MASERS AND LASERS

HOW THEY WORK, WHAT THEY DO

by M. Brotherton

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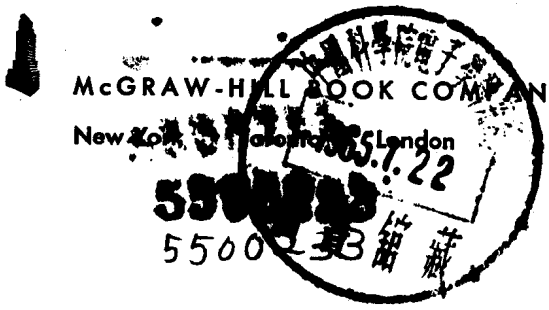

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FOREWORD

Tools, inventions, and technology have always been crucial to the species known as man. And gradually with developing technology has come a systematic knowledge and understanding called science, which is not only important to man's view of himself and his surroundings but which has allowed more complex and subtle tools of civilization to be developed at an ever-increasing rate. Science and technology may now be counted along with "bread" as basic to man's material sustenance. Yet at the same time, science has become sufficiently complex and subtle to be continually in danger of being estranged from the society it serves and by which it in turn must be nourished.

The wheel and the arch could be touched, exam-

ined, or made by any individual, and an understanding of their uses developed over many generations. The latest inventions today are frequently based on great abstractions, they may involve atomic phenomena never really visible to or touchable by anyone, and millions of people may experience their effects and benefits within a short time after discovery.

The maser, with its variant the laser, represents such an invention rooted in abstract atomic and quantum theory. To the quantum scientist, the theory involved is beautiful, and the device fascinatingly powerful in allowing control of radiant energy in the form of electromagnetic waves. But others who do not deal with quantum physics in an everyday way are usually separated from such appreciation by a frustrating chasm; the theory is likely to seem unreal, and the maser itself a most mystifying and fantastic device. This book is designed to show the nonspecialist, by relatively simple steps understandable to the interested mind, how the theory and the device developed, what the maser is and how it works, and the beauty and power of the resulting complete structure.

Brotherton's discussion is a happy combination of an easy and interesting style with anecdote, history, and analogy, careful attention to the significance of each major step, and much closer adherence to scientific reality than is usually achieved in simplified or popular discussions of complex scientific ideas.

His association with the Bell Telephone Laboratories and with its scientists, who have been closely connected with much of the story of the maser, has given him an excellent vantage point from which to produce such a treatment. But also evident is his enthusiasm for an accurate and understandable presentation of exciting science and its applications.

This type of writing is much needed in order to prevent the estrangement of science and scientists from the broader public, and it must be read if this public is to profit best from the enormous potential of science or to remain in sentient control of its own destiny.

C. H. Townes

PREFACE

This book began in 1960 when I was working on a Bell Laboratories advertisement on the maser. I became so intrigued with the device itself and how it worked that I went on to put what I had learned into an article entitled, "Amplifying with Atoms." Published in the *Bell Laboratories Record,* the article proved of such wide interest among science teachers, science students, writers, and others that it was necessary to provide nearly 30,000 reprints.

These events revealed a lively need for science writing in such a vein and at such a level of understanding, and this book developed virtually as a response to that need. In it I have tried to portray the laser and maser against their common generic background, explaining in an elementary way how they

came to be, how they work, how they can benefit science, technology, and communications, and how, in general, they provide an intriguing insight into the workings of nature.

Since the book is intended to communicate only key ideas, all illustrations are made as simple as possible and stylized as necessary, consistent with accuracy. Names of persons, except historical ones, are omitted to simplify the narrative and to avoid invidious omissions.

This book was conceived for that considerable audience of literate people both here and abroad who would like to have an explanation of masers and lasers which, while factual and authentic, stays away from formulas and formulations beyond their grasp.

Written in spare moments during evenings, holidays, and weekends, at home, on park benches, and on commuter trains, this book is a purely personal project. The viewpoint expressed is my own and does not necessarily represent that of Bell Telephone Laboratories. Surely, however, it could not have been written without the perceptive comments and guidance and, by no means least, the sympathetic interest and encouragement of several members of the Bell Laboratories technical staff. Particularly, I want to acknowledge the help of D. F. Nelson, A. N. Holden, J. N. Shive, J. E. Geusic, E. F. Vaage, and D. C. Hogg; also that of Professor C. H. Townes, of Massachusetts Institute of Technology, for guiding me to information sources.

