulse propagates inside the EIT medium? The medium becomes immediately opaque for the probe light and thus we expect no probe field to survive. This is indeed the case. So does this mean the probe pulse is lost? Surprisingly this does not happen!

At the entrance of the medium most of the incoming photons are transferred to atomic excitations during the slowing down. In this process the pulse is also substantially compressed in space, so that it fits inside the medium. The atomic

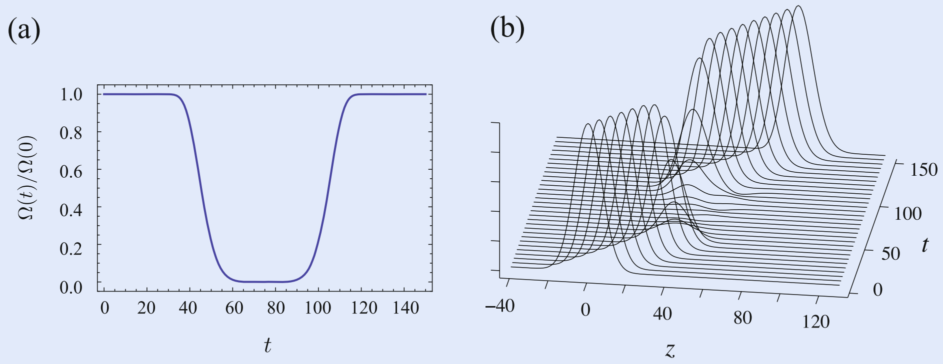


Fig. 15.15 *Light storage and retrieval:* When the strength of the control field is switched off smoothly while the slow-light pulse is in the medium (**a**) the pulse stops but also all photons disappear (**b**). If the control field is, however, switched on again at a later time, the pulse miraculously reappears and continues to propagate as a slow-light pulse in the medium

excitations, carrying information about the incoming pulse, travel together with the remaining photons. If the control field is switched off while the compressed pulse is still inside the medium the light disappears, i.e. no probe light survives. But if the control field is switched on again at a later instant of time, the pulse miraculously reappears! This is shown in the numerical simulation of Fig. 15.15. The right-hand side shows the propagation of the compressed light pulse inside the medium when the control laser is switched off and on again as illustrated on the left-hand side. So obviously we have somehow managed to stop (or more specifically to store) the light pulse for a while and sent it off its way a while later.

This remarkable phenomenon of light stopping (storing) was theoretically predicted in 2000 [12] and experimentally demonstrated in 2001 by two groups at Harvard University [13] and the Roland Institute of Science [14]. Figure 15.16 is a reproduction of the data obtained in one of these experiments from [14]. In these experiments a storage time of up to half a millisecond was reached. In 2009 the group of Immanuel Bloch at the Max Planck Institute for Quantum Optics in Garching, Germany in collaboration with colleagues from Israel has increased the storage time to 240 ms using ultracold atoms in a Mott insulating state in a three-dimensional optical lattice [30]. In the so-called Mott insulating phase atoms are particularly protected from perturbations such as collisions and diffusion, which leads to the prolonged storage duration. The current record for storage times is 1 min [31]. It has been obtained in doped glasses, where impurity atoms behave almost like free atoms in a vapor with the advantage that they do not move as in the Mott insulating state discussed above, and the atomic density is higher than in a gas.

15.5.3 Slow-Light Polaritons

We have seen in Sect. 15.3 that the microscopic picture of light propagation in a transparent medium is that each atomic oscillator absorbs a tiny little bit of an incoming photon, stores it for a short moment and releases it again with a small time delay as electromagnetic energy. The amount of the time delay is determined by the ratio of group velocity and vacuum speed of light. Furthermore the reduction in the group velocity also leads to a spatial compression of a photon pulse at the entrance to the atomic medium, as discussed in the previous subsection. If a light pulse is spatially compressed without increasing its amplitude, this

