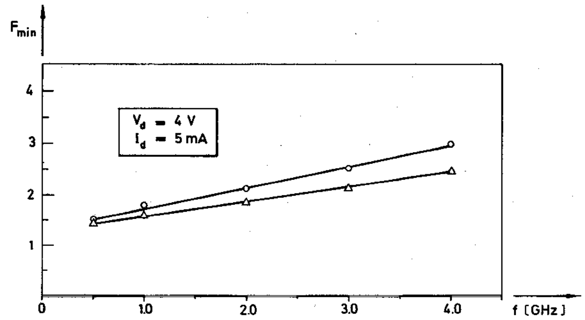

Fig. 4. Minimum noise figure F_{min} of the GaAs FET as a function of the frequency. ○: measured; △: computed.

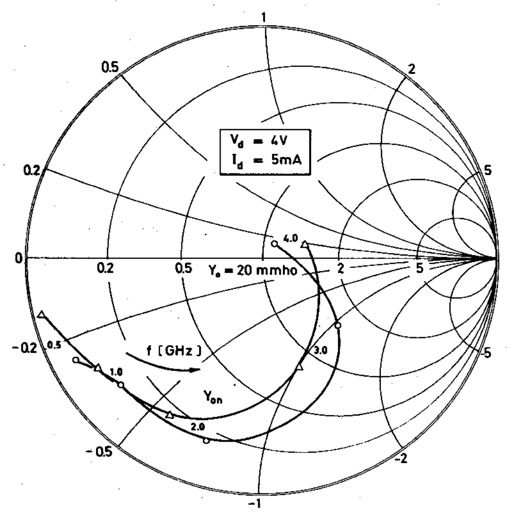

Fig. 5. Optimum source admittance Y_{on} of the GaAs FET with respect noise versus frequency. ○: measured; △: computed.

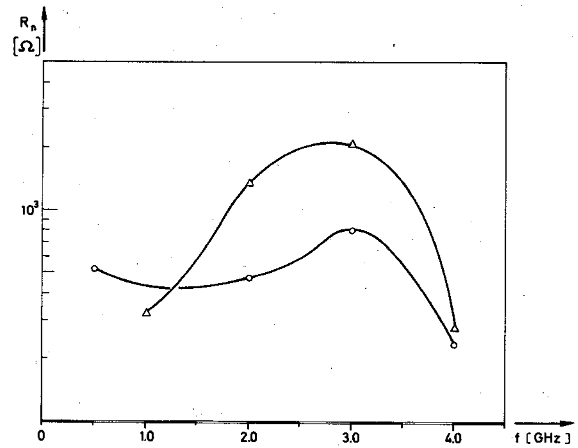

Fig. 6. Noise resistance R_n of the GaAs FET as a function of the frequency. ○: measured; △: computed.

been demonstrated that the compound noise parameters of the GaAs FET, based on the noise model of van der Ziel, are in good accordance with the measured results up to 4 GHz.

References

[1] A. Anastassiou and M. J. O. Strutt, "Experimental gain and noise parameters of microwave GaAs FET's in the *L* and *S* bands," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 419–422, June 1973.

[2] A. van der Ziel, "Thermal noise in field-effect transistors," *Proc. IRE*, vol. 50, pp. 1808–1812, Aug. 1962.

[3] ——, "Gate noise in field effect transistors at moderately high frequencies," *Proc. IEEE*, vol. 51, pp. 461–467, Mar. 1963.

[4] F. N. Troffimenkoff, R. D. S. Silverthorn, and R. S. Cobbold, "Theory and application of the field-effect transistor—Pt. 2 High frequency properties," *Proc. Inst. Elec. Eng.*, vol. 112, pp. 681–687, Apr. 1965.

[5] K. Hartmann, W. Kotyczka, and M. J. O. Strutt, "Equivalent networks for three different microwave bipolar transistor packages in the 2–10 GHz range," *Electron. Lett.*, vol. 7, July 30, 1971.

[6] A. van der Ziel and J. W. Ero, "Small-signal, high-frequency theory of field-effect transistors," *IEEE Trans. Electron Devices*, vol. ED-11, pp. 128–135, Apr. 1964.

[7] W. Baechtold, "Noise behavior of Schottky barrier gate field-effect transistors at microwave frequencies," *IEEE Trans. Electron Devices*, vol. ED-18, pp. 97–104, Feb. 1971.

[8] M. E. Engeli, "Symbal, summary and examples," in *Fides Rechenzentrum*, Publ. 22, 2nd ed., Oct. 1970.

