work optimization," *IEEE Trans. Microwave Theory Tech.* (*1973 Symposium Issue*), vol. MTT-21, pp. 815–818, Dec. 1973.
[13] Y. Ishizaki and H. Watanabe, "An iterative Chebyshev approximation method for network design," *IEEE Trans. Circuit Theory* (*Special Issue on Modern Filter Design*), vol. CT-15, pp. 326–336, Dec. 1968.
[14] R. Fletcher, "A new approach to variable metric algorithms," *Comput. J.*, vol. 13, pp. 317–322, Aug. 1970.
[15] M. R. Osborne and G. A. Watson, "An algorithm for minimax approximation in the non-linear case," *Comput. J.*, vol. 12, pp. 63–68, Feb. 1969.
[16] K. Madsen, H. Schjær-Jacobsen, and J. Voldby, "Automated minimax design of networks," *IEEE Trans. Circuits Syst.*, vol. CAS-22, pp. 791–796, Oct. 1975.
[17] C. G. Broyden, "A class of methods for solving non-linear simultaneous equations," *Math. Comput.*, vol. 19, pp. 577–593, 1965.
[18] M. J. D. Powell, "A Fortran subroutine for unconstrained minimization, requiring first derivatives of the objective functions," AERE, Harwell, Oxon., England, Rep. R 6469, pp. 1–43, July 1970.
[19] ——, "The minimax solution of linear equations subject to bounds on the variables," AERE, Harwell, Oxon., England, Rep. C.S.S. 11, Dec. 1974.
[20] K. Madsen, "Minimax solution of non-linear equations without calculating derivatives," in *Mathematical Programming, Studies No. 3*, P. Wolfe and M. Balinski, Ed. to be published.
[21] K. K. Pang, "Design of microwave filters by sine-plane approach," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 607–611, Oct. 1973.
[22] C. L. Upadhyayula and B. S. Perlman, "Design and performance of transferred electron amplifiers using distributed equalizer networks," *IEEE J. Solid-State Circuits* (*Special Issue on Microwave Integrated Circuits*), vol. SC-8, pp. 29–36, Feb. 1973.
[23] R. W. Paglione and B. S. Perlman, "Computerized design of M/W devices," *Microwave J.*, vol. 16, pp. 23–28, Aug. 1973.
[24] B. S. Perlman and V. G. Gelnovatch, "Computer aided design, simulation and optimization," in *Advances in Microwaves*, vol. 8. New York: Academic, 1974, pp. 321–399.
[25] E. Hammershaimb, P. Jeppesen, and H. Schjær-Jacobsen, "Computer-aided design of broad band reflection type amplifiers," *Int. J. Circuit Theory Appl.*, vol. 2, pp. 261–268, Sept. 1974.
[26] J. R. Whinnery, H. W. Jamieson, and T. E. Robbins, "Coaxial-line discontinuities," *Proc. IRE*, vol. 32, pp. 695–709, Nov. 1944.
[27] P. I. Somlo, "The computation of coaxial line step capacitances," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-15, pp. 48–53, Jan. 1967.
[28] S. H. Izadpanah, B. Jeppsson, P. Jeppesen, and P. Jøndrup, "Stable amplification and high current drop bistable switching in supercritical GaAs TEDs," in *Proc. 4th European Microwave Conf.* (Montreux, Switzerland), Sept. 10–13, 1974, pp. 242–246.

Microwave Effect on Rabbit Superior Cervical Ganglion

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***Abstract*—Rabbit superior cervical ganglia were exposed to CW 2450-MHz fields within a temperature-controlled waveguide environment. Absorbed power densities between 2 and 1000 W/kg failed to significantly influence transmission latencies of responses recorded from postganglionic fibers due to stimulation of either *B* (myelinated) or *C* (unmyelinated) fibers in the preganglionic trunk.**

INTRODUCTION

THERE have been numerous reports on the effects of microwave radiation on the central nervous system (CNS). This can be significant since the nervous system processes the multitudinous information coming in from the periphery and determines the signals to be transmitted back to the different parts of the body to initiate various motor activities. Unfortunately, many of these reports have suffered from a lack of procedural details which make the evaluation of the purported findings difficult [1] and others have based their findings on nonspecific changes which only implicate nervous system involvement.