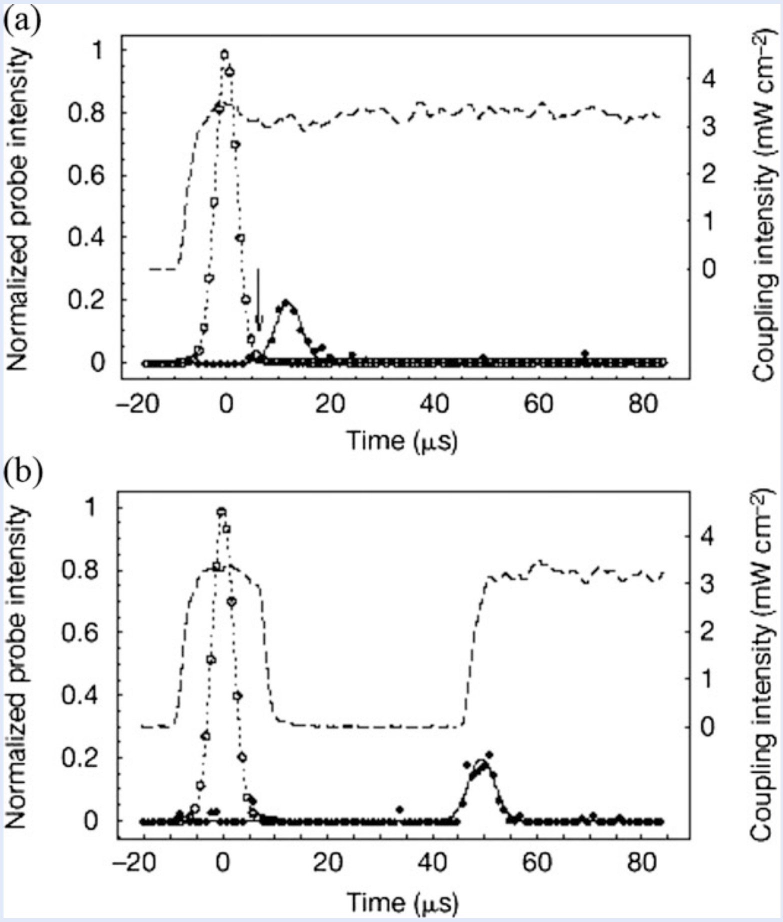
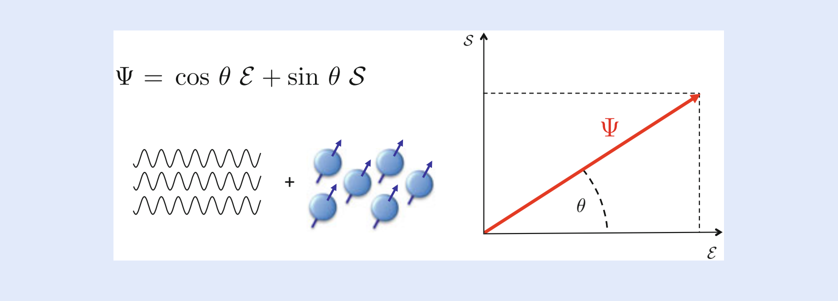


Fig. 15.16 *Light storage experiment:* Reproduction from one of the first experiments on light storage [14] (with permission of the journal Nature). Shown are the control field (*dashed*), the input probe pulse (*open circles and dotted line*) as well as the output probe pulse (*full circles and full line*). The *top curve* shows the pulse delay when the control field is on all the time, the *lower curve* shows the storage of the probe pulse when the control field is switched off and subsequently on again after some time

means that its content of photon energy decreases, i.e. the total number of photons contained in the pulse must be reduced according to the spatial compression. Where do these photons go if the medium is not absorbing? The answer is: They are temporarily stored in the form of atomic spin excitations.

