(indeed, we have employed line with resistances as high as 100 kΩ/ft);[9] and b) microcircuit implementation of the Wheatstone bridge on the upper substrate. The latter alternative requires four lines to the MIC (two for power and two to the detector), but it has the enormous advantage of placing the high-resistance line between the bridge and detector rather than between the thermistor and the bridge. Thus the T_c of the line becomes unimportant when lumped with the input impedance ($>10^8\,\Omega$) of the detector. The detailed description and test results for this system will be the subject of subsequent reports.

VII. CONCLUSIONS

The MIC design with 5-μm conductors and thick-film thermistor has virtual immunity from fast and slow artifact. When the needle is thermally isolated from external conductive monofilament, temperature rise due to the presence of the electrode is below the limit of resolution of the thermograph (Philco–Sierra) for line scans taken at the position of the electrode tip in a comparative pyrometric design with an incident power of 50 mW/cm², CW, at 2450 and 918 MHz.

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REFERENCES

[1] M. Benzinger, "Tympanic thermometry in surgery and anesthesia," *J. Amer. Med. Ass.*, vol. 209, pp. 1207–1211, 1959.
[2] T. H. Benzinger and G. W. Taylor, "Cranial measurements of internal temperature in man," in *Temperature: Its Measurement and Control in Science and Industry*, vol. 3, C. M. Herzfeld, Ed. New York: Rheinhold, 1963, pp. 1–10.
[3] J. M. Hayward and M. A. Baker, "A comparative study of the role of the cerebral arterial blood in the regulation of brain temperature in five mammals," *Brain Res.*, vol. 16, pp. 417–440, 1969.
[4] J. M. R. Delgado and T. Hanai, "Intracerebral temperature in freely moving cats," *Amer. J. Physiol.*, vol. 211, pp. 755–769, 1966.
[5] H. W. Magoun, F. Harrison, J. R. Brobeck, and S. W. Ranson, "Activation of heat loss mechanisms by local heating of the brain," *J. Neurophysiol.*, vol. 1, pp. 101–114, 1938.
[6] A. Anne, "Relative microwave absorption cross sections of biological significance," in *Biological Effects of Microwave Radiation*, vol. I, M. R. Peyton, Ed. New York: Plenum, 1961, pp. 153–176.
[7] A. R. Shapiro, R. F. Lutomirski, and H. T. Yura, "Induced fields and heating within a cranial structure irradiated by an electromagnetic plane wave," *IEEE Trans. Microwave Theory Tech.* (*Special Issue on Biological Effects of Microwaves*), vol. MTT-19, pp. 187–196, Feb. 1971.
[8] S. M. Michaelson, "The tri-service program—A tribute to George M. Krauf, USAF(MC)," *IEEE Trans. Microwave Theory Tech.* (*Special Issue on Biological Effects of Microwaves*), vol. MTT-19, pp. 131–146, Feb. 1971.
[9] C. Von Euler, "Slow temperature potentials in the hypothalamus," *J. Cell. Comp. Physiol.*, vol. 36, pp. 333–350, 1950.
[10] G. Strom, "Central nervous regulation of body temperature," in *Handbook of Physiology, Section 1: Neurophysiology*, vol. II, J. Field, H. W. Magoun, and V. E. Hall, Ed. Washington, D. C.: American Physiological Society, 1960, pp. 1173–1196.
[11] A. S. Presman, *Electromagnetic Fields and Life.* New York: Plenum, 1970, p. 74.
[12] A. W. Guy, F. A. Harris, and H. S. Ho, "Quantification of the effects of microwave radiation on central nervous system function," in *Proc. 6th Annu. Int. Microwave Power Symp.* (Monterey, Calif.), May 1971.
[13] W. H. Vogelman, "Microwave instrumentation for the measurement of biological effects," in *Biological Effects of Microwave Radiation*, vol. I, M. R. Peyton, Ed. New York: Plenum, 1961, pp. 23–31.
[14] R. E. Collin and F. J. Zucker, *Antenna Theory*, pt. I. New York: McGraw-Hill, 1969.
[15] J. F. Lehmann, A. W. Guy, B. J. Delateur, J. B. Stonebridge, and C. G. Warren, "Heating patterns produced by short wave diathermy using helical induction coil applicators," *Arch. Phys. Med. Rehabil.*, vol. 49, pp. 193–198, Apr. 1968.
[16] A. W. Guy, "Analyses of electromagnetic fields induced in biological tissues by thermographic studies on equivalent phantom models," *IEEE Trans. Microwave Theory Tech.* (*Special Issue on Biological Effects of Microwaves*), vol. MTT-19, pp. 205–214, Feb. 1971.
[17] L. E. Larsen, R. A. Moore, and J. Acevedo, "An RF decoupled electrode for measurement of brain temperature during microwave exposure," in *Proc. 1973 G-MTT Int. Microwave Symp.* (Boulder, Colo., June 4–6, 1973).

