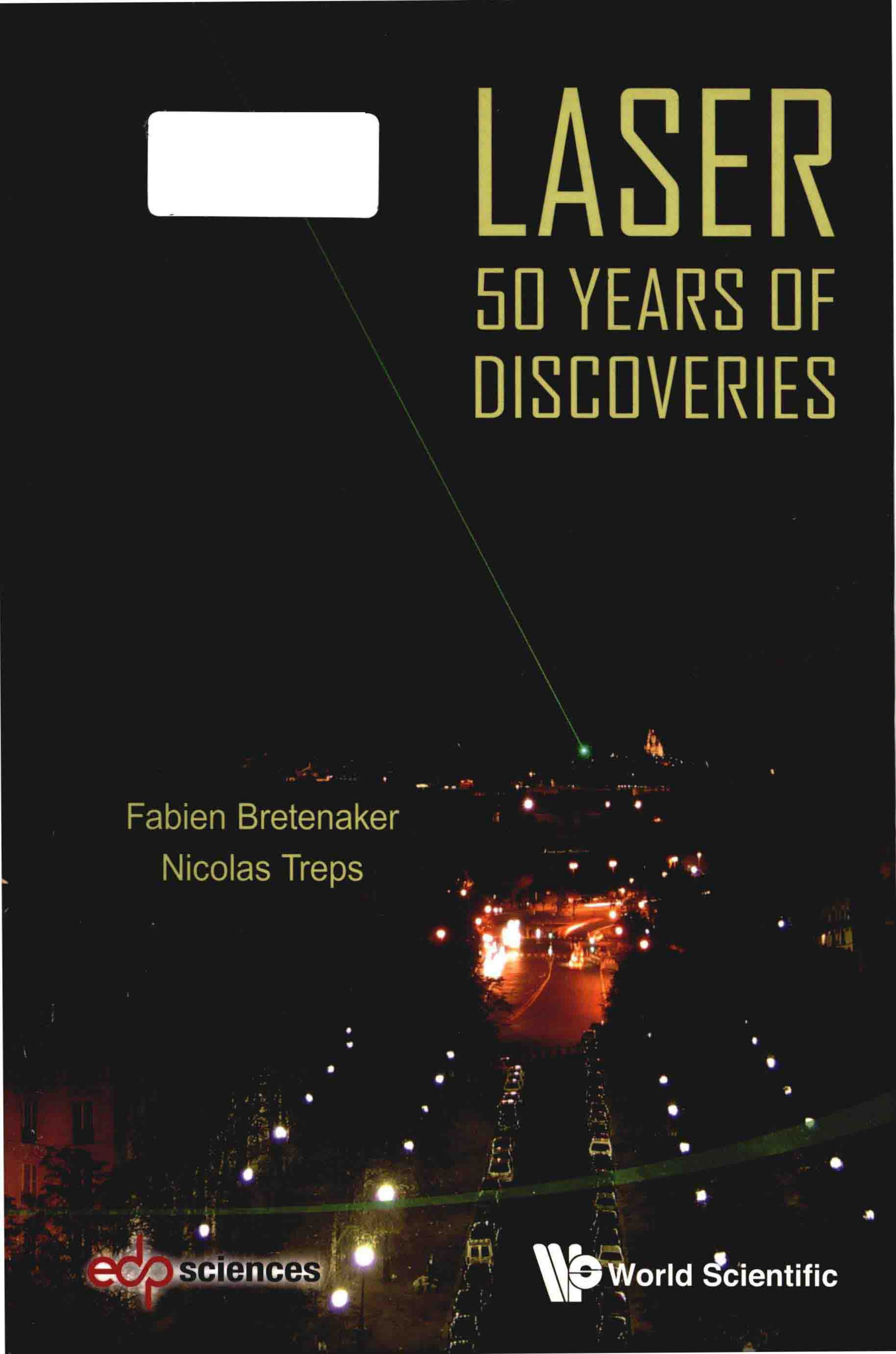

LASER

50 YEARS OF DISCOVERIES

Fabien Bretenaker
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edp sciences
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Preface

Fifty years after their invention, lasers continue to amaze us. Their performance characteristics are constantly reaching new limits, and the scope of their applications continues to expand. Perhaps the best measure of the success of the technology is that we in fact forget that lasers are present in many different facets of our daily lives. Yet it took years of effort by teams of physicists to transform the fundamental notions of Einstein into the first experimental beam of laser light generated in a ruby crystal. Since these pioneering studies, lasers of all sorts and sizes have been developed.