In an usual transparent medium, such as glass, the ratio between the number of atomic excitations and photons is fixed and is very tiny. In an EIT medium this ratio can be large and it can be dynamically modified by tuning the strength of the control laser or by changing the atomic density. The best way to describe this is not to think in terms of photons and atoms separately but in terms of a combined quasiparticle, called polariton, containing a contribution due to both a photon and an atomic spin excitation, i.e. the excitation of the atom from the initially populated atomic ground states g to another ground state s [12, 32, 33]. The polariton picture has been introduced in [12] to describe storing and releasing of slow light following an earlier single-mode treatment [32] used to describe Raman adiabatic passage between the atomic ground states which did not include pulse propagation. We can visualize this polariton as a vector with two components, the



▣ **Fig. 15.17** *Slow-light polariton:* Slow and stored light can most easily be understood in terms of quasiparticles called dark-state polaritons introduced in [12]. They are a superposition of the electric field $\mathcal{E}$ of the probe pulse and an atomic spin excitation S, like a vector in a two-dimensional plane. The mixing angle θ depends on the strength of the control laser and the atom density and thus can be changed. The angle θ also determines the properties of the polaritons, such as their velocity, see Eq. (15.6)

electric field $\mathcal{E}$ and an atomic excitation S indicated in ▣ Fig. 15.17, where the mixing angle θ determines the ratio between the photonic and atomic components making up the polariton. Since the polariton is only partially a photon and only the photons move, the propagation speed is determined by the fraction of photons comprising the polariton:

$$v_{\mathrm{gr}}/c_0 = \cos^2\theta = \frac{\Omega^2}{\alpha\rho + \Omega^2}. \qquad \textbf{(15.6)}$$

The group velocity v_{gr} is evidently less than that of pure photons. (Here α is some constant, which is not relevant for the present discussion.) When the probe pulse is outside the medium, where $\rho = 0$, it can be interpreted as a polariton with $\cos^2\theta = 1$ representing a pure photon without any atomic component. When it enters the medium, e.g. the cloud of ultracold atoms in the BEC experiment of Hau et al. [4], the density ρ increases smoothly in space. As a consequence the polariton turns smoothly into a mixed atomic-photonic excitation, with a large atomic component.

Since Ω, determining the group velocity in Eq. (15.6), is a tunable parameter, the composition of the slow-light polariton can be modified further while the pulse is propagating inside the medium. In the case of slow light, $\cos^2\theta$ is much less than unity already when the probe pulse has just entered the medium and most of the excitations which were originally photons propagate as an atomic excitation. By further reducing the strength of the control laser Ω from the initial value where $\cos^2\theta$ is finite (yet much smaller than unity) all the way to zero, the slow-light polariton looses its photon component altogether and reduces to a pure atomic excitation which does not move any more. By switching on the control laser again at a later time, $\cos^2\theta$ becomes finite again (yet much smaller than unity). The slow-light pulse resumes its motion inside the medium until reaching the end of the atomic cloud where it finally converts completely into a fast, purely photonic pulse. This explains the reappearance of the light pulse, when the control field is turned back on again. As shown in ▣ Fig. 15.18, illustrating the stopping and reacceleration of a slow-light pulse while inside the medium, the light storage and retrieval sequence becomes very clear in terms of the polariton picture. The polariton is there all the time. It only changes its character, first from fast light to slow light, and then to a frozen atomic spin excitation and finally back to a slow polariton and eventually to fast light again.

