QUANTUM ELECTRONICS

A SYMPOSIUM

edited by

CHARLES H. TOWNES

Published in Great Britain, India, and Pakistan
by the Oxford University Press
London, Bombay, and Karachi
Library of Congress Catalog Card Number: 60-8097
Manufactured in the United States of America

PREFACE

This volume represents papers and discussion at the Conference on *Quantum Electronics—Resonance Phenomena* held at Shawanga Lodge, High View, New York on September 14-16, 1959. Origins of the Conference are outlined in the following remarks of Dr. Irving Rowe with which it was opened:

"I want to welcome you to the Conference on Quantum Electronics—Resonance Phenomena on behalf of the sponsor, the Office of Naval Research, and would like to indicate briefly how this conference came into being. The idea for calling this meeting originated with members of the Electronics and Physics Branches of the Office of Naval Research, who realized the growing significance of the field of quantum electronics, which is actually producing a revolution in microwave techniques. We hoped that such a conference would consolidate what knowledge we have today and would act as a stepping stone toward further advances. We asked Professor Townes whether he would be willing to act as chairman for this meeting. Professor Townes agreed that the research stemming from the development of the maser and from related resonance phenomena was reaching a degree of maturity where an international scientific meeting would be well justified. He accepted the chairmanship and formed a steering committee to aid him in establishing the policies of the Conference. From that time on, full credit for selecting the speakers and arranging the program goes to Professor Townes and his committee. We want to thank these people for the great efforts which they exerted in spite of the fact that each of them had a heavy workload of his own.

"Those of you who are not familiar with the Office of Naval Research may wonder why the Navy should spend its money on a scientific conference of this type. The reason is that the Navy is fully aware of the importance of basic research in quantum electronics, and indeed has already begun to utilize its applications. For instance, I believe that the first reported results from a maser as an operating device came from the Naval Research Laboratory, which used the ruby maser built at Columbia University, in conjunction with its own 50-foot radio telescope. This was used to study the emissions from the planets Venus and Jupiter, and from several radio stars. Similarly, the Naval Observatory is charged by law with the responsibility of being the custodian of official time for the United States. The Observatory now uses an atomic clock as its most precise time standard.

"Those of you who have had previous contacts with the Office of Naval Research know, however, that its interests are not devoted primarily to immediate practical applications, although we do welcome them whenever possible. Instead, we are interested primarily in encouraging basic scientific research, with the emphasis on providing a better understanding of the fundamental processes of nature. I am sure that this conference, including both the formal papers and the informal discussions to follow, will be a milestone on the way toward that better understanding."

There have been many significant contributions to the Conference which are not directly recorded in this volume. In addition to the very important services of Dr. Rowe, the ONR through him, Dr. Arnold Shostak, and Frank Isakson gave the initial impetus for this conference and both financial and administrative support. Other Governmental agencies, such as the U. S. Army Signal Research and Development Laboratory, the Air Force Office of Scientific Research, the Bureau of Ships, the Office of Ordnance Research, and the Air Research and Development Command, while not acting as sponsors of the Conference itself, have assisted various parts of the work reported here.

The policies and program of the Conference were planned by the Steering Committee, consisting of:

Dr. G. Birnbaum, Hughes Research and Development Laboratories

Professor N. Bloembergen, Harvard University

Professor R. H. Dicke, Princeton University
Professor Charles Kittel, University of California
Dr. R. Kompfner, Bell Telephone Laboratories
Dr. B. Lax, Lincoln Laboratories, Massachusetts Institute of Technology
Dr. I. Rowe, Office of Naval Research
Professor A. E. Siegman, Stanford University
Dr. G. J. Stanley, California Institute of Technology
Professor M. W. P. Strandberg, Massachusetts Institute of Technology
Professor C. H. Townes, Columbia University, Chairman

Success of the Conference is due in considerable measure to the effort, thought, and support of members of this committee. The Bell Telephone Laboratories provided, through the help of Dr. J. P. Gordon and Miss Muriel Morrow, more than its normal share of assistance.

The Conference is much indebted to the staff of the Columbia University Physics Department: to Ann Hart Rappaport for administrative work in the early stages of the Conference and particularly to Mr. R. W. Siegel and Barbara Turlington Gersfeld for devoted and efficient management of the large burden of administrative details as well as untiring assistance throughout the course of the conference. They and a number of graduate students, including P. Thaddeus, H. Lecar, J. A. Giordmaine, W. Rose, F. R. Nash, I. Abella, and H. Cummins, are also responsible for much of the planning and editing of this volume.

The reader will find that the following pages begin with brief general remarks on the subject matter to be discussed. Principal topics are then introduced by summarizing papers, the majority of which are followed by a number of related specialized topics. Much of the discussion which followed each paper is also recorded and in some cases includes new material as well as clarifying comments.