Previous work in this laboratory has shown that during controlled irradiation of the heads of cats, shifts in the latencies and amplitudes of evoked thalamic responses can occur [2]–[4]. However, these changes were evident only in cases where the incident microwave power was sufficient to induce an increase in the thalamic temperatures. Subsequent experimentation with conduction heating via fluid circulating heat exchanges implanted at the base of the skull also corroborated the preceding observations [5]. The complexity of the thalamic preparation, however, seriously limits the interpretation of the observed phenomenon in terms of precise neural involvement. Consequently, a study was initiated where isolated mammalian and amphibian nerves were irradiated *in vitro* in a Ringer's filled waveguide environment. It was found [6] that the conduction characteristics of these peripheral nerves were not affected by microwave radiation if care was taken to control the temperature surrounding the nervous tissue during microwave exposure. The isolated peripheral nerve functions only as a neural transmission line, however, and these studies do not reveal the sig-

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nificance of nervous system and microwave interaction at more complicated levels of function. There is therefore a need for similar experimental investigations where precisely known doses of microwave radiation are applied to the nervous tissues of higher complexity, i.e., nervous tissue containing synaptic connections.

The superior cervical ganglion of the rabbit (see Fig. 1) was therefore selected for excision and exposure to microwaves within a temperature-controlled waveguide environment. Although the superior cervical ganglion is clearly not as complex in organization as the CNS itself, the use of this peripheral autonomic ganglion was considered a good next logical step after the previous peripheral nerve study. The preganglionic nerves (cervical sympathetic trunk in this case) form integrating synaptic connections of both excitatory and inhibitory types within this ganglion [7]–[9]. The neural outputs of this ganglion serve autonomic nervous system functions related to cardiac acceleration, vasoconstriction, and secretion in the salivary glands, and pupillary dilation and vasoconstriction in the eye. This ganglion has been well studied by physiologists (references in the preceding) and pharmacologists [10], and is known to have synaptic systems utilizing both acetylcholine and catecholamines as transmitting agents.

EXPERIMENTS

A silver-plated S-band WR284 waveguide flushed with 1 l/min of temperature-controlled mammalian Ringer's solution served as the exposure environment. The Ringer's was composed of 3.5-mM KCl, 3.9-mM $CaCl_2$, 15.7-mM $NaHCO_3$, 138.3-mM NaCl, and 8.7-mM glucose and was equilibrated with 95-percent O_2–5-percent CO_2. Fig. 2 depicts the ganglion stretched across the waveguide between a set of stimulating electrodes on the preganglionic side (outside the waveguide) and a suction electrode on the other (with a glass capillary projecting into the waveguide to make contact with the postganglionic nerve inside the waveguide). Right and left superior cervical ganglia were removed from 3- to 6-kg New Zealand white rabbits under urethane anesthesia (1500 mg/kg). The postganglionic nerve (internal carotid) was difficult to dissect out with a length of more than a few millimeters. Thus it was necessary to project the capillary tube of the suction electrode

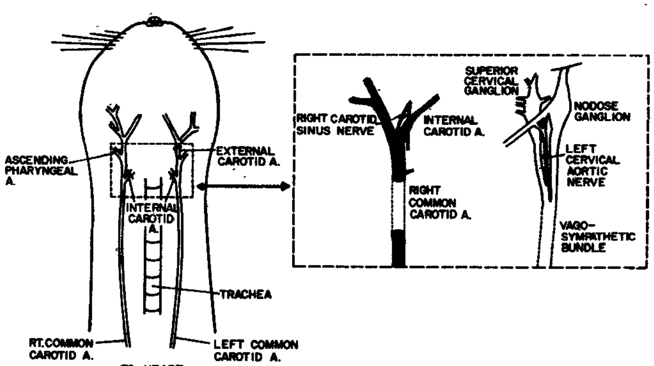

Fig. 1. Appearance and location of rabbit superior cervical ganglion.