[9] A. Leupp and M. J. O. Strutt," High-frequency FET noise parameters and approximation of the optimum source admittance," *IEEE Trans. Electron Devices*, vol. ED-16, pp. 428–431, May 1969.

[10] K. Hartmann, W. Kotyczka, and M. J. O. Strutt," Computer-aided determination of the small-signal equivalent network of a bipolar microwave transistor," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 120–126, Feb. 1972.

[11] A. Leupp and M. J. O. Strutt, "Noise behavior of the MOS-FET at UHF and VHF," *Electron. Lett.*, vol. 4, pp. 313–314, July 26, 1968.

[12] W. Schockley, "A unipolar field-effect transistor," *Proc. IRE*, vol. 40, pp. 1365–1376, Nov. 1952.

[13] A. Turner and B. L. H. Wilson, "Implications of carrier velocity saturation in a GaAs-FET," in *Proc. Symp. GaAs*, pp. 195–204, 1968.

[14] P. L. Hower and N. G. Bechtel, "Current saturation and small-signal characteristics of GaAs field-effect transistors," *IEEE Trans. Electron Devices*, vol. ED-20, pp. 213–220, Mar. 1973.

[15] W. Baechtold, "Noise behavior of GaAs field-effect transistors with short gate lengths," *IEEE Trans. Electron Devices*, vol. ED-19, pp. 674–680, May 1972.

[16] A. Gisolf and R. J. J. Zijlstra, "Lattice interaction noise of hot carriers in single injection solid state diodes," *Solid-State Electron.*, vol. 16, pp. 571–580, 1973.

An Automatic System for Simultaneous Measurement of Amplitude and Phase of Millimeter-Wave Fields

NEVILLE A. MATHEWS AND HENRYK STACHERA

***Abstract*—A measuring system for the simultaneous determination of amplitude and phase distributions of EM fields is described. The system employs the vibrating-dipole technique, which is based on the principle of modulated scattering. The phase-modulated wave scattered by the vibrating dipole contains information about the amplitude and phase of the EM field at the midpoint of the dipole's vibration.**

The system has been made automatic by the inclusion of a servo loop. The measured free-space distributions compare well with those calculated from theory.

I. Glossary of Symbols Defined in [9]

E_0	Amplitude (real) of the reference wave in the waveguide.
E_s	Amplitude (real) of the back-scattered wave in the waveguide.
$\boldsymbol{F}(x,y,z)$	Dimensionless complex vector function of position.
F_x	Amplitude (real) of the x component of $\boldsymbol{F}$.
G	Constant of amplification and rectification.
J_n	Bessel function of the first kind and order n.
K	Constant of proportionality of the detector.
λ	Free-space wavelength.
ϕ_m	$=2\pi d/\lambda$, where d is amplitude of vibration of the dipole.
ϕ_p	Phase lag introduced by the phase shifter.
ϕ_x	Phase of the x component of $\boldsymbol{F}$.
ω_m	Angular frequency of vibration of the dipole.

II. Introduction

The knowledge of EM field distributions is essential in many problems, particularly in diffraction studies of apertures and obstacles. In some cases the amount of required experimental information is so vast that an automatic measuring system becomes indispensable.

Manuscript received April 6, 1973; revised July 9, 1973.

The authors are with the Department of Electronics, University of Southampton, Southampton, England.

Microwave-field measuring techniques usually employ modulated scatterers [1]–[8]. The scattered field is directly related to the electric and/or magnetic field at the location of the scatterer. Being modulated in a characteristic manner, the scattered field can be distinguished from the unmodulated background. In all the techniques reported in the literature, the amplitude and phase of the EM field are measured separately, and each determination requires readjustment of the measuring system [8]. Also, owing to the difficulty of scaling down the size of the scatterer, none of these techniques is suitable for millimeter-wave field measurements.

The vibrating-dipole technique [9] is free from this latter restriction. Further, it lends itself more readily than the other techniques to the simultaneous measurement of amplitude and phase because the wave scattered by the vibrating dipole is phase modulated. In this paper, we describe a modified vibrating-dipole system for the automatic and simultaneous measurement of amplitude and phase distributions of millimeter-wave EM fields. The system was first established by measurements in the far field of a pyramidal horn. A comparison with the calculated distributions of amplitude and phase shows that the system is accurate and capable of high resolution.

III. Principle of Simultaneous Measurement of Amplitude and Phase

The principle of the vibrating-dipole technique has been recently described in detail. In the present paper we are particularly concerned with the simultaneous measurement of amplitude and phase; therefore, extensive references are made to the original paper [9]. In this way, both the underlying principle and the modified measuring system will be explained with little repetition of the fundamentals.