[9] This ultrahigh resistance line was kindly provided by R. Bowman of the NBS, Boulder, Colo.

Short Papers

Microwave Oscillator Noise Measuring System Employing a YIG Discriminator

KENZO WATANABE AND IWAO TAKAO, MEMBER, IEEE

Abstract—A microwave oscillator noise measuring system employing a YIG discriminator has been developed. The resonant frequency of the YIG discriminator is automatically tuned to follow the drift of the carrier frequency of the oscillator under test. This arrangement permits an accurate measurement of FM noise spectra near the carrier frequency as close as several tens of Hz off the carrier. The drift of the carrier frequency is measured over a wide range by monitoring fluctuations of the feedback current in the compensation coil that supports a part of the biasing magnetic field for the YIG discriminator.

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I. INTRODUCTION

The direct-detection systems developed by Ashley *et al.* [1] and Ondria [2] have been widely used for measurements of microwave oscillator noise. FM noise measurements using these systems require elaborate adjustments of the discriminator in order to avoid

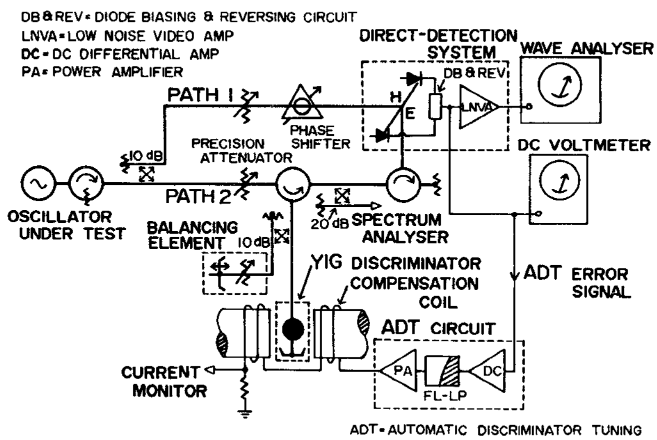

Fig. 1. Complete microwave oscillator noise measuring system.

errors due to the discriminator detuning from the carrier frequency of the oscillator under test.

We have developed a noise measuring system for X-band oscillators which employs an yttrium iron garnet (YIG) sphere as the discriminator. The resonant frequency is automatically tuned to follow the drift of the carrier frequency, thereby avoiding the adjustment problem. This automatic discriminator tuning (ADT) permits an accurate measurement of the FM noise spectra over a wide frequency range, from tens of Hz to several MHz off the carrier. The drift is measured by monitoring fluctuations of the compensation coil current that tunes the YIG discriminator.

II. SYSTEM CONFIGURATION

The configuration of the noise measuring system is shown in Fig. 1. The basic arrangement and operation of the system are the same as those described in [1] and [2], but the YIG discriminator is incorporated into the present system for automatic frequency following.

