Microwave Power Applications

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Invited Paper

***Abstract*—The field of microwave power applications is little recognized within the publications of the IEEE, yet it represents the most universal connection of microwave technology to the everyday life of people worldwide through the microwave oven. The technology of efficient low-cost microwave power sources has progressed not only to permit the economic feasibility of the microwave oven, but also a growing myriad of other commercial and industrial applications. The most successful of these is in the food industry for meat tempering and cooking—mostly of bacon. Other successful applications include plasma discharge devices for UV curing and lighting. In the future, applications to comfort heating of man and animals and various microwave power transmissions are foreseen. Problems of hazard perception and interference are now recognized as potential impediments to accelerated progress. The resolution of these problems requires cooperation between various parties, including the power application industries and the wireless communication industries. Another prerequisite for the realization of the vision by Kapitsa of primacy of power applications is the extension of efficient and economical power sources to a variety of operating frequencies and power levels. At the moment, only the magnetron qualifies as a candidate device for this task, despite its excess noise characteristics. It is in the device area, as well as new applications that surprises are sure to come, repeating the feature of surprise so evident in the history of this field to this point**

***Index Terms*—Cyclotron-wave converter, frequency allocation, industrial–scientific–medical, magnetron, microwave arcing, microwave dryer, microwave heating, microwave lighting, microwave oven, microwave plasma applications, microwave power applications, microwave power transmission, microwave torch, solar power satellite, spurious signals, stirrers, sulfur lamp, tempering.**

List of Acronyms

CD	Compact disc.
CDRH	Center for Devices and Radiological Health.
CENELEC	Comité Européen de Normalization Electro-technique.
CISPR	Comité International Special des Perturbations Radioélectrique.
COMAR	Committee on Man and Radiation.
CVD	Chemical vapor deposition.
CWC	Cyclotron-wave converter.
DoE	Department of Energy.
EMC	Electromagnetic compatibility.
FCC	Federal Communications Commission.
FDA	Food and Drug Administration.
ICES	International Committee on Electromagnetic Safety.
IEC	International Electrotechnical Commission.
IMPI	International Microwave Power Institute.
ISM	Industrial–scientific–medical.
JPL	Jet Propulsion Laboratory.
MBK	Multibeam klystron.
MPT	Microwave power transmission.
NASA	National Air and Space Administration.
PC	Personal computer.
RF	Radio frequency.
SA	Standards Association.
SPS	Solar power satellite.
U.K.	United Kingdom.
U. L.	Underwriters Laboratories.
UV	Ultraviolet.

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I. Scope and History

The practical uses of electromagnetic energy at microwave and radio frequencies have been almost exclusively in the category of processing of information or communication, e.g., broadcasting, communication radar, etc. Only in the last half-century has there arisen significant "power applications" in which microwave energy is used to interact with materials for some end benefit, e.g., microwave diathermy or microwave heating. Recognition of this use of the electromagnetic spectrum was slowly recognized [1] by authorities who regulate the use of the spectrum. These authorities, the FCC in the U.S., and the ITU worldwide, set aside specific bands of frequency, i.e., industrial–scientific-medical (ISM) for these uses. Allen and Garlan describe these actions as implementing a philosophy "to provide frequencies on which unlimited radiation would be permitted and to prescribe severe limitations on radiation on other frequencies." This was in recognition of the aspect of low cost and other factors inherent in economical ISM businesses. Furthermore, while power and efficiency are prime performance features, frequency stability is not and, indeed, could stifle low-cost applications and products. Thus, in Table I, which lists the primary ISM bands available today, we see that the bandwidths are significant, e.g., 100 MHz, or approximately 4% of the most-used ISM frequency in the world, i.e., 2.45 GHz.

Unlike previous papers [2], [3], in this paper, we include only applications involving power or energy transmission and the effects of such energy on materials. We deal with instrumentation

TABLE I
FREQUENCY ALLOCATION OF ISM APPLICATIONS

Frequency, MHz	Region	Conditions
6.765 – 6.795	worldwide	special authorization with CCIR[b] limits both in-band and out-of-band
13.553 – 13.567		
26.957 – 27.283	worldwide	free radiation bands
40.66 – 40.70		
433.05 – 434.79	selected countries in Region 1[c]	free radiation band
433.05 – 434.79	rest of Region 1[c]	special authorization with CCIR[b] limits
886 – 906	U. K. only	in-band limits
902 – 928	Region 2[d]	free radiation band
2.40 – 2.50 x 10^3	worldwide	free radiation band
5.725 – 5.875	worldwide	free radiation band
24.0 – 24.25	worldwide	free radiation band
61.0 – 61.5		special authorization with CCIR[b] limits
122 – 123	worldwide	both in-band and out-of-band
244 – 246		

[a] *Final Acts of the World Administrative Radio Conference*(1979)
[b] CCIR = "International Radio Consultative Committee" of the International Telecommunications Union (ITU)
[c] Region 1 comprises Europe and Parts of Asia; the selected countries are the Federal Republic of Germany, Austria, Liechtenstein, Portugal, Switzerland and Yugoslavia.
[d] Region 2 comprises the Western hemisphere.

applications only with regard to measurement of dielectric parameters of materials. The principal effect is heating and such applications have been previously reviewed [4].

An understanding of the interaction of microwaves with materials requires knowledge of the complex dielectric permittivity ε and rarely the complex permeability μ. The real part of ε, ε' is the dielectric constant that indicates the degree of slowing of microwave propagation in a material while the imaginary part ε'' indicates the degree of absorption or loss in the material. A wealth of information [5] exists on the values of ε for many materials across the microwave spectrum. Data, as a function of temperature in the open literature, however, is limited.

Almost all practical applications of microwave power to materials utilize the mechanism of heating. In some cases, at high-intensity levels, there exist controversies about a possible "non-thermal" effect. In general, only effects derived from heating have resulted in practical applications, even though there are verified field-force effects [6] and microwave/acoustic conversion effects [7]. At low field levels, at microwave frequencies, a critical review [8] suggests no plausible basis for a mechanism other than heating.