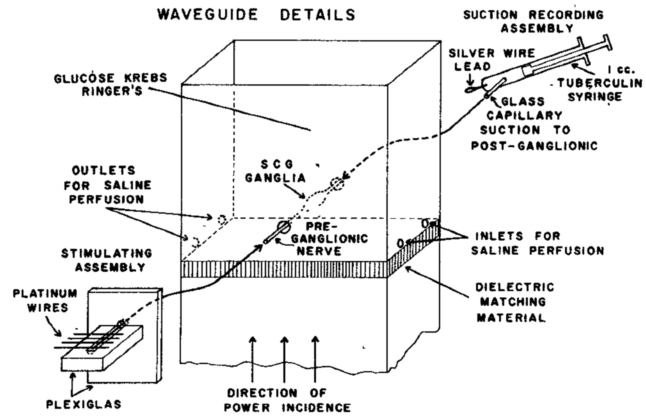

Fig. 2. Waveguide exposure facility for isolated superior cervical ganglion preparation showing the stimulating and recording assemblies on either side.

into the guide so as to leave the ganglion in the center of the microwave fields.

Although silver ions are extremely toxic to nerve tissue, the use of a silver-plated waveguide chamber is not a concern in the present experiment since an examination of a table of standard reduction potentials of chemical reactions would reveal that silver has little (almost no) tendency to reduce sodium or any other ions which may be present in the Ringer's solution. Any residual silver ion concentration would therefore be extremely small. In addition, the superior cervical ganglion is well encapsulated and this encapsulation will also offer protection against possible silver ion toxicity. These considerations are certainly justified by the stability of the responses over relatively long periods of time.

CW power sources operating at 2450 MHz were used to feed the waveguide. A directional coupler placed right in front of the coaxial to waveguide transition allowed constant monitoring of both forward and reflected power with microwave power meters (Hewlett-Packard 430C). Reflected power was found to be 1 percent or less of the forward power at all times.

The absorbed power density P_a in watts per gram by the ganglion at the center of the waveguide is related to the incident power through the following equation:

$$P_a = 4\alpha \frac{W_F - W_R}{A} \exp(-2\alpha z) \tag{1}$$

where $1/\alpha$ is the depth of penetration in the bathing solution, A is the cross-sectional area of the waveguide (square centimeters), z is the distance of the ganglion from the surface of the solution (centimeters), and W_F and W_R are the forward and reflected powers, respectively. The tissue density is assumed to be 1 gm/cm^3. The penetration depth for the mammalian Ringer's solution used is 1.75 cm at 2450 MHz. The average incident power density P_I is calculated from

$$P_I = (W_F - W_R)/A \exp(-2\alpha z). \tag{2}$$

Before going into the microwave experiments it would be useful to describe the effects of temperature alone on transmission latencies through the ganglion. Stimulation of the preganglionic nerve trunk with 4–8-V pulses of 100–300-μs duration (and rates of 1/s) produced a transient positive going potential recorded from the postganglionic nerve stump relative to bath potential. This *B* fiber mediated response occurred after a transmission latency through the ganglion of about 20 ms at 37°C. At higher stimulus strengths, a longer latency *C* fiber mediated response could often be recorded. The general appearance of these recordings is indicated in Fig. 3. Amplitudes of these positive going responses varied from a few hundred microvolts to a millivolt in different experiments. Fig. 4 illustrates the changes in transmission latencies that occur when the temperature of the Ringer's solution was changed systematically. The low-threshold *B* fiber mediated response changed latency at the rate of about 0.5 ms/°C for changes in temperature near body temperature (37°C). The high-threshold *C* fiber mediated response, which occurred at latencies about twice that for the low-threshold response, changed latency at about twice this rate. Thus both response components changed latency by about 3 percent/°C. These kinds of measurements on temperature dependence of the responses will be useful for the interpretation of microwave exposure experiments, where temperature changes may occur in the preparation due to microwave heating.

