TABLE III
SUMARY OF CALORIMETER CHARACTERISTICS

Guide Size	Frequency Range (kmc)	Entry Waveguide	Sensitivity (μv/mw)	Time Constant (minutes)	Power Handling Capacity (mw)	Minimum Measurable Power With 5 Per Cent Accuracy* (in microwatts)
3/8″ Coaxial	0 –10	twin	32	1.2	100	140
RG-51/U	7.5–10	twin	30	4.0	100	250
RG-52/U	8.2–12.4	Y	23	2.6	100	140
RG-107/U	12.4–18	twin	29	2.7	100	140
RG-66/U	18 –26.5	twin	41	1.7	100	170
RG-96/U	26.5–40	Y	46	1.8	300	50
RG-97/U	33 –50	Y	41	1.1	200	50
RG-98/U	50 –75	Y	51	1.1	100	50

* Based on use of Liston-Becker Model 14 Breaker-Amplifier or equivalent.

present when bolometers are used.[10] If one desires, the calorimeters can be calibrated and used as field instruments since they are rugged devices. Sensitivities are such that powers of as low as 50 to 100 μw can be measured with reduced accuracies of the order of 5–10 per cent. Table III is a summary of calorimeter characteristics.

[10] M. Sucher and H. J. Carlin, "The operation of bolometers under pulsed power conditions," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. 3, pp. 45–52; July, 1955.

ACKNOWLEDGMENT

In connection with the material reported in this and the companion paper[1] credit is due E. Barcomb for much of the detailed design work and Miss M. Zusman, E. Molloy and S. Kanarek for many of the rf measurements.

Thanks are also due Miss M. Eschwei and Mrs. C. Ruch for their valuable work in preparing the various thermal isolating sections and film loads.

Amplitude Stabilization of a Microwave Signal Source *

GLENN F. ENGEN†

Summary—**Recent developments in the microwave field have provided new tools for use in regulating the output amplitude of a microwave signal source. An amplitude or power stabilizer has been constructed at the National Bureau of Standards Boulder Laboratories, using the recently developed self-balancing dc bolometer bridge and a commercially available, electrically controlled, ferrite attenuator which achieves power stabilities of a few parts in 10^4 per hour.**

Use of a high directivity directional coupler permits stabilization of the forward traveling component of the signal, thus providing the equivalent of a *matched*, stable generator. In practice, a broad-band source match of vswr less than 1.05 is achieved, and this figure may be further improved, at a given frequency, by suitable tuning. In addition, the device has applications as a precision broad-band attenuator, since known changes in power level may be achieved by switching certain of the associated dc components.

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THE recent and continuing advances in the micro wave measurements art are continually imposing greater demands upon the stability of the microwave signal source. Except for the use of regulated power supplies, and stabilized environmental conditions, the problem of amplitude or power stability has received comparatively little attention—much less than the companion problem of frequency stability, and such efforts as have been made in this field[1,2] have apparently stopped short of recognizing all of the potential advantages of this technique. On the general philosophy of stabilization a recent author has appropriately

[1] I. K. Munsen, "Microwave power stabilizer," *Rev. Sci. Instr.*, vol. 21, p. 622; July, 1950.
[2] J. P. Vinding, "An automatic gain control system for microwaves," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. 4, pp. 244–245; October, 1956.

commented, "that voltage and temperature regulators are themselves feeedback or servo systems. It therefore is logical to apply the feedback loop directly to the output. The extreme precision in the control of contributory factors can ben be relaxed."[3]

General Description

The power stabilizer to be described in the following paragraphs follows this general plan (Fig. 1). A portion of the output signal is split off by the directional coupler, detected, a correction signal is derived, and following amplification, this portion is used to drive the electrically controlled ferrite attenuator in the required direction to maintain a constant output.

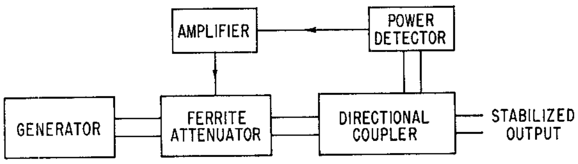

Fig. 1—Block diagram of power stabilizer.

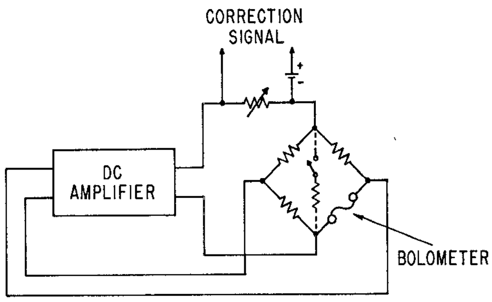

Fig. 2—Basic circuit of power detector.

Power detection is achieved by means of a self-balancing dc bolometer bridge which has been described in an earlier paper.[4] The basic circuit is shown in Fig. 2. Fluctuations in the microwave signal are reflected as changes in the current required to maintain the bridge balance, and comparison of this current with the potential of a mercury cell by use of a suitable variable resistor yields the desired correction signal.

The absolute stability which may be achieved by a system of this type is limited, for practical purposes, by the detector stability. Because a bolometer (barretter) has a higher inherent stability than a crystal, it was chosen for this application; in addition, the use of a bolometer makes possible a novel attenuator to be described later. The bolometer does require, however, a temperature controlled environment, in this case to $\pm 0.005°C$.

[3] D. D. King, "Measurements at Centimeter Wavelength," D. Van Nostrand Co., New York, N. Y., p. 167; 1952.