II. SOURCES OF MICROWAVE POWER

The key requirements for a power source used in power applications are efficiency, low cost, power, and reliability. Although not mentioned in recent papers [9] of vacuum electron devices (a.k.a. tubes), the most successful tube for power applications is the magnetron, a device thought to be on the verge of being obsolete by experts 40 years ago. Currently available magnetrons include the cooker magnetron for microwave ovens and its derivatives (300–3000 W) and the high power (25–100 kW and even more) magnetron at 915 MHz (or 896 MHz for the U.K.).

The cooker magnetron is the remarkable breakthrough that was key to the microwave-oven revolution. Its history has been reviewed [4]. The cooker magnetron typically provides approximately 800–1000 W into a matched load at 2.45 GHz with an efficiency of approximately 70%. It operates at 4 kV and 0.3-A average current (1.0-A peak) as driven typically by unfiltered doubler supplies. It weighs between 1–2 lb, employs inexpensive ferrite magnets, a simple filter box around electrode leads, and in large quantities, has a sales price of approximately $10.00. Suppliers exist in Japan, Korea, Thailand, Russia, and China. The estimated worldwide production of this magnetron and its derivatives is between 30–40 million tubes per year. This eclipses by far the production of any microwave device including other tubes [9]. It is used in consumer microwave ovens, commercial (for restaurants and institutions) microwave ovens, and for most of the industrial applications of microwaves.

The tube used in most practical industrial applications, in the food industry, is the magnetron described in a recent paper [10] of microwave heating systems in all areas—consumer, commercial, and industrial. In the laboratory, it is capable of over 90% efficiency and typically 85% in the field. It operates at 15–20 kV and 2-A to greater than 6-A anode current. It utilizes a large solenoid for the magnetic field, which draws several amperes current. The associated transmitter power supplies are mostly of the linear type that allows the tubes to be operated at a constant (dc) current, albeit with significant ripple of 10%–25%.

In 1975, during a period when technological forecasting was fashionable in the IEEE, a group of 50 experts predicted [11] by consensus that solid-state devices would replace the cooker magnetron by 1985 and that the "cold cathode" would be feasible by 1984. Both predictions failed dramatically. Later in 1995, in another paper [12], promising devices like solid state and the multiple-beam klystron (MBK) again were found to fail by a wide margin to match the performance of the cooker magnetron.

The properties of the cooker magnetron have been reported in detail [13]. It is emphasized that this device is now a unique standard device in modern technology, even though manufactured by different organizations around the world. There are three regions of anode current with correspondingly different noise properties of high random noise, discrete spurious signals, and low noise (quiet). The boundaries between these regions are remarkably reproducible and universal. Any modern computer model for crossed-field devices can be considered valid only if it first demonstrates an ability to predict the boundaries between these three regions of current.

The cooker magnetron is fairly well understood, but the 915-MHz industrial magnetrons still present more questions on the phenomena underlying mode boundaries and failure modes. Both the cooker and high-power magnetrons are capable of somewhat more efficiency, e.g., a few percent. Both are inherently narrow-band, except for the frequency variation achieved through pulling or pushing phenomena. There have been demonstrations [14] that the traveling-wave tube (TWT) could provide wide bandwidth at power of hundreds of watts and, thus, improve uniformity of heating. Unfortunately, the cost of TWTs and their more complicated associated power supplies inhibit their widespread use.

Upon reflection, one is struck by the unfortunately narrow family of magnetrons suitable for modern power applications. An inexpensive cooker magnetron exists only for powers at approximately 500–1000 W at 2.45 GHz. Economical high-power magnetrons, suitable for industrial application, exist only at 915 MHz, although some alternatives, e.g., 25 kW at 2.45 GHz, are in sight. There is a need for magnetrons at higher frequency, especially at the 5.8-GHz ISM band (cf. Table I). In addition, low-power (e.g., variable from 10 to 100 W) magnetrons at 2.45 GHz would find many uses until, and if, efficient low-cost solid-state devices are developed.

III. Microwave Oven

The microwave oven is the unequaled success in the field of microwave power applications. In 1964 [15], its success was not foreseen, and later even in 1987, its true history was not appreciated [16]. Since 1980, annual sales in the U.S. has fluctuated from 8 to 12 million ovens, mostly imports [17] Most of these ovens are countertop models with less than 1% incorporated into ranges and about 3% combining convection with microwaves. In the last decade, the proportion for over-the-range models has grown to approximately 20%. Prices in the U.S. range from less than $100 to over $500.

From data in trade publications,[1] a reasonable estimate for total world consumption is over 30 million ovens per year. The total number of consumer ovens in the U.S. is well over 100 million and the world total is estimated to be over 250 million.

[1]See issues of *Appliance Magazine* and other trade publications.

The characteristics and design features of existing microwave ovens are described in more detail elsewhere [4], [10], [18]. We note here a few of the continuing problems that could be mitigated with further engineering work. The first is uniformity. Even though a great variety of devices such as stirrers, rotating antennas, rotating tables, multiaperture feeds, and tray-level cyclers have been used, uniformity is never close to an acceptable degree when the wide variety of foods and food positions are considered. Arcing is a common phenomenon in microwave ovens and is usually harmless, except when it is one phase of overheating of food due to programming excessive heating time that leads to fires. The modern microwave oven incorporates suitable fire detectors that will shut off the oven and confine the fire inside the oven. Commercial ovens often utilize two or three tubes. The interaction between tubes and feeds still presents some significant design problems. The design of door seals and other means of leakage suppression are now quite effective with regard to leakage limits for safety considerations, but may need tightening to mitigate interference.