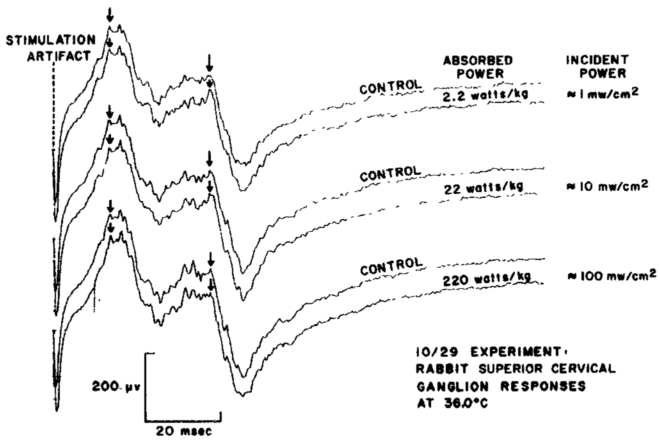

Fig. 3. Electrically evoked responses recorded extracellularly from isolated rabbit superior cervical ganglion during and between exposures to 2450-MHz CW irradiation. Several successive traces averaged with a computer of average transients.

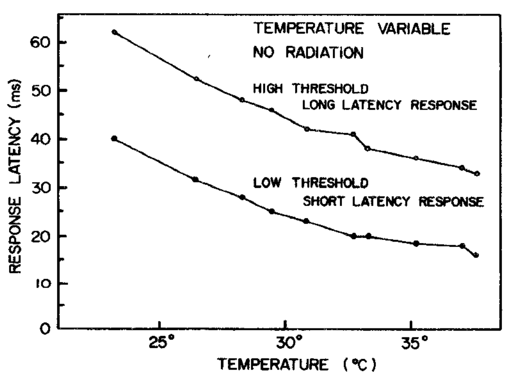

Fig. 4. Effect of temperature on synaptic transmission latencies of the low-threshold (*B* fiber mediated) and high-threshold (*C* fiber mediated) responses.

The basic measurement made when the ganglia were irradiated with microwaves is shown in Fig. 3. These records were averaged results made with a computer of average transients to eliminate some 60-cycle noise that was present. Generally, stimulus strengths sufficient to excite both classes of preganglionic fibers (*B* and *C* fibers) were used and measurements of response latencies of both components (indicated by arrows) were made for various radiation levels. 2450-MHz radiation was applied at the indicated levels for periods of 1 min with 1 min between radiations allowed for control measurements. Only at absorbed power densities above 100 W/kg (50 mW/cm²) did we observe temperature changes of 0.1°C or more in the solution just exciting the waveguide. Before the radiation exposures were started, the temperature dependences of the response latencies were also investigated and were found to be 0.6, 0.5, and 0.5 ms/°C for the low-threshold short-latency responses and 1.4, 1.2, and 1.9 ms/°C for the high-threshold responses in the 10/29, 11/12*B*, and 11/12*A* experiments, respectively.

Fig. 5 summarizes averaged low-threshold response latency measurements for three trials of CW radiation and the intervening three control periods for three different ganglia at several increasing radiation levels; 5-percent *t*-tests failed to reveal any significant differences between control and exposure period latencies. Standard errors were typically 0.1 ms for any one point on the graph except for the disparate third pair of points in the 11/12*A* experiment. Fig. 6 illustrates, in a similar fashion, some measurements on the high-threshold longer latency responses of the same three ganglia. Again no significant differences (at the 5-percent level) were found between averaged responses during exposure and control periods. The slight temperature rises that occur due to microwave heating are the same in Figs. 5 and 6. For each indicated data line, measurements were taken by starting at low radiation levels and following with increasing levels of radiation.