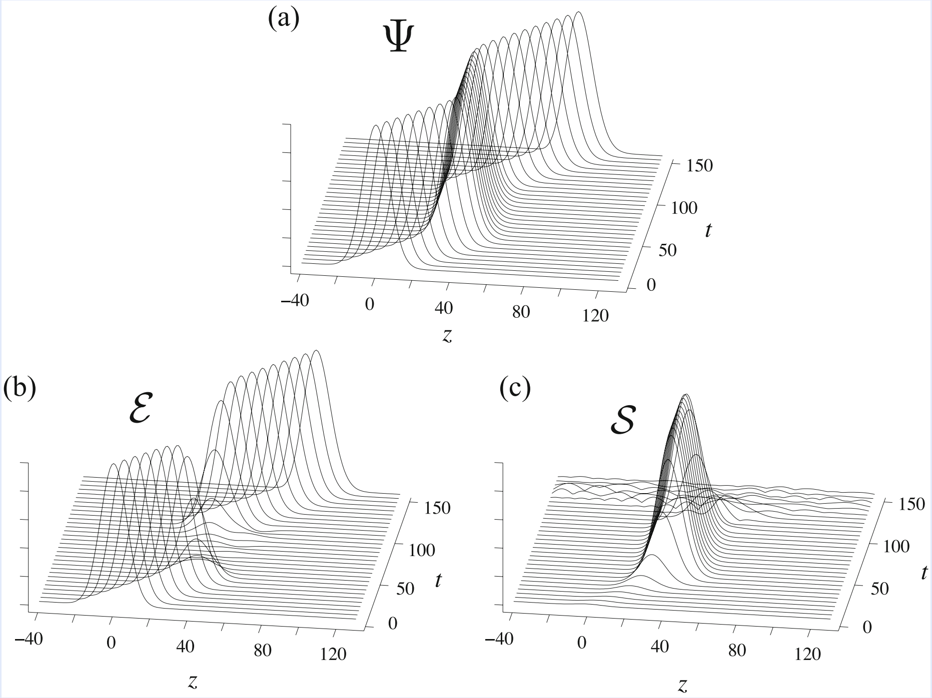


Fig. 15.18 *Polariton picture of light storage:* Light storage and retrieval, as shown in Fig. 15.15. This time also the propagation of the polariton (**a**) and the spin excitation (**c**) are shown. One recognizes that light storage is nothing else than a smooth conversion of the slow-light polariton from a polariton containing an electric-field component into a pure atomic excitation and back

15.6 Stationary Light

We have seen in the last section that a light pulse can be brought to a complete stop without loosing the information it contains by storing it in an atomic excitation. When the light pulse is at a halt, no photon is left in the medium anymore, so the polariton becomes entirely an atomic excitation. In the example of cars and trailers this corresponds to the case when all cars are converted into trailers. Thus there is no car left to pull and everything comes to a stop. There is, however, a way to keep the cars from driving without converting all of them to trailers. If two cars driving in opposite directions pull the same trailer, their forces can compensate and neither of the two can move forward. This is exactly what is happening in a situation called *stationary light*, which we will explain in the following.

A very interesting aspect of stationary light is that it mimics the behaviour of a massive quantum particle described by the Schrödinger equation for the amplitude of the stationary light polariton Ψ_{ss}:

$$i\hbar \frac{d}{dt} \Psi_{ss} = -\frac{\hbar^2}{2m^*} \frac{d^2}{dx^2} \Psi_{ss}. \tag{15.7}$$

Unlike photons in free space, which always propagate at the speed of light c, massive particles can stand still, or more precisely, as we are talking about quantum particles, can have a zero average velocity. Importantly the effective mass m^* of the stationary light polaritons is not a fixed quantity such as the mass of an electron or a proton, but is a tunable parameter. It can be changed by the strength of the control laser fields. This property makes stationary light an

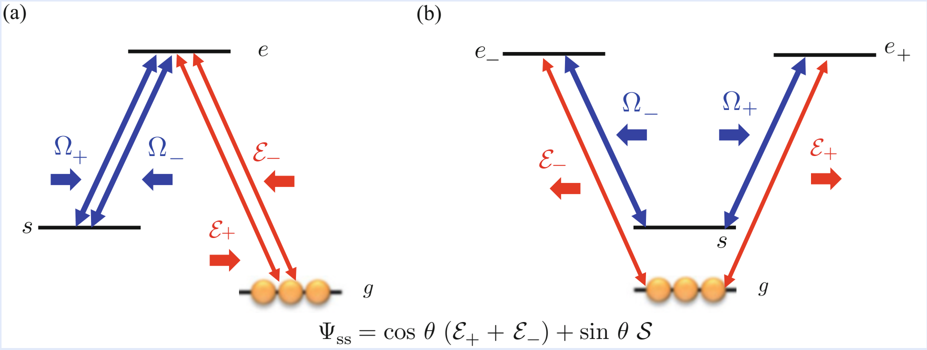


Fig. 15.19 *Stationary light:* If two counter-propagating drive fields of equal strength couple a Λ system of atomic levels (**a**), two counter-propagating probe field components of equal strength are formed. These fields interfere with each other and form a stationary-wave pattern. The same happens if the two drive fields have orthogonal polarizations and couple to two different transitions in a four-level (double Λ) scheme (**b**). In this case two counter-propagating probe fields are generated which also have orthogonal polarizations, but which nevertheless form a stationary-wave pattern. In these ways an excitation wavepacket is created which does not move and has still a non-vanishing electric-field component

interesting model system for analyzing fundamental properties of massive quantum particles.