Much information, as well as misinformation about microwave ovens is available today on the Internet. Besides the website for the FDA Center for Devices and Radiological Health (CDRH), where information on regulations is available, educational material is available on a linked web site.[2] In addition, there are a multitude of other sites that present versions of the history, design and performance of microwave ovens. A number of these sites[3] describe the various arcing and discharge phenomena that can be provoked in an oven. One urban legend is not well treated in these popular circles, that of "superheating." This phenomenon occurs because of the appearance of internal hot spots of heating for a range of food shapes and sizes and *because of the programming of excessive heating time*. Although 50 years ago skeptics asked who would pay $500 for a hot-dog warmer, today, polls (e.g., by Gallup) have shown that the microwave oven is near the top in ratings of home appliances as appreciated by the public.

Although the market for commercial ovens is at best only a few percent of the market for consumer microwave ovens, there are some noteworthy distinctions. Whereas consumer ovens operate a few times per day with and accumulated operating time of a few minutes, in a commercial setting, ovens operate hundreds of times per day with accumulated operating time of many hours per day. Thus, it is clear that magnetron life is a serious consideration for commercial ovens, as well as a host of phenomena such as starting transients, spurious signals, and noise, as well as damage from "no-load" operation, etc. Some of these special design considerations are discussed in the literature [10].

IV. Industrial Applications

In 1965, leading thinkers within the IEEE did not foresee the microwave-oven explosion, but did believe in a steady expansion of an industrial market for microwave power tubes [15]. In fact, the impressive literature in this field supports that judgment

[2][Online]. Available: http://rabi.phys.virginia.edu/HTW/microwave_ovens.html

[3][Online]. Available: http://www.physics.ohio-state.edu/~maarten/microwave/microwave.html

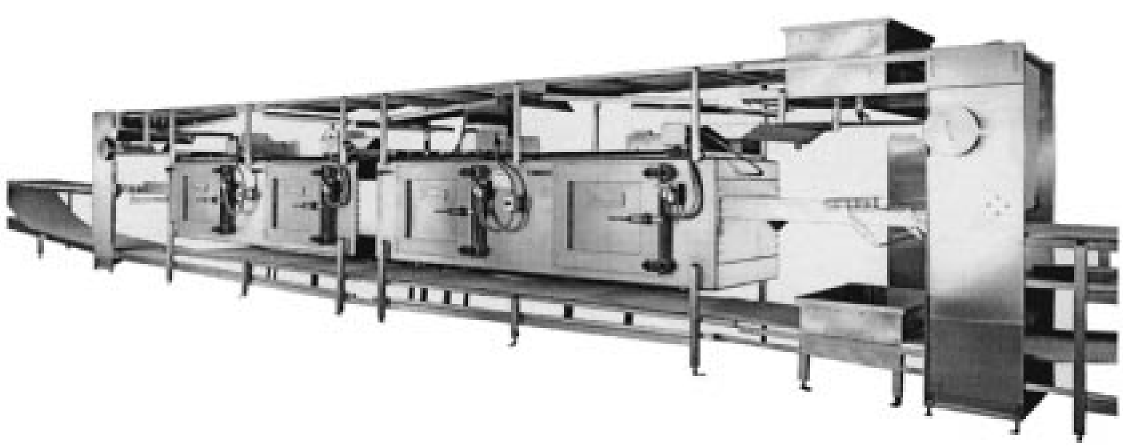

Fig. 1. Two-cavity QMP2103 industrial microwave oven—continuous cooking system. Microwave power at 915 MHz between 225–300 kW. Used for cooking of bacon and other foods (courtesy of Amana Appliances).

and yet the size of the market for industrial equipment has not met expectations [4], [10]. Still, at least in the food industry, the value of food product processed through microwave machines annually is estimated at tens of billions of dollars even though the market for equipment hovers around $100 million in the U.S.

As shown in recent papers [10], [19], [20] of the field, there are literally dozens of different subjects or areas of application of microwave power. In those papers and here, a detailed description of techniques is not possible for all subjects, no matter how interesting or promising. We address in more detail only those few application areas that have had significant economic impact. The reader should be aware that the primary literature in the field of microwave power applications is in the publications of the IMPI[4] with which the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) has had a long liaison relationship.

The basic design problem for microwave industrial heating systems is to couple energy from magnetrons efficiently and uniformly into a material load, whether food, ceramic, or plasma. In almost all cases, a ferrite circulator is utilized. The other main feature that distinguishes most industrial systems from the microwave oven case is the use of a conveyor, although some batch-process ovens do exist in industries. The conveyor passes through "suppression tunnels" at each end of an industrial cavity, which may be each fed by one or two magnetrons. A complete conveyor system may contain as many as five cavities. An example of such a system is shown in Fig. 1. In this case, there are two cavities each of which has two feeds and two doors. The system operates at 915 MHz as a bacon cooker. In the case of small-height tunnels, a multipin choke structure is feasible. For large tunnels that permit passage of large boxes, as in a tempering machine, absorbing walls (with circulating liquids) are required. A well-known design handbook for microwave power machines is that by Metaxas *et al.* [21]. More recent handbooks [22], [23] also exist. A brief review of the design process is presented in [10]. Sometimes various energy sources are combined. An overview [24] of this broader field, called "electroheat," points to the broader design procedures, as well as the much greater market than with microwave alone.

Although difficult to estimate, especially worldwide, the industrial market is of the order of $100 million or more likely between $100–$200 million. The major markets are in the food industry, mostly at 915 MHz, the use of ultraviolet lamps at 2.45 GHz for curing, and perhaps a remaining third of the market divided into many small markets.

A. Food Processing

At present, the leading type of marketable industrial microwave heating equipment is that for bacon cookers. A simple two-cavity version is shown in Fig. 1. Most systems in the field may have four or five cavities. The installed power of a system is typically between 400–600 kW at 915 MHz or 896 MHz in the U.K. (cf. Table I). There are approximately 50 such systems installed in the world. Since each system has a throughput of about 60 000 slices per hour, one can calculate that the worldwide output of cooked bacon in these machines is approximately 400 million pounds (input) or 12.1 billion slices (output) annually [10]. In addition, there is an estimated rendered fat from these machines of approximately 240 million pounds annually, which is collected for sale and reuse. Most of this product is for the restaurant and institutional market, with obvious advantages compared to cooking on site.