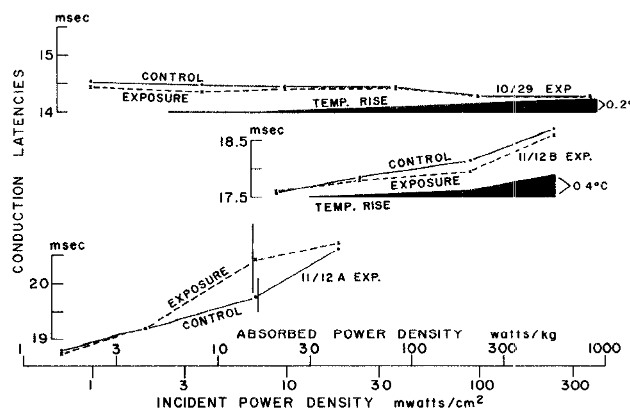

Fig. 5. Low-threshold fast response latencies of rabbit superior cervical ganglia exposed to 2450-MHz CW radiation. Each point represents the average of three trials like those illustrated in Fig. 4.

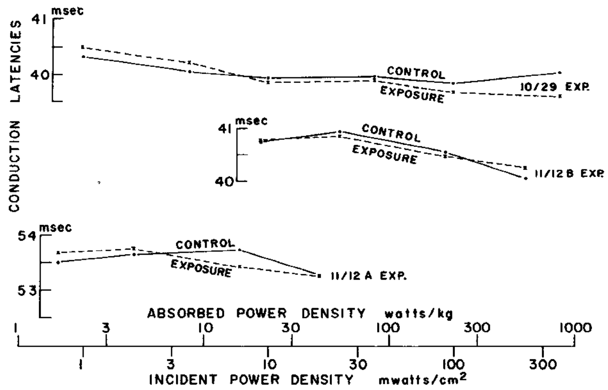

Fig. 6. High-threshold slow response latencies of rabbit superior cervical ganglia exposed to 2450-MHz CW radiation.

DISCUSSION AND CONCLUSION

Although significant differences in electrically evoked response latencies between control and exposure periods did not occur in the experiments illustrated in Figs. 5 and 6, some changes in the response latencies over time were occurring. One may therefore speculate that drifts in response latency could be a result of microwave irradiation. However, the experiments shown in Fig. 7 seem to negate this conjecture. Fig. 7(a) shows the low-threshold response latency drift for a ganglion recorded for over a 70-min period. It can clearly be seen that response latency changes occur without microwave exposure. Fig. 7(b) and (c) show similar kinds of measurements over a 35-min period on another ganglion. This time the preparation was exposed to five alternating 1-min periods of CW 2450-MHz radiation at levels of 30-mW/cm² incident power density, corresponding to 65-W/kg absorbed power. The preparation was not exposed to radiation for intervening 1-min periods as in the experiments already described in Figs. 5 and 6. Again it is seen that response latency changes can occur over time and that microwave exposure at these levels does not seem to modulate this process.

In accordance with previous reports [2]–[5] of decreases in latency of synaptically mediated responses upon exposure to microwaves within the CNS, this investigation shows that within a temperature-controlled environment, where there is no temperature rise due to microwave absorption, latency changes are not observed in this particular synaptic system. It is therefore reasonable to suggest that continuous microwave interaction with nervous tissue, simple or complex, is likely to be related to the heat generating capacity of the radiation. It should be emphasized that the normal asynchronous activity of various elements within the ganglion in an intact animal may be considerably different from the synchronous volleys of activity evoked by electrical stimulation.