Without having the ambition to cover all applications that have now become numerous in both scientific laboratories and in industry, this book provides an overview (from many writers and different perspectives) of various aspects of science and technology that have developed as a result of the laser's invention. The foreword is written by Charles Townes, one of the inventors of the laser, and 1964 Nobel Laureate in physics. His reflections vividly trace the little known and sometimes amusing history of the pioneering discovery that has revolutionized the panoramas of science and industry for over half a century. After presentation of the principles of laser operation, each chapter then describes different types of laser sources (from the largest to smallest) as well as their applications. Long considered a laboratory curiosity ("a solution in search of a problem"), lasers have now become central in many areas of fundamental research and industry. This is an important lesson for the future.

Lasers first become indispensable in the field of metrology: telemetry to measure distances, vibrometry for testing solid structures; the use of gyroscopes for aircraft, ships and spacecraft etc. Lidar technology today brings us security and improved quality of life through improved air transport safety and the detection of air pollution. Lasers have rapidly become essential tools in areas such as medicine, chemistry, and mechanical engineering. The industry of machine tooling has been revolutionized by the development of powerful lasers for welding, cutting, soldering, and marking.

For the general public, the incredible emergence of lasers in practical life has arisen with the advent of semiconductor lasers (the size of a pinhead!), CDs and DVDs that allow massive information storage, and the Internet where information coded on laser light is propagated globally through optical fibers to shape daily life of the modern world.

Lasers have also enabled spectacular advances in basic research: quantum optics, potential detection of gravitational wave, tests of general relativity and theories of cosmology. Research over the past 30 years on "cold atoms" is leading to important applications for space navigation. And we are also very far from completing the basic research in laser sources themselves, constantly pushing the limits of technology to new frontiers. Ultraviolet and X-ray lasers are only in their infancy, and at the other end of the spectrum, terahertz lasers are seeing spectacular growth and should find many applications in chemistry and in the field of detection and security. The development of very high power "extreme light" lasers is a field of research very active internationally, for both fundamental tests of basic physics as well as for an important test of models and simulations. On the horizon for tomorrow are many new applications of lasers in medicine, such as the treatment of macular degeneration of the eye, an affliction affecting tens of millions of people worldwide.

The laser clearly has a very bright and unexplored future ahead of it. The content of this book has been written by leading researchers involved in the development and applications of lasers, with the authors and their affiliations given at the beginning of each chapter. Putting this book together has been coordinated by two brilliant young researchers Fabien Bretenaker and Nicolas Treps. This book is destined for all who are curious about science and technology. It is particularly aimed at those at high school, their teachers as well as science students at all levels. The book covers a wide variety of topics, all treated as simply as possible and in a way that is clear and easy to follow. There are many figures and diagrams and very few equations.

The publication of this book in English is particularly appropriate to celebrate the International Year of Light and Light-based Technologies in 2015, where the United Nations General Assembly has recognized the importance of both fundamental and applied research in lasers and their applications. This year will allow a truly global appreciation of the many ways in which the laser has played a central role in modern life, and how it will be a central tool to develop solutions for challenges of the future in healthcare, communications and quality of life worldwide.

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Coordinators, Contributors, and Acknowledgments

This collective book has been written by 15 co-authors whose names are reproduced at the beginning of each chapter and below. The coordination has been performed by Fabien Bretenaker and Nicolas Treps, with the complicity of Michèle Leduc and Michel Le Bellac.

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Fabien Bretenaker is senior scientist at CNRS. He graduated from Ecole Polytechnique in 1988 and received in 1992 the PhD degree from University of Rennes, France, after having worked on ring lasers and their applications to rotation sensing. He worked during some years for Sagem company and joined CNRS in 1994, first in the laser physics lab in Rennes. In 2003, he joined Laboratoire Aimé Cotton in Orsay, France. He is also professor at Ecole Polytechnique. His research deals with laser physics, nonlinear optics, quantum optics, with applications ranging from microwave photonics to sensors.

Nicolas Treps is professor at university Pierre and Marie Curie in Paris, France. He graduated from Ecole Polytechnique and received the PhD degree in 2001 after his work on quantum properties of optical images in Laboratoire Kastler-Brossel. He was then a post-doctoral researcher at Australian National University in Canberra, during which he worked on quantum information protocols. Since 2002, he has been working in Laboratoire Kastler-Brossel. His research covers the fields of quantum aspects of light, high sensitivity measurements, nonlinear optics, and quantum information science.