One can see from Fig. 1 that a rectangular guide is used between transmitters and cavities. In most systems, either a rotating antenna ("rotawave") or rotating three-port "Radaring" is employed to feed the microwave energy into the cavities, which are typically 12 ft in length and accommodate a 3-ft-wide conveyor belt. The doors, as in most industrial heating apparatus, contain a two section slotted-choke door seal [25].

The earliest successful application was that of tempering, and now over 300 such systems exist throughout the world. The operating powers vary from 50 to over 150 kW at 915 (896) MHz. A typical one-cavity tempering system is shown in Fig. 2. Tempering of frozen meats involves raising the temperature from approximately 0° to approximately 27° to permit further mechanical processing such as slicing, dicing, grinding, pressing, and molding of the product, which may be hamburger, sausage,

[4]International Microwave Power Institute (IMPI), Manassas, VA, publisher of the *Journal of Microwave Power and Electromagnetic Energy*, *Microwave World*, and the proceedings of annual microwave power symposia.

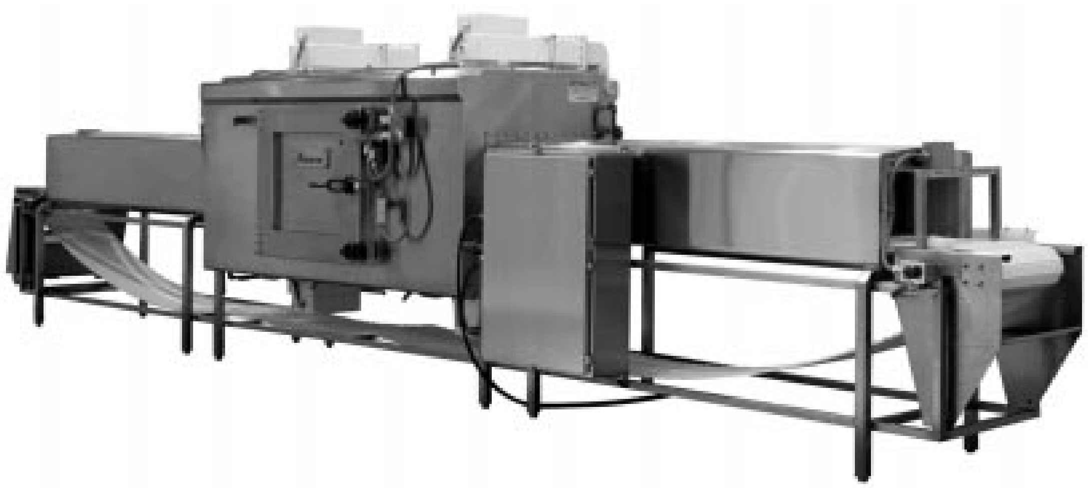

Fig. 2. One-cavity QMP1679 industrial microwave oven—continuous tempering tunnel system. Microwave power of 75 kW at 915 MHz (courtesy of Amana Appliances).

canned meat, fish, etc. It is estimated [10] that over 4 billion pounds of such products are tempered annually. Since the microwave tempering is fast, it permits minimum exposure of food product to room temperature. One can infer that a large part of the meat products in the supermarket have been processed through such machines.

The technical design of such machines is similar to the bacon cookers, but with the challenge of achieving a uniform heating without significant thawing. If the latter then occurs because of the great increase [4] in ε'' of water and goods at the freezing point 0 °C or 32°, there is the danger of thermal runaway with portions of the product cooked while most of the product is still frozen.

From Fig. 2, we can see that the size (e.g., 1-ft height) of the suppression tunnels is much greater than for the bacon-cooker machines. This then requires the incorporation of lossy walls in the tunnel, using a mixture of water and glycol for optimum transmission loss along the tunnel. In industrial machines, the leakage is typically maintained at the levels specified by the U.S. FDA (CDRH) for microwave ovens [4].

There are other industrial applications in the food industry, but of lesser scope. One noteworthy example is that of the processing of potato chips [10], [19]. In this case, there is the problem of light loading, which could lead to inefficiency and arcing. In addition, hot air is used to remove the moisture liberated by the microwave energy. Sometimes, the serpentine waveguide applicator [4], [10] is used instead of the multimode cavity for better coupling to the raw chip.

There are many other food applications, but few, if any, have shown the widespread economic potential described in the above applications. Microwave heating has been applied to inhibition of mold growth, conditioning of wheat, baking, poultry cooking, sherry making, chewing gum manufacture, pasteurization of beer, and other uses [19]. It should be noted that technical success does not insure practical economic success. The *Journal of Microwave Power* records many such case studies. Unfortunately, exhaustive studies [26] show no promise in controlling insects and pests in agriculture, at least if the only mechanism of interaction is heating and with practically available power sources.

We note that, in general, microwave processing appears attractive because of speed of internal heating and because of efficiency. Most high-power uses are explored at 915 MHz. Many other of the explored applications were at 2.45 GHz with less power, usually below 100 kW. Although we feature the role of conveyor machines here, in practice, there are many batch-process machines without conveyor belts.