CHARLES H. TOWNES
Columbia University

INTRODUCTION

The subject matter of this symposium lies near the interface between two highly developed disciplines—the field of electronics and that of spectroscopy. We are grateful to Dr. Rowe and the Office of Naval Research for recognizing the rapidly expanding interactions at this interface and for initiating and supporting the present conference. The wide variety of interests represented here provides an opportunity for clarifying and unifying basic ideas which are common or may become common to both disciplines, for discussing recent developments, and possibly for preliminary examination of areas where important research developments may be expected in the future.

Electronic techniques have been used for what might be called spectroscopy over a long period of time, if we recognize as spectroscopy the study of dielectric constants and losses in the radiofrequency region. However, we are concerned here primarily with resonance spectroscopy and resonant interactions examined by approximately coherent electromagnetic waves The resonances of interest are of course not those which are primarily dependent on macroscopic properties such as mass or size of a piece of material—that is, those which are dependent on the number of molecules—but the resonances which are primarily determined by characteristics of individual atoms or molecules. There were, of course, important developments in examining the resonant interactions between molecules and radiofrequency or microwaves before the war with the experiments of Cleeton and Williams, and those of Rabi and his associates. However, much more intensive activity in this area has occurred during the last fifteen years.

Immediately following the war, there were many physicists who had of necessity become quite familiar with electronics and who rapidly applied the techniques and apparatus of this field to spectroscopy. More recently, there has been a diffusion of information and techniques back again from spectroscopy and physics across the interface into regions clearly recognizable as engineering, and the area of interaction between the two fields has considerably widened. We now have from resonant spectroscopy a wide variety of practical devices such as nonreciprocal circuits, nonlinear elements, detectors, coherent amplifiers, and oscillators. In fact, the spectroscopist can probably produce from atomic and molecular resonances almost any type of circuit element or phenomenon to which the electronics engineer is normally accustomed.

It is quite natural that electronic use of ferromagnetic resonance, cyclotron resonance, and orbital resonances of electrons have been among the first to be developed, since these involve very large matrix elements and hence strong interactions with the electromagnetic field. The large matrix elements also imply large angular momenta and hence an essentially classical situation. Although electron orbital motions and ferromagnets are included in the symposium to some degree, primary emphasis will be placed on situations where quantum effects more characteristically appear, and which are perhaps not yet so familiar to the field of electronics. In many cases, the physical ideas and phenomena involved are still not well understood, and are the subject of very active research efforts and discussion among those who feel no great concern about electronics itself.

As one progresses towards higher frequencies, interactions between electromagnetic waves and molecules or atoms become increasingly prominent; furthermore, classical electronic techniques become more difficult and quanta larger. It is hence natural that spectroscopic techniques or ideas and quantum phenomena will become increasingly important in the high-frequency region, providing perhaps the principal means for affecting and controlling electromagnetic waves having wavelengths shorter than one millimeter. Thus the electronics engineer, as clearly as the physicist, needs to become acquainted with quantum physics to be able to utilize the most sophisticated electronics.

Both electronics and spectroscopy are, in fact, more techniques and tools than fields of knowledge in themselves. They are, furthermore, characterized by great precision and delicacy and provide techniques for a wide variety of beautiful experiments in physics and for a great deal of technology. Thus this symposium leads in a number of directions and includes discussions of problems in such fields as fundamental physics, radioastronomy, and communications.

C. H. T.

CONTENTS

QUANTUM ELECTRONICS

A SYMPOSIUM

Edited by CHARLES H. TOWNES

New York 1960

COLUMBIA UNIVERSITY PRESS

MOLECULAR BEAM MASERS

J. P. GORDON
Bell Telephone Laboratories, Murray Hill, New Jersey

IN THE early 1950's, microwave spectroscopy of gases had reached a level where most of the more straightforward experiments had been done, and experimenters were looking for new directions in which to go. Several groups were attempting to achieve exceptionally high resolution through utilization of restricted velocity classes of molecules, thus partly eliminating doppler broadening of the spectral lines. Some of the experiments I might mention are those of Newell and Dicke (1951),[(1)] Johnson and Strandberg (1952)[(2)] (I believe this was the first detection of a molecular beam by microwave methods), Strandberg and Dreicer (1954),[(3)] and Romer and Dicke (1955).[(4)] All of these experiments were concerned with the intense inversion spectrum of ammonia. At the same time, others were concerned with the possibility of microwave amplification and generation on the maser principle,[(5)] although to be sure the word maser had not yet been coined. Gordon, Zeiger, and Townes began work on what was to be the first ammonia beam maser. Weber[(6)] suggested that maser amplification was possible, and gave figures for the gain which might follow an extremely rapid Stark field reversal in a waveguide filled with ammonia. Bassov and Prokhorov,[(7)] in 1954, published some conjectures about the use of beams for spectroscopy. They observed that since beams could be deflected by nonuniform fields, and since in this way one could separate an upper state from a lower state, it might be possible to construct a molecular oscillator. For the particular example they took, that of CsF, they calculated that oscillation could be obtained if a cavity Q of 7×10^6 could be achieved. In 1954 came publication of the first successful molecular beam