What is the physics behind stationary light? Suppose there are two (rather than one) control laser beams of equal strength $\Omega_+ = \Omega_- = \Omega$ and two (rather than one) probe fields $\mathcal{E}_\pm$ inducing transitions in a three-level Λ-system or a four-level system, as shown in Fig. 15.19.

The four-level system can be viewed as two Λ sub-systems, one for fields propagating in the forward direction (+), and another sub-system for the fields propagating in the backward direction (−). Since the two control fields have the same amplitude, so do the probe fields. In each of these Lambda systems the respective pairs of control and probe fields induce a transition from the ground atomic state g to the metastable state s (see Fig. 15.19). In such a situation the two counter-propagating probe beams drive the same atomic transition $g \longrightarrow s$. Since the amplitudes of both probe fields are the same, each photon propagating forward has its counterpart, a photon propagating backward, and a stationary pattern of light is formed, frozen in the medium. This is as if two racing cars driving in opposite directions try to pull the same trailer but are not able to move it since their forces compensate (see Fig. 15.3).

For stationary light it is important that the counter-propagating probe fields are coupled to each other by the atomic medium. To see this let us draw an analogy with the string of a guitar: When a guitar player pulls the string at some place, *two* waves of equal frequency are created which propagate along the string in opposite directions. If two wavepackets of equal strength and opposite propagation directions are superimposed, a standing wave forms, but only for the short period of time for which they overlap. The two wavepackets would continue to propagate each in its own direction. Soon they would not overlap anymore and would be two spatially separated wavepackets. To prevent this another element is needed: At the points where the string is fixed to the body of the guitar, the wavepackets get reflected and the effect of this is a true standing wave that does not smear out. In a similar manner, one could produce a standing wave of light by confining the radiation in a resonator between parallel mirrors, so that the forward propagating light is permanently reflected to the backward propagating direction and vice versa. This principle is used, e.g., in a laser allowing the light to pass many times the lasing medium.

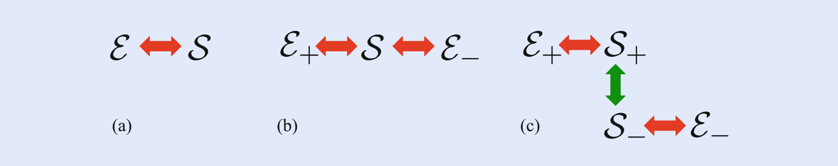
Stationary light also involves a permanent reflection of one component into the other but with no mirrors, and one can think of a kind of a mirrorless resonator. So what takes over the role of the fixing points of the guitar string or the mirrors reflecting the light? In fact we have here a whole periodic sequence of 'fixing' points, which causes reflection. In the case of a simple Λ-scheme, shown in ◘ Fig. 15.19a, the control lasers form a stationary *intensity* pattern that oscillates in space. Thus there is a periodic grating where the total control field intensity vanishes, which also means that in a periodic spatial pattern there are points without EIT for the probe light. This periodic array acts in a similar way as an absorption grating and reflects the forward and backward propagating components of the probe field. In the case of the four-level scheme, shown in ◘ Fig. 15.19b, the situation is somewhat different. Here the two control fields are not only propagating in opposite directions, but they also have opposite circular polarizations. Now, superimposing two light waves of equal intensity and with opposite circular polarization results in constant total field intensity with a linear polarization. Yet, since the two control beams propagate opposite to each other, the linear polarization rotates in space, forming a polarization grating. This polarization grating has the same effect as the intensity grating in the case of the simple Λ-scheme, it reflects forward- and backward propagating components into each other making the light stationary.