B. Microwave Plasma Applications

This is an application area of significant economic value in industry and of promise for the future, but the related technical and scientific literature is sparse and the patent literature is considerable. One of the earliest studies was on microwave surface-wave plasmas or a microwave torch [27]. A more relevant study was that of a "cavity-operated electrodeless high-pressure microwave discharge system" [28]. In this study, a cylindrical mercury discharge tube is aligned along the center of a cavity operating in the TM_{010} mode. Although this paper does not directly relate to practical applications, it is relevant to a very successful line of microwave discharge lamps [29] used for curing in industry through its efficient production of ultraviolet light with less infrared and heating than with conventional UV sources. The lamps utilize magnetrons derived from the cooker magnetron, at power of 2–3 kW, and the simple power supplies developed for microwave ovens. One can see that the lamps must start repetitively as microwave power is applied cyclically (50/60 Hz) when the cavity is a lightly loaded cavity of many resonances and then evolve to an efficient discharge state at full power when the discharge effectively damps the significant resonances. In addition, often two magnetrons are used and interaction effects are avoided by separating the magnetron frequencies by approximately 25 MHz. The annual market for these microwave lamp UV curing systems (conveyorized) is believed to be over \$50 million and possibly over \$100 million. Companies in the U.S., currently involved as manufacturers, include Fusion UV Inc., Gaithersburg, and the Nordson Corporation, Westlake, OH.

A related product is the "sulfur lamp" used for lighting applications. The microwave discharge in a quartz bulb of gases including those from the heating of a pellet of sulfur can produce light resembling that from the sun with high efficiency [30]. They are found to be more efficient than any other lamp, including metal halide lamps. The microwave lamp when driven by kilowatts of microwave power at 2.45 GHz produces intense light, which is transmitted by a reflector through fine mesh screens to long (e.g., 240 ft) plastic pipes that act to distribute the light uniformly into a large space. Such light sources, with support of the U.S. Energy Department, are in use at the National Air and Space Museum and the Forrestal building, Washington, DC. [31], [32]. These lamps are being investigated around the world and are very promising, at least for outdoor lighting and lighting in large buildings. At the moment, the only known manufacturer is Fusion Lighting, Rockville, MD, a spinoff from Fusion Systems (now Fusion UV).

Another successful plasma application is the production of diamond coatings through chemical vapor deposition (CVD) occurring in a microwave plasma in appropriate gases [33].

C. Other Applications

Dozens of different applications of microwave heating exist to a small degree or have come and gone, usually for economic reasons. In the latter category are the tempering, vulcanizing, or preheating of rubber or rubber tires [10], [19]. As many as 200 installations in this category were deployed. They were notable for the use of a few tens of cooker magnetrons all independently coupling to a large multimode cavity at 2.45 GHz. It was reported that effects (e.g., locking) due to tube-to-tube interaction were minimal and that data on tube life showed values in the thousands of hours. Similar systems at 2.45 GHz (about 20) were used for drying of sand cores in foundries.

One application that has triggered hundreds of papers is that of ceramics processing. In a plenary address [34] Prof. Rustum Roy, Pennsylvania State University, University Park, recalled the birth of that field after incidentally observing the runaway heating of a ceramic like alumina in a microwave oven. (Melted spots in alumina trays in microwave ovens have been observed in commercial ovens, after significant use in the field.) This is surprising since alumina is considered a relatively low-loss microwave material. Since then, various processes on ceramics have been demonstrated, including sintering and synthesis of ceramics. Most of the papers on processing of materials including ceramics have appeared in the publications of the American Ceramics Society and the Materials Research Society. In many of these studies, power sources other than magnetrons have been used including high-power TWTs, klystrons, and gyrotrons. Despite many impressive results, for some reason, a large economic impact has not yet been achieved in the industries for materials processing, the support of utilities not withstanding [35].

In the field of chemistry, there is a large literature on microwave-enhanced chemical reactions. In the trade literature, one can find microwave ovens modified for use in chemical reaction studies. A key accessory is a dielectric container called a “bomb” in which the reactants are placed and closed to withstand high pressures under microwave heating. Here again, while there are hundreds of papers in the literature, large industrial applications for microwave power seem not to have been realized. However, the value of such modified ovens as analytical tools is acknowledged. In fact a sizable market for ovens modified to perform a variety of analytical procedures and moisture and solids analysis exists [36], [37]. Although information in fields of pasteurization, sterilization, and pharmaceutical drying is sparse, it is believed [34] that there are a few dozens of industrial installations in this field. In addition, there are significant accomplishments in tissue fixation, as well as warming of physiological fluids [38].

Both in the fields of ceramics and chemistry there are claims of a nonthermal effect, of course, at high levels of heating. In chemistry, it has been shown [39], however, that the evidence is not there for a nonthermal effect.

A wide variety of successful drying applications have been recorded [19], [20] with products like pasta, wood, plastics, textiles, and in Japan, the drying of green-tea leaf before roasting [10]. Considerable work [40] has shown the technical feasibility of microwave clothes dryers for commercial or consumer markets. One obstacle is the potential problem of arcing around metallic objects in clothes and subsequent potential damage to clothes or beyond through fires. In the U.S., with its proactive liability trial lawyers, it is unlikely the clothes dryer will come to market until a solution is found.

There is considerable work on waste remediation of all type through microwave heating, including human waste [19], [20]. Practical feasibility, however, is evidently still to be sought.

Futuristic applications on which little experimental work, but some analysis has been done, include the comfort heating of humans and animals following the proposal [41] of Pound, recovery of oil shale [42], and weather modification. In the latter area, many years ago, the protection of plants by microwave heating against frost was demonstrated [43]. Although economically unfeasible today, in the distant future, where microwave beams for power transmission from satellites exist, one can revisit the feasibility of area heating and the proposal [44] to use high-power microwave beams to suppress the development of tornadoes.

V. Microwave Power Transmission

Serious consideration for a role of microwaves for power transmission began after the demonstration [45] in the early 1960s by W. C. Brown of the Raytheon Company, Waltham and Burlington, MA, and recipient of awards like the Pioneer medal from the IEEE MTT-S, that conversion from ac power to microwave power could be done with efficiency of approximately 90% (at least at frequencies below 3 GHz). He also showed that microwaves could be converted to dc or ac electricity with an efficiency of close to 90%. For this, he invented an array of solid-state rectifying diodes, called a rectenna, that could act as antenna and rectifier of an intercepted radiated microwave beam. Shortly thereafter, Dunn and colleagues at Stanford University, Stanford, CA, conducted a theoretical study [46], [47] that showed the potential feasibility of transmitting gigawatts of microwave power in metal pipes of a few feet in diameter. This assumed that mode conversion from the low-loss TE_{01} mode in a cylindrical guide, despite bends, etc., could be minimized to achieve a loss of only 1 dB in pipe lengths of more than 100 mi.

