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APPLICATIONS

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PREFACE

This book introduces the new electronics technology of microwave power and its applications. This technology emphasizes microwave (and eventually quantum) electronics for direct power utilization and transmission purposes rather than exclusively for information and communications applications. Because only fixed frequencies are involved in most present applications, phase and delay distortions as well as bandwidth and coherence considerations, associated with information transmission systems, are less important. Essentially, microwave power can be divided into microwave heating, microwave processing, microwave dynamics, and microwave power transmission involving generation and power amplification, direct power utilization, and closed waveguide or radiation beam propagation for remote utilization and rectification. Emphasis is on: (1) the microwave frequency spectrum, in relation to minimum size, specific weight (i.e., power/unit weight), and cost considerations; (2) constant or continuous wave (CW) rather than periodic pulsed power; (3) very high efficiency; (4) reliability; and (5) long life.

While the proceedings of the first symposium on this subject have been reviewed in the October, 1964 issue of IEEE *Spectrum*, a thorough coherent introduction to this subject now seems timely. In particular, this book seeks to present a review of the state-of-the-art accomplishments with respect to components, systems, and applications and their prevailing limitations in the light of modern knowledge of the microwave power technology. Recommendations are included with respect to what can be done to accelerate a balanced growth of the subject and to attract more creative interest and support.

The dominant microwave state-of-the-art generators and power amplifiers, with respect to power capabilities and efficiency, include the magnetron, the Amplitron, and the klystron, whereas the magnetron has been found most suited to the widely varying impedances associated with batch processes. The dominant state-of-the-art microwave rectifiers, in this same respect, include the thermionic (ultra-close spaced, vacuum, electrostatic) diode, the point contact and Schottky barrier semiconductor diodes, and the (electrostatically focused) inverse klystron. Other theoretically promising microwave rectifiers include the transverse wave and traveling-wave devices.

Microwave heating and other processes of materials, including food, utilize the magnetron predominantly, and also the klystron, in drying and freeze drying, sealing, cooking, reheating, thawing, moisture leveling, etc. Other applications include (1) microwave ionized gases presently on an experimental basis for chemical processing, space (propulsion), and scientific (controlled nuclear fusion) purposes; (2) particle accelerators for scientific, medical, and industrial purposes; (3) military and aerospace for phased array focused microwave energy, experimental vehicle hovering, etc; and (4) dynamics, for experimental microwave motors and experimental waveguide vehicle transport, etc. Besides these applications of microwaves and those under development, there are also considerations of radiation hazards and other biological factors.

Microwave rectification applications are presently predominantly experimental for diode array antenna of experimental hovering aerospace vehicles, experimental microwave motors, experimental waveguide vehicle transport, etc. Much higher power rectification will be required for microwave power transmission and distribution, vehicle transport, etc., whenever these become practical realities for which high power microwave rectifiers are in a very primitive state of development.

Waveguide power transmission has the advantage that it is not affected by the weather, but also has the serious disadvantage that its (ohmic) attenuation for efficient long distance CW power transmission must be at least one thousandth of that which is tolerable for communications. Such low attenuation (i.e., 0.001 dB/km), for example, may be realized with the circular electric mode (i.e., TE_{01}°) in oversized circular waveguide having a diameter of approximately 10λ, provided the generation of spurious modes can be minimized at least as successfully as it has been for communications purposes. This problem has received scant attention until recently, even in the light of the fact that waveguide power capacity is no barrier. For example, waveguide power capacity can match and exceed that of even the future super high voltage transmission line capable of the order of 4 GW. It is appropriate to mention in this context that the oversized rectangular waveguide has received considerable attention recently for relatively short waveguide runs. With cross-sectional dimensions equal to approximately 2λ, an order of magnitude increase can be obtained in CW power transmission compared to standard size waveguide.