Several related studies have appeared in the literature in recent years. One study alluded to changes in spontaneous impulse frequencies in the crayfish and prawn abdominal ganglia exposed to 100 W/kg of 11-GHz radiation [11]. The report also discussed possible mechanisms of interaction. However, it is difficult to make any direct comparison with the present study since information regarding the incident and absorbed power densities is not available. Another study using ganglia from *Aplysia*, has shown that absorbed microwave power densities less than 5 W/kg (2450 MHz) produced alterations in the regular firing patterns of the cells [12]. Although the firing pattern changes were reproducible in the majority of the experiment using convective heating, in some cases, changes were attributed to polarizing currents produced by microwaves. The present set of experiments using 2450-MHz CW irradiation of the isolated rabbit superior cervical ganglion has shown that absorbed power densities between 2 and 1000 W/kg failed to significantly influence transmission latencies of responses recorded from postganglionic fibers due to electrical stimulation of either *B* (myelinated) or *C* (unmyelinated) fibers in the preganglionic trunk as long as the ganglion temperature was held constant.

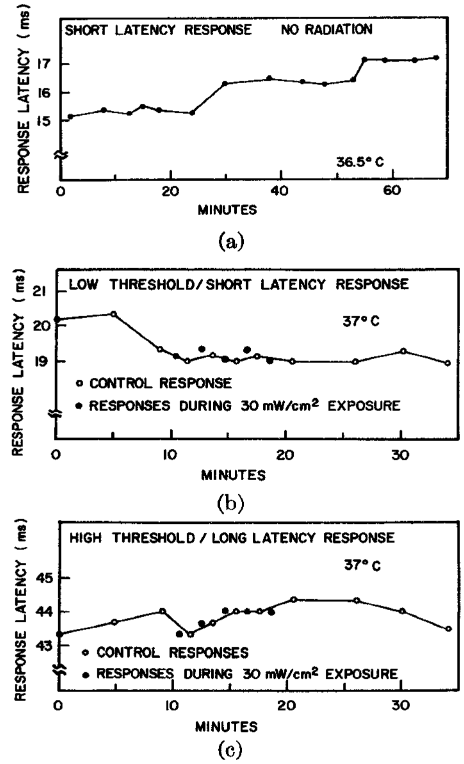

Fig. 7. Stability of response latencies over time. (a) The low-threshold response latency monitored for a 70-min period. Six sweeps averaged with a computer of average transients were used to make each measurement. (b) Similar measurement on another ganglia but with five 1-min microwave exposures of 30 mW/cm² occurring during alternating minutes in the middle of this experiment. Sweeps averaged for each measurement. (c) Simultaneous measurements for high-threshold longer latency response recorded during same experiment as in (b).

REFERENCES

[1] C. C. Johnson and A. W. Guy, "Nonionizing electromagnetic wave effects in biological materials and systems," *Proc. IEEE*, vol. 60, pp. 692–718, June 1972.
[2] A. W. Guy, F. A. Harris, and H. S. Ho, "Quantitation of the effects of microwave radiation on central nervous system function," in *Proc. 6th Annu. Int. Microwave Power Symp.* (Monterey, Calif., May 1971).
[3] A. W. Guy, J. C. Lin, and F. A. Harris, "The effect of microwave radiation on evoked tactile and auditory CNS responses