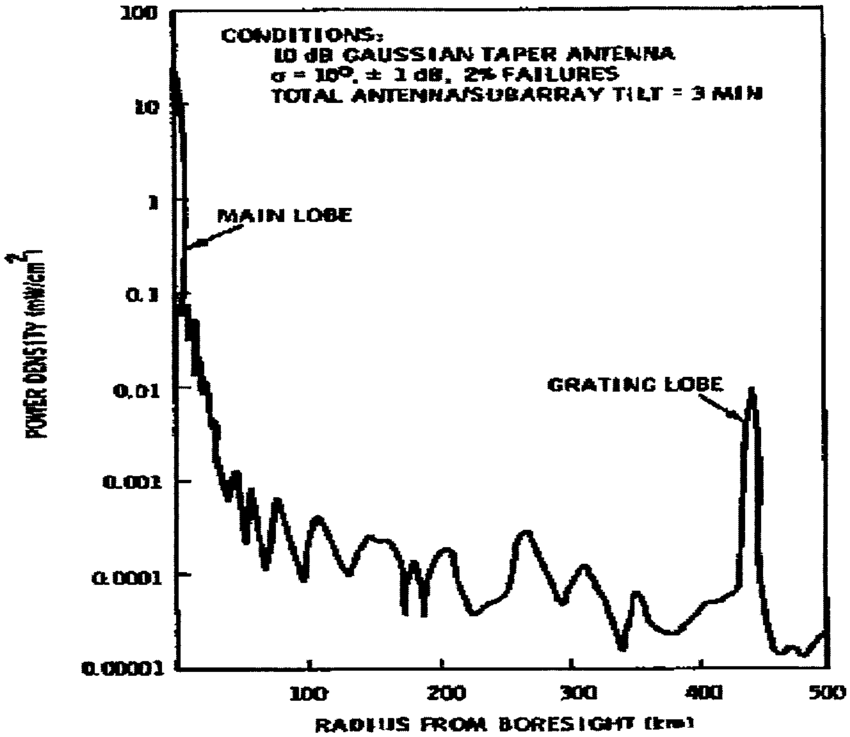

Fig. 3. Peak power density for SPS sidelobes and grating lobe as a function of distance from rectenna (from [51]).

Rough estimates of an economical metallized plastic pipe construction were also done. At that time, however, practical considerations did not allow this proposal to proceed any further. (It is interesting to note that Brown and others formed IMPI after it was perceived that the IEEE [48] was not receptive to holding interdisciplinary meetings on use of microwaves in a variety of professions and industries.)

This alternative of using the efficient power transmission by a microwave beam was developed with a credible amount of laboratory verification of performance [49] by Brown. He demonstrated in the laboratory a dc to dc efficiency of 54% using a transmitted microwave beam. At the JPL Goldstone facility in the Mojave desert, with NASA support, 30 kW of microwave power was transmitted over a 1-mi distance and converted to dc at an efficiency of 84%.

Also in the 1960s, Glaser [50] conceived of the idea of a solar power satellite held at geosynchronous orbit in which electricity generated from solar cells would be somehow beamed to earth for use. After the ideas of Brown and Glaser were merged, there ensued a very large study program under the auspices of the DoE on the feasibility of a "reference system." This was designed for the transmission of 5 GW of power at 2.45 GHz from klystrons in the satellite. The study resulted in many papers and extensive documentation [51]. All aspects of the project were investigated and, in the end, economic doubts were the main reason for the cessation of further work under auspices of the U.S. government. A perceived risk of exposure to microwave energy appeared to be a serious obstacle to public acceptance. In the last decade, it was judged [52] that the microwave exposure problem was one of perception, but the problem of potential interference was serious. However, a recent paper [53] on the environmental safety issues involving exposure to microwaves for the SPS was done with more attention to effects on species other than man. In Fig. 3, we show the expected level of microwave power density on the earth as a function of distance from the rectenna site for a reference system. Generally, the levels are far below 1 μW/cm^2. Since most safety standards for humans specify limits of the order of 1000 μW/cm^2, it is felt that eventually people would accept such microwave energy as benign, and comparable or less than is present in the vicinity of broadcast towers. The power densities over the rectenna sites would be around 25 000 μW/cm^2 or 25 mW/cm^2 and a potential problem for some birds, but not serious since they could easily escape from the site. Furthermore, recent studies of human exposure [54] have shown that man can tolerate easily such exposure at least for periods of an hour or so at moderate environmental temperatures.

Over the last two decades, there has been an enormous amount of work around the world, particularly in Japan, Russia, France, Canada, and Germany on various derivatives of the SPS concept—at lower powers, different satellite orbits, different frequencies, as well as some earthbound projects for microwave power transmission (MPT). This work was recorded in a recent book [55]. Work in the U.S. has continued at universities in Texas and Alaska and in the new NASA project "A Fresh Look" [56]. NASA has appeared to shift its favored frequency from 2.45 to 5.8 GHz, particularly to minimize potential interference with the expanding wireless communications in the 2.45-GHz band. NASA also is looking to solid-state sources for powering the 5.8-GHz satellite.

In the last decade, as fears of global warming intensified and appreciation of limits on oil resources grew, sentiment for alternative sources of energy has grown. In the utility community, a renewed interest in the SPS appeared [57] in the year 2000.