We have shown [9, fig. 1 and eq. (6)] that the detected current contains a component at the dipole's vibration frequency

$$i(\omega_m) = 4KE_0E_sJ_1(2\phi_m) \sin [2(\phi_x - \phi_p)] \sin w_m t. \quad (1)$$

The rectified output from the selective amplifier [9, fig. 3] tuned to this frequency [9, eq. (7)] is

$$V(\omega_m) = 4KGE_0E_sJ_1(2\phi_m) \mid \sin 2(\phi_x - \phi_p) \mid \quad (2)$$

which, in view of [9, eq. (5)] can be written

$$V_1 = V(\omega_m) = A_1J_1(2\phi_m)F_x^2 \mid \sin 2(\phi_x - \phi_p) \mid \quad (3)$$

where the constant A_1 includes the relevant parameters of the detector, amplifier, waveguide, and scatterer.

A similar expression can be readily deduced for the detected, amplified, and rectified second-harmonic component $(2\omega_m)$:

$$V_2 = V(2\omega_m) = A_2J_2(2\phi_m)F_x^2 \mid \cos 2(\phi_x - \phi_p) \mid. \quad (4)$$

Equations (3) and (4) show that when the phase shifter is adjusted so that $2(\phi_x - \phi_p) = n\pi$, with $n = 0,1,2,\cdots$, a null in V_1 is observed, while V_2 is at a maximum. Thus observations of amplitude and phase can be made simultaneously. The output V_2 is a measure of the amplitude while the phase-shifter setting measures the phase of the EM field at the midpoint of the dipole's vibration.

In the above analysis it has been assumed that the phase shifter and the antenna are matched to the waveguide. A mismatch results in a reflected unmodulated wave which gives rise to errors of measurement. This problem has been fully discussed in [9, sec. V], and we have shown that the mismatch effect can be virtually eliminated by adopting a coherent detection system, as in [9, fig. 3].

This is in essence also the measuring system of Fig. 1, except that now two selective amplifiers are employed. Their rectified outputs yield the fundamental and second-harmonic components, the form of which is given by (3) and (4).

IV. Automatic Operation

Simultaneous measurements of amplitude and phase can be performed automatically, by means of a servo system incorporating the phase shifter. The rectified fundamental-frequency output provides the error signal for the servo system, which positions the phase shifter at a null in the rectified fundamental output. In this way the driven phase shifter tracks the phase of the EM field incident on the dipole.

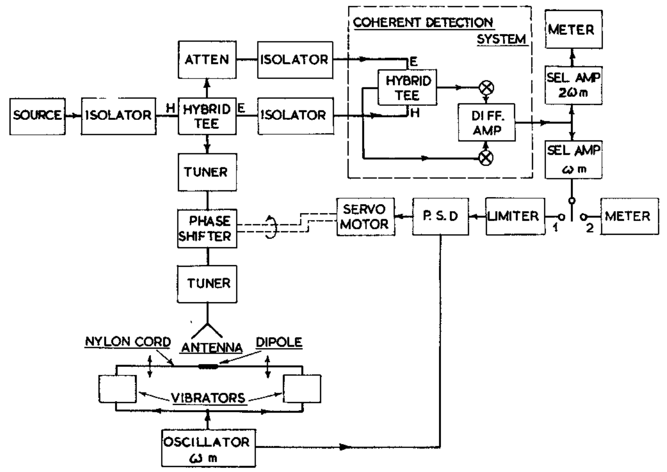

Fig. 1. System for the simultaneous measurement of amplitude and phase.

The above method, though simple and valid in principle, is not practicable for two reasons. First, the error signal which actuates the servo system is unidirectional. It is of the form $F_x^2 \mid \sin \delta\phi \mid$ where $\delta\phi$ is the difference in phase from the true null condition. Therefore, there is an ambiguity in the operation of the servo motor. Second, the error signal is proportional to the square of the amplitude of the EM field at the location of the dipole. Thus the effective gain of the servo system varies with the field strength and instability may result.

The first difficulty can be overcome with the help of a phase-sensitive detector (PSD). The fundamental component of the detected, but not rectified, signal in the form $F_x^2 \sin \delta\phi \sin \omega_m t$ is fed directly to the PSD. A square-wave reference signal from the generator which vibrates the dipole is fed to the PSD's reference port. The PSD produces a dc error output, the polarity of which depends on the sign of $\delta\phi$.