Stationary light has been first observed in 2003 by the group of Mikhail Lukin at Harvard University [17] using a Λ-type atom-light coupling which involves pairs of counter-propagating control (probe) beams with the same frequency, shown in ◘ Fig. 15.19a. One difficulty of these experiments is to make the 'non-moving light' visible. A trick used here is that the stationary light tends to excite also further off-resonant transitions to other excited states with a small probability. These excitations are then visible due to the spontaneous emission from these states.

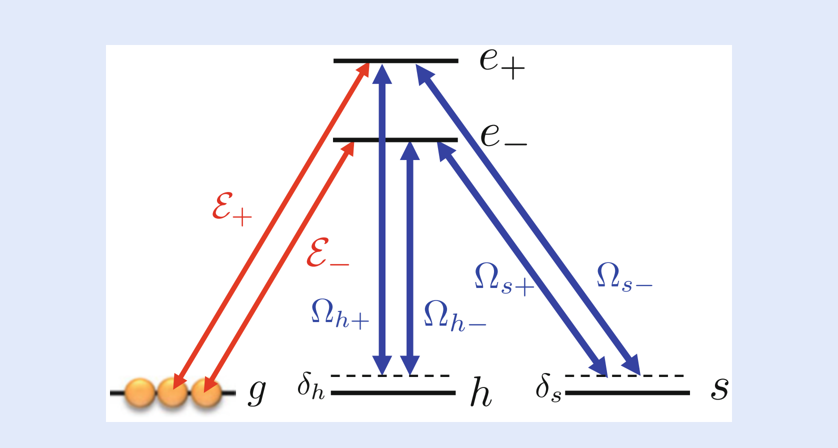
Another form of stationary light, called bichromatic stationary light was observed in 2009 by the group of Ite Yu at the National Tsing Hua University in Taiwan [20] using a double Λ coupling scheme, as shown in ◘ Fig. 15.19b. Here the frequency (or color) of the two control fields and, respectively, the two probe fields were different, thus the name 'bichromatic'. Stationary light pulses maximize the interaction time and thus can provide a considerable interaction efficiency even at a single-photon level. Interaction of two stationary light pulses through the medium was experimentally demonstrated by the same group 3 years later [21].

15.7 Multi-Component Slow Light

We have seen that slow light can be turned into something that behaves like a massive quantum particle. It is known from quantum physics that certain particles can show up in different forms, i.e. they can have different internal states. Electrons, for example, possess two different spin states, spin-up and spin-down states. In a bit oversimplified picture the spin of a particle can be viewed as a tiny gyroscope resulting from rotation of the particle around its center. Such a rotation is often accompanied with a magnetic dipole, so an electron represents a little magnet pointing up or down depending on the spin state relative to the chosen axis. More exotic particles can have not only spin but also other internal degrees of freedom, such as isospin, colour or flavour. So an interesting question is: Can we give slow light internal properties such that it mimics massive quantum particles with, e.g., spin? The answer is yes, and this makes slow light an even more interesting object for quantum physicists. We note that in quantum mechanics the spin of, e.g., an electron is a relativistic effect, so slow light with spin can be used to investigate relativistic quantum physics.



▣ **Fig. 15.20** *Slow (a), stationary (b) and two-component (c) slow light:* In (**a**) a single probe field $\mathcal{E}$ is coupled to a single atomic coherence S. The radiation has to push the atomic coherence forwards and thus the light slows down. In (**b**) two counter-propagating probe beams $\mathcal{E}_\pm$ drive the same atomic coherence characterized by the amplitude S. One probe field pushes the atomic coherence forwards and the other backwards. The velocities of the probe photons compensate leading to stationary light. In (**c**) two counter-propagating probe beams $\mathcal{E}_\pm$ drive two different atomic coherences characterized by the amplitudes S_+ and S_-. If there is a coupling between these coherences indicated by the *green double arrow*, two-component stationary light is formed