More recently, an opening plenary session at an international symposium [58] in Japan was devoted to the Solar Power Satellite and MPT. The role of Japan as the leader in this field was eloquently described by Matsumoto of Kyoto University, Kyoto, Japan,[5] in his plenary address. This was supplemented by other papers, a live demonstration of power transmission at 5.8 GHz, and a CD on the experiments and goals in Japan. Experiments with power transmission to a balloon and flying model airplane were described. The commitment of the Japanese government to deploy some type of SPS by 2040 was announced. In the interim, there is a project SPS-2000 to transmit microwave power from a satellite in equatorial Earth orbit to several rectenna sites on earth. The power goal was initially 10 MW, but it appears now to be scaled back to 100 kW. Contributing to the preparations [58] for this MPT experiment are Hashimoto and Shinohara of Kyoto University, as well as work at the Mitsubishi Electric Corporation and Matshushita Corporation. The French also have a project, based in Reunion island in the Indian Ocean, to transmit a modest amount of microwave power across 700 m in an ecologically sensitive valley to a remote resort. There is also a report that the Matsushita Corporation will develop a magnetron at several hundred watts power at 5.8 GHz, with a goal of at least 70% efficiency.

In Russia, there has been much work on the SPS, including many systems studies [55]. In the area of MPT and the microwave technology required for the SPS, the group under Vanke of Moscow State University, Moscow, Russia, has reported many advances in system design, antenna design, and design of microwave components [59], [60]. More recently, they have reported development of a cyclotron-wave converter (CWC) tube [61] and its application to MPT/SPS projects [62], the latter work in collaboration with the group at Kyoto University. In application to MPT, it is planned to focus incoming microwave beams through "concentrators" onto a slotted waveguide array, which then would transmit the energy to the CWC tube. Various experimental results have been reported at powers over 100 W and efficiencies of over 50%. The best results are said to range to 83% efficiency (RF to dc) obtained at the Istok Tube Company, with power of the order of 10 kW and an output dc voltage of 15–20 kV.

It should be remembered that, in this paper, we are addressing only the approaches to an SPS that rely on MPT, i.e., transmission at microwave frequencies. Other proposals exist that would rely either on millimeter-wave beams or even laser beams. An overview comparing the potential of beams across the spectrum was published 20 years ago [63].

VI. Computer-Aided Design

The exploitation of the revolution in computer power has affected all of microwave design and microwave power applications as well, albeit more slowly. The work of Taflove [64] and others helped usher in computer modeling in most areas of microwave design. When a complicated system, like an eight-dipole array for hyperthermia is studied [65], however, anomalous results such as "mode flipping" without transition to a steady state are obtained. Although this could be interpreted as real "physical" phenomena, it is more likely a hint of the limits of the computation model in simulating a complicated system, We note that traditionally design of microwave heating systems [4], [10], [19] is done in large measure by empirical means, including the incorporation of a mechanical "stirrer" or other means of randomizing the instantaneous heating patterns so as to achieve a suitable average and avoid instantaneous patterns that feature hot and cold spots in general. Especially for cases of light loading, the designer of microwave heating systems invariably experiences an aspect of unreproducible results or a "chaos." For similar reasons, the designer of reverberation chambers [66] continue to seek improved methods of "stirring," e.g., by frequency variation instead of mechanical stirrers.

For study of small or simple cavities, conventional modeling [67] is adequate. For multimode (i.e., large) cavities and absorbing loads, the problem is more involved.

Risman, with a modern PC and available software, has obtained impressive results [68] for heating patterns in loads of simple geometry in a microwave oven fed at a single point with no stirring. He believes that this design tool could make viable applicators for industrial use [69]–[71] that employ no variable elements like stirrers. In a similar manner, Reader and colleagues with a PC and a Mathlab routine have succeeded [72] in modeling a variety of simple geometry loads in an oven, again without a stirrer. Both Risman and Reader and colleagues have also used various experimental techniques to confirm theoretical patterns.

A wider array of problems is being modeled [73], [74] by Metaxas and colleagues at Cambridge University, Cambridge, U.K. Industrial systems at both RF and microwave frequencies are being modeled as well as the microwave oven with fairly complicated simulated foods and with several feeds. In order to model a microwave oven with a stirrer, a network of workstations or a supercomputer is required [75]. The computed field patterns on a load surface show fair resemblance to experimental results from an infrared camera. Finally, the Metaxas group is studying [76] corona development at RF frequencies. This is an important precursor to a very important subject, i.e., that of arcing, especially of foods, in microwave ovens and industrial systems.

I note that one involved in development of computer modeling, in a recent review [77], concludes that, in the design of an optimum applicator for microwave heating, there remains an irreducible degree of art.

It is clear that, in this millennium, there will be very great strides through computer modeling of microwave heating systems. It remains to be seen if the modeling can completely capture the "chaotic" nature of heating in many cases of light loads or whether there are more fundamental considerations. (Note that physicists who study quantum chaos [78] use a variety of microwave cavities as an analogue tool.)

VII. Frequency Allocation and EMC Issues

It was pointed out above that over 50 years ago the international authorities allocated the ISM bands to encourage power applications. Only IMPI has, on behalf of the small power appli-

[5]The extensive work Kyoto University can be viewed online. [Online]. Available: http://www.kurasc.kyoto-u.ac.jp/plasma-group/index.html

cation community, fought to protect existing bands for ISM, including those set aside for the future—i.e., the millimeter-wave bands for which inexpensive power sources remain to be developed.

There is a critical need for clarifying the appropriate band for MPT and the SPS. In the past, it was assumed the ideal frequency was 2.45 GHz, but SPS supporters [55], especially in the U.S., believe that band may be lost for SPS because of the growing use of that band by wireless groups, e.g., Bluetooth. Frequency allocation is a key policy issue [79] for the SPS. It is clear that supporters of the SPS must supply information [80] to various national bodies that will make recommendations to the ITU at the next WARC.