Contributors

The following people have contributed to the writing of this book: Mehdi Alouini, Philippe Balcou, Claude Boccara, Christian Chardonnet, Pierre-François Cohadon, Nicolas Forget, Sébastien Forget, Saïda Guelatti-Khélifa, Manuel Joffre, Lucile Julien, Michèle Leduc, Serge Mordon, Isabelle Robert-Philip, Thierry Ruchon, and Catherine Schwob. We warmly thank them for their work and the friendly atmosphere which has governed our collaboration.

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Foreword

Charles H. Townes

Professor at University of California, Berkeley

The physical principles by which lasers operate were known quite early in the 20th century; in 1924 Richard Tolman wrote "Molecules in the upper quantum state may return to the lower quantum state in such a way as to reinforce the primary beam by negative absorption — it will be pointed out that for absorption experiments as usually performed the amount of negative absorption can be neglected".[1] But it was about 30 years later before the usefulness of amplification by "negative absorption" was really recognized. Furthermore, lasers and many masers have existed around particular stars for billions of years. If we had taken the trouble some time ago to look systematically in the microwave range, we would have found the intense microwave radiation from masers around stars, probably figured out how this radiation was produced, and initiated the field of masers and lasers earlier.

In the 1950s, I was doing microwave spectroscopy on molecules using electronic oscillators. This provided very high spectral resolution, but such oscillators could not produce wavelengths shorter than a few millimeters and I was eager to get to shorter wavelengths — into the infrared, because of the wealth of interesting spectra there. After some unsuccessful work in this direction, I was asked to chair a national committee to investigate such possibilities. We visited many laboratories and had much discussion, but found no solution. Before the committee's last meeting, I woke up

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[1] Richard Tolman, *Phys. Rev.* **24**, 297 (1924).

early in the morning worrying about our lack of success. It was a bright morning, and I went outside to sit on a park bench. I thought that of course, molecules and atoms can produce short wavelengths, but I had previously ruled out their use because thermodynamics limits the intensity of radiation to an amount determined by their temperature. Suddenly I woke up to the fact that molecules and atoms do not have to obey thermodynamics; we can put more in the upper than in the lower state. Since I was then at Columbia University where much work was being done with molecular and atomic beams to separate their different states, I thought of using this technique. Pulling out paper and pencil from my pockets, I wrote down appropriate equations and numbers. It looked like it could work!

On returning to Columbia I persuaded a graduate student, Jim Gordon, to try to build such a system for amplification. Since I had much microwave equipment and was very familiar with the microwave spectra of molecules, I thought we should try it first with beams of ammonia molecules, to amplify and produce an oscillator at about 1 cm wavelength. After Gordon, with the help of a post doc Herb Zeiger, had worked a couple of years on building such a system, Prof Kusch, chairman of the physics department, and Prof. Rabi, the previous chairman of the department, came into my lab saying "Charlie, that's not going to work, and you know it won't work. You're wasting the department's money, and must stop". I disagreed, and they left my lab annoyed. About two months later, in April, 1954, Jim Gordon came into the seminar where I was teaching, and announced "It's working". We all left the class and went to the lab to see this new oscillator. Kusch and Rabi were both specialists in molecular beams and both won Nobel Prizes. This shows it is not just intelligence that produces new results. We must leave the known routes and take chances.

Although it turned out that Basov and Prokhorov in the Soviet Union had an idea somewhat similar to mine, we were not in contact until after our system was working (theirs was not yet). Many Americans and some Europeans had visited my lab and seen our experiment underway, but were doubtful and hence not interested. And no one I knew was interested or optimistic enough to compete with our work.

My students and I, one day at lunch, had picked out the name "maser" for the new device, the acronym for "microwave amplification by stimulated emission of radiation". After we announced operation of the new amplifier, many people became interested. It became a hot field with much competition.

I continued work on masers, but soon went to the Ecole Normale Supérieure in Paris on sabbatical leave. There I worked in Alfred Kastler's lab, where Claude Cohen-Tannoudji, then a student, Jean Combrisson, and Arnold Honig, one of my former students, were all busy with research. The latter two were working on electron spin resonances in semiconductors, and had just discovered long relaxation times of electron spin excitation. Wow! That meant that electron spins could be in the excited state for some time, and tunable masers could be made, on which we published. This is an example of the importance of interaction of scientists in different fields, which often produces new ideas.