▣ **Fig. 15.21** *Two-component slow light:* Atom-light coupling scheme of the double-tripod type for implementation of two-component stationary light adapted from [24]. The scheme involves three atomic ground states g, s and h coupled to two excited states $e_\pm$ by six fields: a pair of counter-propagating probe beams $\mathcal{E}_\pm$, as well as two pairs of counter-propagating control beams $\Omega_{s\pm}$ and $\Omega_{h\pm}$

Slow light as introduced in ▣ Sect. 15.5 and the stationary light discussed in ▣ Sect. 15.6 both involve only one spin component associated with a transition from the initially populated ground state g to one other ground state s, and described by the amplitude S, as illustrated in ▣ Fig. 15.20a, b. This represents a single normal mode of oscillations of the coupled atom-light system (a single polariton) even though there are two counter-propagating probe fields, as in the case of the stationary light depicted in ▣ Fig. 15.20b.

In order for stationary light to have two components, the counter-propagating probe fields $\mathcal{E}_\pm$ (together with a number of control beams) should drive *two different* spin coherences described by two amplitudes $S_\pm$. This is illustrated in ▣ Fig. 15.20c. Two-component stationary light can be implemented using a tripod [23] or a double-tripod [24] atom-light coupling scheme, the latter shown in ▣ Fig. 15.21. Here one has two pairs of counter-propagating control fields with Rabi frequencies $\Omega_{s\pm}$ and $\Omega_{h\pm}$ inducing the atomic transitions $s \to e_\pm$ and $h \to e_\pm$, respectively. Compared to the double Λ scheme used for stationary light (▣ Fig. 15.19b) now there is an extra pair of counter-propagating control laser beams $\Omega_{h\pm}$, as well as an extra atomic ground state h. This leads to EIT for a pair of counter-propagating probe fields $\mathcal{E}_\pm$ inducing transitions (together with the control fields) from the initially populated ground state g to two superpositions of the initially unpopulated atomic ground states s and h. Consequently the fields $\mathcal{E}_+$ and $\mathcal{E}_-$ drive different spin coherences characterized by the amplitudes S_+ and S_-.

If S_+ and S_- were not coupled to each other, the two probe beams would propagate in opposite directions slowly and independently from each other. The coupling emerges though a two-photon detuning $\delta = \delta_s = -\delta_h$ shown in ▪ Fig. 15.21. The corresponding two types of polaritons behave like particles with positive and negative effective masses, i.e. like electrons and positrons representing particles and antiparticles in the relativistic Dirac theory. Thus the two-component (spinor) slow-light polaritons Ψ obey an effective one-dimensional Dirac equation

$$i\hbar\frac{\partial}{\partial t}\Psi = \left(i\hbar v_{\rm gr}\sigma_z\frac{\partial}{\partial z} + m^* c^{*2}\sigma_y\right)\Psi, \qquad \Psi = \begin{pmatrix}\Psi_1\\ \Psi_2\end{pmatrix}, \tag{15.8}$$

where σ_z and σ_y are the 2×2 Pauli matrices. For zero two-photon detuning δ, the two polaritons propagate in opposite directions with an effective speed $c^* = v_{\rm gr}$ given by the slow-light group velocity. A non-vanishing two-photon detuning introduces a coupling between the counter-propagating polaritons, providing a particle–antiparticle type dispersion with a variable mass $m^* = \hbar\delta/v_{\rm gr}^2$ [24]. An important feature of spinor slow light is that the relevant scales of velocity, energy and length, where relativistic effects start to matter, are very different from the values for say electrons. The effective 'vacuum speed of light' $c^* = v_{\rm gr}$ can now be a few meters per second instead of 300,000 km/s. The relativistic rest energy $m^* c^{*2} = \hbar\delta$ can be many orders of magnitude smaller than that for an electron, making it possible to observe particle–antiparticle pair generation processes in a conventional laser lab. Finally the relativistic length scale, called Compton length $\lambda_C^* = \hbar/m^* c^*$, is now large enough to be resolved in laboratory experiments as opposed to the value of 10^{-12} m for an electron. The possibility of a locally adjustable mass allows furthermore to observe a number of other interesting phenomena. For instance, if the mass m^* of the Dirac particle suddenly changes at a certain point in space from the value $+\,|m|$ to $-\,|m|$, a localized, topological mid-gap (zero-energy) state is created. If m^* is a randomly varying function of space with a vanishing mean-value, there exist mid-gap states with unusual correlations [23, 34, 35].