The YIG discriminator is a magnetically biased YIG sphere placed in a length of waveguide short-circuited at one end. Resonant frequency f_0 of the YIG sphere is given by $f_0 = 2.8H_0$, where f_0 is given in megahertz and H_0, the applied magnetic field, in gauss. Unloaded Q of the discriminator is about 6000. Coupling coefficient is nearly unity, but can be adjusted by varying the distance between the YIG sphere and the shorted end. The residual carrier component due to the reflection from the YIG discriminator and the circulator feedthrough is reduced to the lowest possible value by adjusting the balancing element.

When the oscillator frequency drifts, an unbalanced carrier wave is detected by the phase sensitive detector in path 1, and the output is fed into the ADT circuit consisting of a dc differential amplifier, a low pass filter, and a power amplifier. The detector output contains both the FM-noise and frequency-drift components, but only the latter goes through the low pass filter to reach the compensation coil. The resonant frequency of the YIG discriminator varies linearly with a slope of 234 kHz/mA against the current in the compensation coil. Since the feedback system has a high gain, the resonant frequency of the YIG discriminator follows the drift of the carrier frequency closely. Thus the fluctuation of the feedback current in the compensation coil measures the drift of the carrier frequency, which is monitored and recorded.

The calibration of the FM–AM conversion sensitivity of the YIG discriminator is accomplished by the dc method: incremental changes in dc output voltage measured by a dc voltmeter are plotted against incremental changes in the resonant frequency of the YIG discriminator, which are deliberately introduced by means of varying the current in the compensation coil. The slope gives the FM–AM conversion sensitivity. The sensitivity of the present system when the incident power on the discriminator is 10 mW is 1 μV/Hz.

III. MEASUREMENT AND ERROR

Two factors contribute to errors in FM noise measurements when using a direct-detection system: the detuning of the discriminator from the carrier frequency and the FM noise measuring threshold of the system. In a conventional system, the major factor is the discriminator detuning, while, in the present system, it is the FM noise measuring threshold, since the detuning is eliminated.

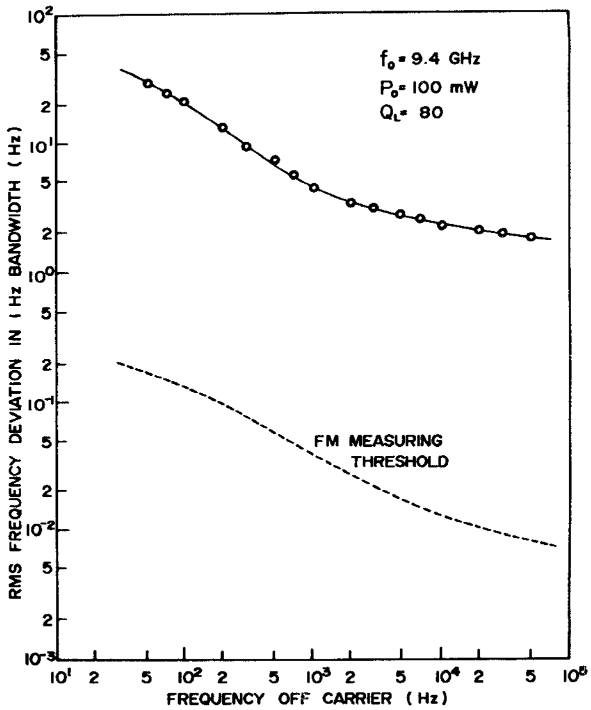

Fig. 2. FM noise spectra of the X-band Gunn oscillator (solid curve) and FM noise measuring threshold of the system (dotted curve). The incident power on the discriminator is 10 mW.

The FM measuring threshold is determined by three sources: 1) the noise generated in the direct-detection system; 2) the residual AM noise due to the mismatch of two detector diodes and the unbalance of the magic T [2], [4]; and 3) the random fluctuation of the resonant frequency of the YIG discriminator due to the noise in the biasing magnetic field and the ADT circuit, which is a drawback of the present system.

The FM measuring threshold Δf_{thr} due to 1) and 2) is shown by the dotted curve in Fig. 2, when the discriminator sensitivity is 1 μV/Hz. The contribution of 3) is estimated to be about one tenth of Δf_{thr}. Thus the fractional error ϵ_{thr} in FM noise measurements with using the present system is given by $\epsilon_{thr} = \Delta f_{thr}/\Delta f_{rms}$, where Δf_{rms} is the measured FM noise of the oscillator under test expressed in terms of the rms frequency deviation.