in cats," in *Summary Int. Microwave Power Symp.* (Ottawa, Ont., Canada, May 1972).
[4] A. W. Guy, J. C. Lin, and C.-K. Chou, "Electrophysiologic effects of electromagnetic fields on animals," in *Fundamental and Applied Aspects of Nonionizing Radiation*, 1974.
[5] E. M. Taylor, A. W. Guy, B. Ashleman, and J. C. Lin, "Microwave effects on central nervous system attributed to thermal factors," in *Dig. Tech. Papers, IEEE Int. Microwave Symp.* (Boulder, Colo., June 1973).
[6] C.-K. Chou and A. W. Guy, "Effect of 2450 MHz microwave on peripheral nerve," in *Dig. Tech. Papers, IEEE Int. Microwave Symp.* (Boulder, Colo., June 1973).
[7] R. M. Eccles, "Action potentials of isolated mammalian sympathetic ganglia," *J. Physiol.*, vol. 117, pp. 181–195, 1952.
[8] B. Libet, "Generation of slow inhibitory and excitatory postsynaptic potentials," *Fed. Proc.* (Abstr.), vol. 29, pp. 1945–1956, 1970.
[9] S. D. Erulkar and J. K. Woodward, "Intracellular recording from mammalian superior cervical ganglion in situ," *J. Physiol.* (London), vol. 199, pp. 189–203, 1968.
[10] U. Trendelenburg, "Some aspects of pharmacology of autonomic ganglion cells," *Ergeb. Physiol.*, vol. 9, pp. 1–85, 1967.
[11] I. Yamaura and S. Chichibu, "Superhigh frequency electric field and crustacean ganglionic discharges," *Tohoku J. Exp. Med.*, vol. 93, pp. 249–259, 1967.
[12] H. Wachtel, R. Seaman, and W. Joines, "The effects of microwaves on isolated neurons," presented at the *N. Y. Acad. Sci. Conf. Biological Effects Non-ionizing Radiation*, Feb. 1974.

Nonreciprocal Delay Line for Use in *S* Band Tubes

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***Abstract*—In an effort to make ferrites available for broad-band resonance isolator applications in high-power mirowave tubes, seven lithium ferrites and four nonlithium spinel ferrites were tested for resonance-loss behavior near an *S* band (2.0–4.0-GHz) linear helix.**

The observed behavior, i.e., the dependence of the absorption on the dimensions of the ferrites, can be attributed to excitation of surface magnetostatic modes. Using the results of the Damon–Eshbach theory for surface magnetostatic modes in semi-infinite slabs, resonance frequency and surface-wave attenuation factors were numerically calculated as a function of the propagation coefficient and the ratio of magnetization to internal field.

I. INTRODUCTION

THE ability of ferrites, biased by magnetic fields, to act as isolators and phase shifters, has been known for a long time, and in many cases ferrites have been used external to high-power microwave tubes to protect them from load mismatch. For many years there has been a need for ferrites inside high-power tubes to improve their efficiency and, in the case of pulsed operation, decrease the turn-on time. In crossed-field amplifier (CFA) tubes, ferrites were needed as unidirectional attenuators in band. Ferrites were not used in tubes previously because spinel ferrites tended to give off gases when heated up, and to become dielectrically lossy when assembled inside tubes, whereas garnet ferrites never offered the range of saturation magnetization or Curie temperature to make them suitable. Improvements in spinel-ferrite fabrication through the years and recent work at Raytheon [1] has shown, however, that in regard to spinel ferrites, the previously experienced difficulties can be overcome.

The major difference between designing ordinary isolators and isolators for use inside tubes is the fact that for tubes the magnetic field strength is generally fixed by other requirements. This means that the resonance frequency of the isolator must be adjusted to the desired value by suitable choice of other parameters such as the sample shape, the saturation magnetization, and the effective gyromagnetic ratio g_{eff}. Additional constraints upon the isolator design are imposed by the requirement that it should work with the existing tube structure without the need for any modification. It is, therefore, very important to be able to predict the performance of a tube isolator with some accuracy, because a purely empirical design procedure would be very costly.

There are several equations for predicting the frequency at which a specific ferrite will exhibit resonance loss: the equation selected depending on boundary conditions, ferrite geometry, propagation constant, and the like. Each equation requires that one know the saturation magnetization $4\pi M$, the internal magnetic field strength, and the effective gyromagnetic ratio g_{eff} of the polycrystalline ferrite. The theories from which the equations originate are based on assumptions regarding the wavelength of the RF signal relative to ferrite dimensions, the polarization of the RF field relative to the magnetic field and propagation direction, the uniformity of the biasing and RF field throughout the ferrite region, and the degree of saturation of the ferrite. Seldom are all requirements for a given theory satisfied in practice. Vendors in general state the X band g_{eff} in catalog listings. The g_{eff} [2] for ferrite spheres are, in general, frequency dependent due to the

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