The other difficulty is removed by limiting the level of the fundamental component before it reaches the PSD. The limiter prevents instability of the servo system when the scattered signal is large. This might happen, for example, when the dipole is very close to a transmitting antenna.

V. Apparatus

Fig. 1 shows the experimental arrangement for automatic and simultaneous measurement of EM fields. The source is a reflex klystron with an output of 200 mW over the 62.3–62.8-GHz frequency range and the waveguide components are standard RG98/U (WG 25).

Fig. 1 should be compared with [9, fig. 3]; comments can therefore be restricted to the additional features in Fig. 1. The detected output from the differential amplifier feeds two selective amplifiers, one tuned to f_m, the frequency of the dipole's vibration, and the other to $2f_m$. The second-harmonic output, measured by a moving-coil meter, represents the square of the amplitude of the electric field. The output from the selective amplifier tuned to f_m is connected to a switch. In position 1, the operation of the system is automatic. The amplified output from the PSD actuates the servo motor, which positions the dielectric vane of the calibrated phase shifter. With the switch in position 2 the output of the selective amplifier is displayed on the moving-coil meter and field measurements are taken by manually adjusting the phase shifter.

For details of the mechanism for supporting and vibrating the dipole and positioning it in the EM field, reference should be made to the original paper [9].

VI. Far-Field Measurements

In order to verify the system's performance, we explored the far-field region of a linearly polarized pyramidal horn. The simple theoretical formulas for the amplitude and phase variations with distance from a point source provide a convenient check. In all the measurements here reported, $\lambda = 4.8$ mm and the dipole was a straight piece of SWG45 copper wire 2.1 mm long.

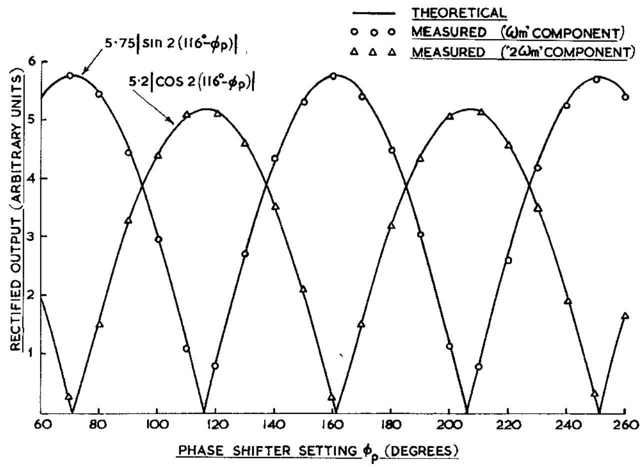

Fig. 2. Variations of the fundamental and second-harmonic components of the detected signal with phase-shifter setting.

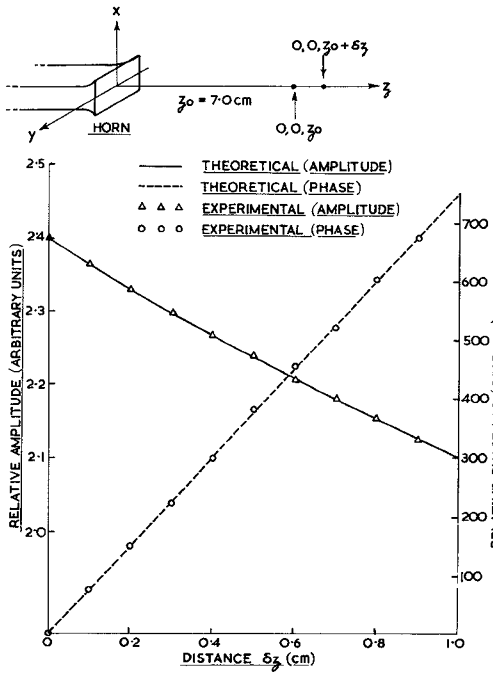

Fig. 3. Far-field amplitude and phase of a pyramidal horn.

A. Dependence of the Fundamental and Second-Harmonic Components of the Detected Signal on the Phase-Shifter Setting

Before measuring the field, a preliminary experiment was performed to verify that the rectified outputs of the two selective amplifiers depend on the phase-shifter setting according to (3) and (4). These equations form the basis of the simultaneous determination of amplitude and phase. In this test, the system was operated manually and the dipole was located in the far field of the horn.

The observations are presented in Fig. 2. It is particularly important to note that the maxima of each component are equal, because this is an indication that: 1) the differential amplifier was properly adjusted, and 2) the antenna was correctly matched to the phase shifter. Subsequent field measurements were therefore free from errors due to the back-scattered unmodulated signal [9].