A free-running Gunn oscillator, 9.4 GHz, 100 mW, was subjected to FM noise measurement with using this system and the result is given by the solid curve in Fig. 2. The Gunn diode was mounted in a rectangular cavity with a loaded Q of 80. The incident power on the discriminator was 10 mW. The cutoff frequency of the low pass filter was 1 Hz. The measuring error ϵ_{thr} due to the FM measuring threshold Δf_{thr} was about 7 percent. The measured off-carrier frequency range is limited by the wave analyzer used in this measurement, which can be extended by employing a wide-band analyzer.

The recorder output of the current monitor showed that the frequency of the oscillator drifted and decreased by about 15 MHz in a half hour after the start of operation to settle down at a steady state value. FM noise measurement was possible during this turn-on transient, which is not possible with the conventional method.

IV. CONCLUSIONS

A microwave oscillator noise measuring system employing a YIG discriminator is described. The factors contributing to errors in FM noise measurements with using the noise measuring system are discussed. The system capabilities are also demonstrated by the measured FM noise spectra for a typical X-band Gunn oscillator. The noise measuring system permits precise and easy measurements of microwave oscillator noise, in particular, measurements of FM noise spectra close to the carrier frequency.

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REFERENCES

[1] J. R. Ashley, C. B. Searles, and F. M. Palka, "The measurement of oscillator noise at microwave frequencies," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 753–760, Sept. 1968.
[2] J. G. Ondria, "A microwave system for measurements of AM and FM noise spectra," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 767–781, Sept. 1968.
[3] J. L. Fikart, J. Nigrin, and P. A. Goud, "The accuracy of AM and FM noise measurements employing a carrier suppression filter and phase detector, *IEEE Trans. Microwave Theory Tech.* (Short Papers), vol. MTT-20, pp. 702–703, Oct. 1972.
[4] J. L. Fikart and P. A. Goud, "The direct-detection noise-measuring system and its threshold," *IEEE Trans. Instrum. Meas.*, vol. IM-21, pp. 219–224, Aug. 1972.

A Numerical Method Based on the Discretization of Maxwell Equations in Integral Form

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Abstract—**A method is described for the solution of the electromagnetic field inside resonant cavities and waveguides of arbitrary shape, whether homogeneously or inhomogeneously filled. The method, suitably programmed for use with a digital computer, is based on the direct discretization of the Maxwell equations in integral form. Since the method works with the components of the electromagnetic field, the numerical solution directly gives the distributions of the field in the structure, in addition to the resonant frequencies of cavities or the propagation constants of waveguides. Some numerical applications of the method are given.**

I. INTRODUCTION

Numerous satisfactory numerical methods are available today for determining the electromagnetic field, both in structures in which the field can be derived from a single scalar potential, as in the case of empty guides of arbitrary shape [1]–[3], and in more general structures in which the field has all the components differing from 0, such as waveguides loaded with axial dielectrics [4]–[9] or resonant cavities of arbitrary shape, whether empty or loaded with dielectric regions [8]. Comparative discussions of these methods [2], [3], [7] show that "no single solution method has proved to be best for all requirements that might be imposed."

In this short paper, a method based on the direct discretization of the Maxwell equations in integral form is presented. The method does not require the introduction of auxiliary potential functions or the use of particular analytical procedures to formulate the problem in a computationally convenient form, and it therefore represents a very direct approach for the solution of a large class of structures. Moreover, the method presented allows the solution, with unified treatment, of both two- and three-dimensional structures.