Radiation beam (or "wireless" power) transmission has received encouraging laboratory attention as a direct result of international developments in CW power microwave electronics, especially at *S* and *X* bands. Aerospace and military requirements now provide significant incentive for developing a novel relatively large area, but extremely light weight, unfurl, self-rectifying diode array antenna for hovering aerospace vehicles or perhaps even orbiting or synchronous space vehicles. The much more cumbersome and much heavier precision parabolic sheet antenna is limited to the order of 1000 sq ft for hovering aerospace and/or space vehicles at the desired distances (e.g., in near space or up to synchronous orbit) though are presently impractical.

The remaining topics concern the state-of-the-art of these various components, systems, and especially the applications of this new electronics technology, both from a theoretical and experimental applied basis. Most of the experimental work has been done in microwave generation and power amplification and their applications and to a lesser degree in microwave rectification and transmission of microwave power.

Those units utilized in the particular industry or activity represented by the article were incorporated as a matter of mutual convenience.

May 1968 ERNEST C. OKRESS

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APPLICATIONS

5.1 Microwave Heating

5.1.1 INTRODUCTION

Robert V. Decareau and Paul W. Crapuchettes

I. Food Field

There is a certain amount of similarity between the food and (nonfood) materials fields with respect to microwave processing, especially in the electronic aspects of the equipment, yet there are also vast differences. In many cases, nonfood materials have fixed and uniform dimensions; e.g., in such applications as plywood bonding, veneer drying, and paper drying. Food materials on the other hand may vary in all dimensions with no two pieces exactly alike in shape or composition; take, for examples, shrimp, lobster tails, and cut-up poultry parts. As a consequence, it may be necessary to size grade a product in order to avoid extremes in size and thereby minimize over and under heating. Since size grading is an operation with which food plant operators are familiar, this additional operation presents no particular problem.

Size changes are not uncommon in food processing, such as in the baking of bread in which volume and therefore, product density change. Dielectric properties usually undergo significant changes during processing, as in dehydration in which a product which initially represented a good load becomes a progressively poorer load. Compensation in power input must be made for these changes. Even more substantial changes in dielectric properties occur during microwave thawing of frozen foods, in which a product changes from essentially transparent to relatively opaque. In all such cases, compensation must be made in equipment design. This can be accomplished perhaps most easily in process equipment in which the energy can be profiled; i.e., various sections can be operated at different power levels. Batch ovens for food service use, however, must be a compromise design at best, with comparatively elaborate instructions for their use for a wide variety of foods to be thawed, cooked, or just heated. Three sections of this book are devoted to microwave ovens, their plumbing aspects, and the problem of energy conversion.

For the freeze-drying process, if microwave energy is used to accelerate the drying cycle, it is necessary to cope with a very low pressure environment. The normal operating pressure for this process is that at which corona discharge is easily triggered, particularly as the product approaches dryness and the load becomes an extremely poor one. This is considered by the food industry to be a very important process and considerable space is devoted in this volume to it and to solutions to the corona problem.

Several pages are devoted to a discussion of microwave finish drying of potato chips, a process in which there is industry interest to the extent of about 800 kW of operating equipment. The market potential is estimated at 10 000 kW by one writer, but this figure could easily be exceeded. This is a use of microwave energy into a relatively poor load, yet the advantages it brings to the potato chipper are substantial enough so that it may become an essential procedure in this industry.

The only other food application which is currently a user of production microwave equipment involves the continuous cooking of poultry in a microwave and steam environment. This 130 kW installation is an example of the multiple generator design philosophy and is discussed and compared with the single high powered generator approach in the section on microwave ovens. Numerous other food applications could profit from a judicious use of microwave energy, in most cases, in combination with other forms of thermal energy. Although a very substantial start has been made, this is an industry with literally a huge reservoir of untapped applications. The following sections will undoubtedly suggest to the reader many new uses.

II. Materials Field

Microwave heating is rapidly becoming the key to new techniques and processes. This technique has begun to proliferate as the cost of its use has come within range of an increasing number of users. The range of applicability of microwave heating is determined by economic factors which include but may not be limited to (1) the price per pound of the finished product, (2) the existence of special preferences such as instantaneous heat programing or