In the last decade, the CISPR/B Committee of the IEC issued new limits [81] on out-of-band emissions (for frequencies above 1 GHz) from domestic ISM equipment, which operate above 400 MHz. This means microwave ovens and microwave lights, which use magnetrons operating at 2.45 GHz. These are stringent on an "average basis"—i.e., 60 dB $(\mu\text{V/m})$ at 3 m with a video bandwidth of 10 Hz and a standard load of 1000 ml of water. The allowed peak value is 92 dB $(\mu\text{V/m})$ at most frequencies, but it is tightened between 11.7–12.7 GHz to 73 dB $(\mu\text{V/m})$ and relaxed to 110 dB $(\mu\text{V/m})$ between 2.3–2.4 GHz.

Although most microwave ovens and lights (and UV sources) can meet these limits they may be objectionable to operators of satellite broadcast (audio) at frequencies between 2.3–2.4 GHz.

There are no in-band limits, except for safety reasons by the FDA or IEC. Since wireless groups are beginning to utilize the 2.45-GHz band, there are appearing interference incidents even though theorists had predicted immunity for wireless operating with spread-spectrum and digital techniques. The result is a debate between ISM interests and wireless interests [82], [83]. The FCC is being pressured in some cases to impose more stringent limits on ISM source emission both in-band and out-of-band.

In Fig. 4, we show a typical waveform of a spurious out-of-band signal from equipment using the cooker magnetron. We see that, per the characteristics described in [13], the spurious signals exist only at low current and, hence, occur as short (e.g., 1 ms) pulses twice during one cycle (50/60 Hz). The in-band signals from most microwave-oven equipment occur only during half of the 50/60-Hz period because of the use of a half-wave doubler voltage supply.

If one notes the finite duty cycle of such signals from most ISM equipments operating at 2.45 GHz, there is some opportunity for mitigation of the interference problem through time sharing—or multiplexing. It may be that such a principle may be of value in the design of many power applications including that for MPT and SPS. In the meantime, even though the ISM equipment is the "radiator" and wireless the "victim," the public must be educated on the prior rights of equipment, and that fault does not always lie with the "radiator."

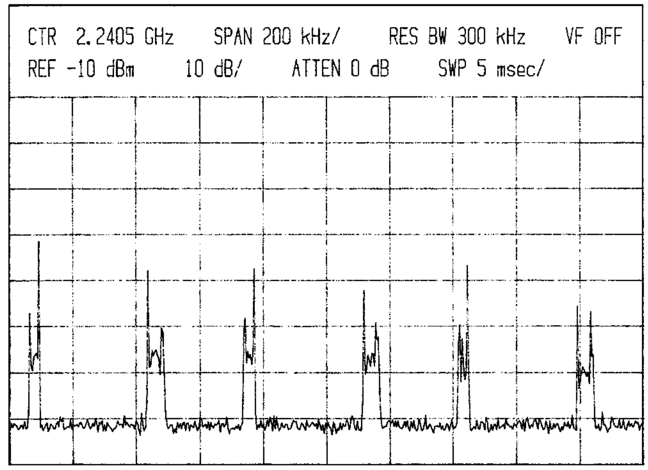

Fig. 4. Waveform of a typical spurious (sideband) signal from a consumer microwave oven.

VIII. Impact of Microwave Safety Issues on Microwave Power Applications

It is a fact that many power applications, especially those of MPT and SPS, in large part have been prohibited or delayed because of irrational fears of "microwaves" [84]. The antidote is the development of rational standards developed through broad consensus with adherence to due process as required by the IEEE Standards Association (SA). The vehicle for this is the newly formed International Committee on Electromagnetic Safety (ICES).[6] Through its activities there is hope that international harmonization [85] of standards will eventually be achieved. In addition, public education as through IEEE-COMAR[7] [86] needs to be strengthened and continued.

There is reason to believe the recent terrorism crisis will act to trigger a return to rational weighing of risks and benefits. Thus, people are now more willing to allow higher magnetic fields from weapons detector devices if that increases the reliability of antiterrorist measures.

Finally, more rational assessment of microwaves by everybody will help spur further development of microwave power applications including MPT and the SPS.

IX. Future Outlook and Conclusions

Over the last 50 years, the microwave oven was an unexpected success, while other predictions did not materialize, e.g., the replacement of the magnetron by solid state. What will happen in the following 50 years relative to microwave power applications? My predictions are as follows.

- New magnetrons will be developed at 5.8 GHz and elsewhere and this will stimulate new applications.
- Solid-state sources will be developed for applications requiring less than 100 W and low weight, especially for the professional markets, e.g., MDs.
- The microwave dryer will become a success both for consumer and commercial markets, after the problem of arcing is solved by novel means.
- Novel means will be developed for modulation of magnetron-like devices broadening the scope of microwave power applications.

[6]Comprising IEEE Standards Coordinating Committee–28 (SCC-28) and five subcommittees; for development of safety standards for the use of electromagnetic energy between 0–300 GHz; IEEE Standards activities. [Online]. Available: http://grouper.IEEE.org/groups/scc28

[7][Online]. Available: http://homepage.seas.upenn.edu/~kfoster/comar.html

- Computer modeling will be refined for all microwave power systems with a resolution of the "chaos" paradox for lightly loaded multimode cavities.
- A prototype SPS will be deployed by Japan at a power above 0.01 GW.
- Development of the SPS and associated MPT will trigger renewed interest in power transmission through buried waveguides, perhaps utilizing breakthroughs in superconductivity.
- Enough of these predictions will come to pass so that the vision of Kapitsa (in [59]) becomes believable:

"It is worth noting that, before electrical engineering was pressed into service by power engineering, it was almost exclusively occupied with electrical communication problems (telegraphy, signaling, and so on). It is very probable that history will repeat itself. At present, electronics are used mainly in radio communication, but its future lies in solving major problems in power engineering."

Finally, even if only part of this vision becomes real, the field of microwave power applications will no longer be considered a "niche" application among microwave engineers.

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