II. DISCRETIZATION OF MAXWELL'S EQUATIONS IN INTEGRAL FORM

Considering a source-free region and assuming $\exp[j\omega t]$ as time dependence, Maxwell's equations in integral form may be written

$$\oint_s \boldsymbol{t}\cdot\boldsymbol{E}\, ds = -\int_S \boldsymbol{n}\cdot\boldsymbol{H}\, dS \tag{1a}$$

$$\oint_s \boldsymbol{t}\cdot\boldsymbol{H}\, ds = -\int_S \epsilon_r(P)\boldsymbol{n}\cdot\boldsymbol{E}\, dS \tag{1b}$$

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where $\epsilon_r(P)$ is the permittivity of the medium in the structure. In (1) the lengths and the electric field are normalized to $1/\omega(\mu_0\epsilon_0)^{1/2}$ and $j(\mu_0/\epsilon_0)^{1/2}$, respectively; that is,

$$s = \omega(\mu_0\epsilon_0)^{1/2}\bar{s} \tag{2a}$$

$$\boldsymbol{E} = -j\bar{\boldsymbol{E}}/(\mu_0/\epsilon_0)^{1/2} \tag{2b}$$

where $\bar{s}$ and $\bar{E}$ are the effective length and electric field.

A. Cavities of Arbitrary Shape Inhomogeneously Filled

A cavity of arbitrary shape, bounded by a perfect conductor, and loaded with an inhomogeneous dielectric medium is considered first. In order to obtain a finite set of algebraic equations, a finite-difference procedure of discretization, the cell method [10], [11], is followed. The method consists of subdividing the cavity into cubic cells of side h, each assumed homogeneously filled, and considering the field as a function defined on the cells. Two types of cell may be considered: internal and boundary cells (Fig. 1). For all the cells of the structure, we assume the following hypotheses on the distribution of the electromagnetic field. 1) Inside each cell the components of the field have constant value. 2) On the interface between two contiguous cells, the components of the field have a value equal to the mean of the values in the two cells considered.

In this way, the continuous electromagnetic field is replaced by a set of discrete values. By applying (1a) and (1b) to each cell of the structure, we obtain a finite system of simultaneous algebraic equations. Assuming a rectangular coordinates set (x, y, z), for the generic internal cell we have

$$2hH_x + E_y(z-h) - E_y(z+h) + E_z(y+h) - E_z(y-h) = 0 \tag{3a}$$

$$2hE_x + \epsilon_r^{-1}[H_y(z-h) - H_y(z+h) + H_z(y+h) - H_z(y-h)] = 0 \tag{3b}$$

where H_x stands for $H_x(x,y,z)$ and $E_y(z-h)$ stands for $E_y(x,y,z-h)$.

The other four equations are obtained with two successive permutations of the coordinate index in (3a) and (3b). For each internal cell, six equations analogous to the preceding ones may be written; the only point to be noted is that the value of ϵ_r must be that of the medium filling the cell. At the boundary cells the electric field is assumed to be 0, while the magnetic field is assumed to be different from 0 because of the surface currents J_s on the boundary, which have not been taken into account in (1). With these hypotheses, from (1a) we obtain for the boundary cell Q of Fig. 1:

$$2hH_{xQ} = 0 \tag{4a}$$

$$2hH_{yQ} - E_{zP} = 0 \tag{4b}$$

$$2hH_{zQ} - E_{yP} = 0. \tag{4c}$$

Applying (3) and (4) to all the cells of the structure, we obtain a homogeneous system of equations that can be expressed as a matrix eigenvalue problem:

$$(A - 2hI)x = 0 \tag{5}$$

where A has not more than four nonzero elements for each row.

Because of the high number of equations necessary to obtain the field distribution with a fair degree of approximation, the eigenvalue problem can be solved numerically only with iterative methods [1].

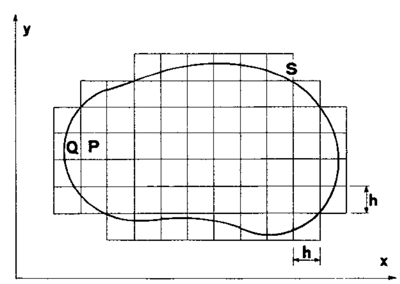

Fig. 1. Cross section of a cavity of arbitrary shape. S is the cavity boundary, P an internal cell, Q a boundary cell.