Two-component slow light has been recently implemented in an experiment [25] using the double-tripod coupling scheme, like the one shown in ▪ Fig. 15.21 but with co-propagating rather than counter-propagating control and probe laser fields. Oscillations due to an effective interaction between the two components of the probe field have been observed revealing the two-component nature of the slow light. It was demonstrated that the double-tripod scheme enables precision measurements of frequency detunings. Furthermore a possible application of the double-tripod scheme as quantum memory/rotator for a two-colour qubit was experimentally demonstrated. This offers potential applications in quantum computation and quantum information processing.

15.8 Quo Vadis Slow Light?

Light is fascinating! Light has very many uses and modern life would be unthinkable without them. Thus there is plenty of reason for us to celebrate the Year of Light. We believe that the applications of slow light based on EIT and its generalizations, which we have discussed in this chapter of the book, are important additions to this list of reasons. We have seen that coupling light to atomic media, which are specially prepared by external laser fields, allows us to dramatically modify the property of photons. We can change their effective propagation velocity, can store them or more precisely their information content with important applications for quantum information networks based on light, and we can turn them into massive quantum particles with tunable mass. Finally we can even use them to model relativistic quantum particles with spin.

It is interesting to note that EIT and slow light are not restricted to light in the optical frequency spectrum coupled to atoms. EIT can also be generated in other type of coupled oscillators, such as meta-materials build up of periodic arrays of small metallic antennas [36]. This allows to access the microwave part of the electromagnetic spectrum. On the other hand, the storage and release of light can also be carried out beyond atomic systems. Recently the conversion of light pulses into mechanical excitations of a silica optomechanical resonator and the subsequent retrieval of radiation using a method closely related to the EIT was experimentally demonstrated [37].

All phenomena we have discussed so far in this chapter address the single-particle properties of slow light, i.e. properties of *individual* photons. Yet it is also highly desirable to make photons interact with each other sufficiently strongly. Strong and controlled interactions between individual photons would, e.g., allow to implement quantum logic operations in the so-called quantum gates, the second important ingredient next to a quantum memory for photon-based quantum information technology. Interactions are also crucial for most applications of slow light to fundamental science. Several ideas have been put forward here to exploit the properties of slow light for implementing strong interactions. For example, the possibility offered by EIT to operate close to atomic resonances without suffering from absorption can be exploited to enhance nonlinear optical processes in atomic media [21, 38–44]. Another very promising direction is to combine EIT with the so-called Rydberg atoms. Here the atomic state s populated during the propagation and storage of light is not a hyperfine (spin) ground state of an atom, but rather a Rydberg state corresponding to a very high atomic level close to the ionization threshold. Such a state is metastable and has a very long lifetime. Atoms in Rydberg states exhibit very strong and long-range dipole–dipole interactions. This property is carried over to slow-light polaritons, whose spin component contains the Rydberg state, thus making these Rydberg polaritons strongly interacting [45]. The strongly nonlinear and nonlocal interaction between Rydberg polaritons has been observed in a number of recent experiments [46–50]. This opens many more fascinating applications in fundamental science and in quantum technology, and we anticipate a bright future for slow light.

15.9 Conclusions

In this chapter we have explained what slow light is and what it is good for, how to understand the physics of it and how one can practically make light go so slow. To answer these questions, we used simple pictures, on the one hand, and supplemented them with a little bit of details, on the other hand, for those who want to go slightly deeper into the field. Subsequently we discussed recent generalizations of slow light, such as stationary and spinor slow light which are interesting model system and can be used to understand more complex quantum systems. The chapter also presents important applications of the slow light in photon-based quantum information technology.

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