In Europe, I met Niels Bohr and while walking on the street with him he asked what I was working on. I told him about the ammonia maser, and the very pure frequency of oscillation it produced. "Oh no, that can't be right", he said. "You must misunderstand". I explained to him that yes, we had measured it and this was true, but we parted without his ever believing it. He must have been thinking of the uncertainty principle, and not allowing for averaging over a large number of molecules. But this illustrates how even the greatest often get locked into their own fixed ideas, and don't see new ones.

The maser became a very hot field. But I was, of course, interested in getting to shorter wavelengths. Almost everyone thought there was no chance of producing much shorter waves, but after a couple of years with the maser I decided I must see how best to get on to shorter waves, and I took some time to think more about it. This led me to recognize, and show numerically, that we could make "masers" that operated right on down to optical wavelengths. But I decided to keep quiet about it until I worked it all out, because the field was then exciting and I knew someone would compete and try to publish the first paper once they recognized this possibility. I was consulting at Bell Labs, where my former post doc, Art Schawlow, who became my brother-in-law by marrying my kid sister, was then working. I mentioned my idea and the possibility of getting down to light waves. He responded "Oh, I've been wondering about that — could be work together on it". I said "sure", and we did. He added the important idea of two parallel plates as a resonator (he had done spectroscopy with a Fabry–Perot, which probably gave him the idea). This was an important improvement over my plan to use simply a closed cavity, as I had done at microwave frequencies. We decided to first publish a theoretical paper before doing experiments, since once anyone recognized the possibility, they were likely to compete and try to publish before us. So we published such a paper.

Before publication, Schawlow and I decided it appropriate to give the patent on "optical masers" to Bell Labs, and he took it to their patent lawyers. He telephoned me a few days later. Bell Labs' patent lawyers had said light was of no value to communications, and hence they were not interested and we could patent it ourselves if we wished. We knew they were wrong — another example of the turndown of new ideas by experienced people — and I asked him to go back to persuade them it could be used for communications. They then agreed to write a patent, which we labeled "Optical Masers and Communication".

Schawlow and I wrote and published the paper "Optical Masers" to establish the field before trying to build one. The natural name "Laser" for Light Amplification by Stimulated Emission of Radiation came along a little later. With this publication, many people began to try to build a laser, including students in my lab. However, at that time I was asked to go to Washington and take an important position in advising the government, which I agreed to do. This gave me little time to help my students build the first laser, and they didn't.

Ted Maiman produced the first laser in May, 1960, using a ruby crystal and an intense light flash. The latter was a great idea to provide at least temporary excitation, and I had not thought of it. Maiman succeeded, and produced a great flash — not only of red light, but also in the public press! It was the first operating laser. A number were subsequently produced. The next new lasers were made by Mirek Stevenson and Peter Sorokin at General Electric, and then the helium–neon gas laser by Ali Javan, one of my former students, along with Bill Bennett and Don Herriott, at Bell Labs. All of the inventors of the early lasers had recently been students at universities working in fields related to spectroscopy, and all of the inventions were in industrial laboratories. Industry had become interested, could work fast, and was very successful!

Many people, engineers and scientists, have contributed to the rapid growth and enormous usefulness of lasers. It has transformed the field of optics. It is important in many fields, a number of which were not envisioned during the initiation of the laser. I did not, for example, foresee any medical usages. But now that is a big and important application. Nonlinear optics is one of the many new creations. And still shorter laser waves which were not initially foreseen — X-rays and gamma-rays — have become interesting. No new acronyms, such as xasers for X-rays have been introduced — devices are lasers at every wavelength except for microwaves. The latter are still masers even though there is no distinction between masers and lasers except that the name maser is for wavelengths above about 1 millimeter.

I was initially especially interested in scientific uses of the new device, and am delighted to see all the new science produced. I'm now using lasers to measure the sizes and shapes of stars. More than a dozen Nobel Prizes have been awarded to scientists who used masers or lasers as critical instruments in their work. Penzias and Wilson used a maser amplifier in discovery the "big bang" origin of the universe.

Technical applications of lasers have, of course, made an even bigger impact on our society and on economics than the pure science applications. The laser industry now involves many, many billions of dollars per year, and can be expected to continue to grow rapidly.

The laser is a classic example of how fundamental research contributes not only to science, but also, enormously, many times completely unexpectedly, to economics. Basic science is fascinating, and also is likely to help human welfare enormously. The interesting chapters of this book will provide some examples.