I am indebted to articles in *Scientific American*. For possible uses of these devices, I have consulted the report of a study entitled "Masers and Lasers," prepared by graduates of Harvard University Graduate School of Business Administration. Information about why the laser was not invented earlier was found in a thesis prepared by Michael Feld for Massachusetts Institute of Technology. Finally, I must acknowledge my indebtedness to Bell Telephone Laboratories for the use of its facilities and for permission to publish most of the illustrations.

M. Brotherton

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INTRODUCTION

One day in 1954 a Columbia University professor and his students startled the world of science by generating radio waves without using the customary electron tube. They generated these waves (which are about one-half inch long and known in electronics as *microwaves*) in a small metal box which contained nothing but a small quantity of ammonia gas differing chemically in no way from the household cleanser you pick up in the chain store. Instead of drawing upon the energy of a stream of electrons as was done in all earlier types of radio-wave generators as far back as Hertz's pioneer radio experiments in 1887, they produced microwaves by stimulating the emission of energy which was stored in the ammonia molecules. Fittingly these pioneer Columbia University scientists

named their device *maser,* which is short for *m*icrowave *a*mplification by *s*timulated *e*mission of *r*adiation.

As a practical tool of communication the maser may never compete with other less complex microwave amplifiers, which it is able to outclass in only one important particular. The significance of the discovery lay in the radically new amplifying principle it revealed. Dramatically, it drew attention to an exciting vista of possibilities for harnessing atoms and molecules to store and manipulate radiant energy both as tools for probing matter and in practical devices. In numerous universities and industrial concerns physicists began looking for ways to apply the new principle at shorter wavelengths and with different materials and techniques.

By 1959, the operating frequency had been thrust upward through the electromagnetic spectrum a hundred thousandfold to create the *optical maser,* or *laser,* capable of working with light waves only a tiny fraction of an inch in length. Essentially a laser [1] consists of an active medium which may be a crystal, gas, or semiconductor. It is bounded on two ends by parallel mirrors which reflect light waves back and forth. The atoms of the medium through which the

[1] Some prefer the term *optical maser,* in which the letter m is made to stand for *molecular* instead of its originally assigned denotation of *microwave.* While this viewpoint is logical, we shall here employ the word *laser,* since it has the virtue of brevity and has won popular acceptance.

light waves are reflected are conditioned to give off light when light hits them. As the light waves race to and fro, they release new energy from the atoms and are thus amplified. By making one of the end mirrors partially transparent, the amplified light is caused to emerge as a beam.

The laser achieves the historical distinction of being the first device capable of amplifying light waves per se. This may seem strange when we consider that we have had excellent radio-wave amplifiers for many years and that light waves are of exactly the same electromagnetic nature as radio waves, differing from them only in wavelength and frequency. What is there about the laser that enables it to handle light waves while other amplifiers cannot?

One factor is that the laser handles and amplifies waves as waves without having to convert them into a vibration of electrons as was necessary in earlier amplifiers. Paradoxically, the three-element electron tube, which more than any other invention made possible our fabulous world of radio, is quite incapable of handling radio waves as such, that is, as vibrations in "empty" space. Strangely enough, the only part of a radio receiver that actually handles radio waves is the antenna. Scooping radio-wave energy out of space, the antenna converts it into vibrations of electrons in wires, and it is these vibrations which the electron tube handles and amplifies. By its very nature the three-element tube is incapable of

operating at extremely high frequencies. Consequently, for more than a generation, with no other amplifier available, communications science was hampered in its quest for higher frequencies.

Then in 1938 came a new kind of electron tube called the *klystron,* and in 1946 the traveling-wave tube in which waves interact directly with an amplifying electron stream. Eliminating the necessity for having to convert the waves into vibrations in a wire circuit, the klystron and traveling-wave tube can handle enormously higher frequencies, that is, shorter wavelengths, than the earlier tubes.

Great as are the advances made possible by the klystron and traveling-wave principles in handling short wavelengths, still they are incapable of operating at the extremely short wavelengths of light mainly because physical parts cannot be made small enough or electrons made to move fast enough. By creating a situation in which light waves amplify themselves by drawing directly upon energy stored in atoms, the laser takes a giant leap over both obstacles, opening the way for the manipulation and application of light waves in ways never before possible. Broadly the applications fall into three categories.

1. For pure science, the laser principle offers a new and useful point of view from which to study the behavior of matter, while the light itself affords a new and potent source for spec-