B. Measurements of Amplitude and Phase

The far field of the horn was explored by measuring both the amplitude and phase of the x component of the electric field. The measurements were made at discrete points along the z axis, using the automatic system. The results of the measurements are shown in Fig. 3. The theoretical curves are those for a distant point-source located in the throat of the horn.

VII. Conclusions

An automatic system which simultaneously measures amplitude and phase distributions of millimeter-wave fields has been described. The principle of the system is that of the vibrating-dipole technique. The high accuracy of the system has been demonstrated by measurements in a far field of known configuration.

The simultaneous measurement of amplitude and phase in a homodyne detection system which uses only one hybrid junction is possible because the wave reradiated by the vibrating dipole is phase modulated. The amplitudes of the fundamental and second-harmonic components of the detected signal vary as the sine and cosine, respectively, of the same phase angle. All the other modulated-scattering techniques employ double-sideband amplitude modulation with carrier (DSBWC) of the scattered wave [8]. The simultaneous measurement of amplitude and phase in a homodyne system with DSBWC is possible [10], but requires two hybrid junctions and also a 3-dB coupler.

To take full advantage of the automatic system the phase shifter employed should have a sufficiently large differential phase-shift. Our phase shifter was of the dielectric-vane type, with maximum differential phase-shift of only 180°. Therefore automatic field measurements were restricted to such regions in space in which phase changes were within 180°. To continue measurements beyond this region it was necessary to switch off the servo system and to manually adjust the phase shifter to a new convenient setting.

References

[1] J. H. Richmond, "A modulated scattering technique for measurement of field distributions," *IRE Trans. Microwave Theory Tech.*, vol. MTT-3, pp. 13–15, July 1955.
[2] B. J. Strait and D. K. Cheng, "Microwave magnetic-field measurements by a modulated scattering technique," *Proc. Inst. Elec. Eng.*, vol. 109B, pp. 33–39, Jan. 1962.
[3] A. Vural, D. K. Cheng, and B. J. Strait, "Measurement of diffraction fields of finite cones by a scattering technique using light modulation," *IEEE Trans. Antennas Propagat.* (Commun.), vol. AP-11, pp. 200–201, Mar. 1963.
[4] T. Toyonaga, "Antennas for measurement of microwave electromagnetic field by a light-modulated scattering technique," *Electron. Commun. Japan*, vol. 54-B, 1971.
[5] K. Iizuka, "Photoconductive probe for measuring electromagnetic fields," *Proc. Inst. Elec. Eng.*, vol. 110, pp. 1747–1754, Oct. 1963.
[6] A. L. Cullen and J. C. Parr, "A new perturbation method for measuring microwave fields in free-space," *Proc. Inst. Elec. Eng.*, vol. 106B, pp. 836–844, Nov. 1955.
[7] K. Iizuka, "A new technique for measuring an electromagnetic field by a coil spring," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-11, pp. 498–505, Nov. 1963.
[8] R. J. King, "An amplitude and phase measuring system using a small modulated scatterer," *Microwave J.*, vol. 8, pp. 173–190, Mar. 1965.
[9] N. A. Mathews and H. Stachera, "A vibrating-dipole technique for measuring millimeter-wave fields in free space," this issue, pp. 103–110.
[10] J. D. Dyson, "The measurement of phase at UHF and microwave frequencies," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-14, pp. 410–423, Sept. 1966.

High-Frequency Gunn Oscillators

THOMAS G. RUTTAN

***Abstract*—Recent work to achieve high output power of "fundamental mode" Gunn-effect oscillators at frequencies ranging from 25 to 71 GHz is described. Ambient powers of 370 mW at 6.7-percent efficiency at 25 GHz, 260 mW at 4.5-percent efficiency at 38 GHz 150 mW at 4-percent efficiency at 54 GHz, and 30 mW at 1-percent efficiency at 71 GHz were obtained from single-diode structures. Combining two diodes in a push–pull circuit yielded 400 mW at 3.5-percent efficiency at 32 GHz and 260 mW at 4.0-percent efficiency at 42 GHz. This represents some of the highest powers and efficiencies reported to date from millimeter-wave Gunn-effect oscillators.**

I. Introduction

Millimeter-wave Gunn-effect oscillators have been in existence since the early days of Gunn-effect work [1]–[5], but have only been capable of low output power for some local oscillator applica-

Manuscript received April 9, 1973; revised August 29, 1973.
The author is with Varian Associates, Palo Alto, Calif. 94303.