[4] G. F. Engen, "A self-balancing dc bridge for accurate bolometric power measurements," *J. of Res., Natl. Bureau of Standards*, vol. 59, p. 101; August, 1957, R.P. 2776.

Equivalent Circuit

The use of a directional coupler to sample the output signal has been described. But the output signal provided by the side arm of an ideal coupler connected in the indicated manner is a measure only of the *forward* traveling component of the signal. Accordingly, it is this forward component which is held constant by the stabilizer. But this is characteristic of a matched generator, thus it is recognized intuitively that not only does this technique provide the equivalent of a *stable* generator, but that of a *matched* generator as well.

In order to put these ideas in more definite form, reference is first made to the circuit of a conventional generator feeding an arbitrary line. In Fig. 3 let $\boldsymbol{b}$ and $\boldsymbol{a}$ represent the amplitudes of the forward and reverse voltage waves respectively, with the other quantities defined in the usual manner. Then

$$\boldsymbol{b} = \frac{e}{2}(1 - \Gamma_g) + \boldsymbol{a}\Gamma_g \qquad (1)$$

where

$$\Gamma_g = \frac{Z_g - Z_0}{Z_g + Z_0}.$$

In particular it is noted that even though a stable generator, e, is postulated, $\boldsymbol{b}$ has, in general, a functional dependence upon $\boldsymbol{a}$ through the factor Γ_g. Only for the special case $\Gamma_g = 0$ is $\boldsymbol{b}$ independent of $\boldsymbol{a}$.

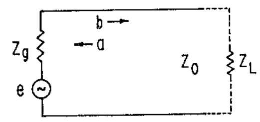

Fig. 3—Circuit for (1).

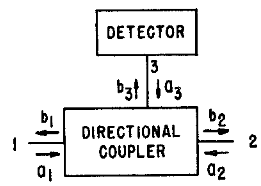

Fig. 4—Circuit for (2).

Consider next the relationships that prevail at the terminal surfaces of the directional coupler. In Fig. 4 the $\boldsymbol{a}$'s and $\boldsymbol{b}$'s represent the amplitudes of the incident and emergent waves respectively. It can be shown that[5]

$$\boldsymbol{b}_2 = \boldsymbol{b}_3\left[\frac{S_{12}}{S_{13}} + \Gamma_d\left(S_{23} - \frac{S_{12}S_{33}}{S_{13}}\right)\right] + \boldsymbol{a}_2\left(S_{22} - \frac{S_{12}S_{23}}{S_{13}}\right) \qquad (2)$$

[5] The derivation is a straightforward solution of the scattering equations of a three-arm junction.

where Γd is the reflection coefficient of the power detector, and the $S_{m,n}$ are the scattering coefficients of the coupler.

The first term on the right is a measure of the signal delivered to the detector and is held constant by the stabilizer. Thus it is noted that the output, or outgoing wave is given by the sum of a constant term and a term proportional to the reverse wave. Comparison of (2) with (1) indicates that the factor

$$\left(S_{22} - \frac{S_{12}S_{23}}{S_{13}}\right)$$

plays the role of Γ_g in the stabilized output.

The term S_{22} is the reflection coefficient of Arm 2 with the first and third arms terminated in matched loads. For a main guide vswr of 1.05, S_{22} has a magnitude of approximately 0.025. In addition, $|S_{12}| < 1$ while

$$\left|\frac{S_{23}}{S_{13}}\right| = 0.01$$

for a coupler directivity of 40 db. Assuming these values combine in the worst phase, the equivalent $|\Gamma_g|$ has a value less than 0.035, which corresponds to a source vswr of 1.07.

The term

$$\left(S_{22} - \frac{S_{12}S_{23}}{S_{13}}\right)$$

may also be measured experimentally by the following technique. Arm 1 of the coupler is terminated in a variable load which is adjusted to produce a null in the output of Arm 3 with Arm 2 connected to the signal source. It can be shown, subject to this adjustment, that the input reflection coefficient at Arm 2 is just the desired quantity,

$$S_{22} - \frac{S_{12}S_{23}}{S_{13}}.$$

Measurement of a commercially available coupler yielded for this quantity corresponding values of vswr < 1.05 over an entire waveguide band.

Finally, if a tuning transformer is included in Arm 2, this term may be reduced at a given frequency to as low a value as the state of the impedance measuring art permits by tuning for an impedance match at Arm 2 after the previous adjustment has been made.

Thus far the analysis has assumed that the first term on the right in (2) is held constant by the stabilizer action. This assumption is in error on two distinct counts: first the feedback loop does not have infinite gain and second, no method of adjusting the phase of this term is provided. A change in the phase of b_3 is equivalent, however, to a shift in phase of the generator, and thus is of no concern since in practice the signal source has in general a frequency or phase instability far in excess of what could be introduced by the stabilizer operation. The treatment of noninfinite gain will be reserved for the Appendix where it will be shown that the deterioration in performance due to this effect is negligible in this instrument.

Performance

The performance of the system is shown in Fig. 5 and Fig. 6 which are recordings of the fluctuations in power output of the main guide as measured by a dc bridge[4] of the type referenced. In Fig. 5 the improvement in performance over an unstabilized klystron is shown, where the klystron was operated with stabilized beam, reflector, and heater potentials, and in a stabilized environment. The result of introducing a 3-db power change (by means of an attenuator) ahead of the stabilizer is shown in Fig. 6, where the time scale has been reduced to one minute per division instead of one hour as in Fig. 5. It will be noted that the change in power level is just discernible. The stabilization factor as determined from these measurements is approximately 10,000.

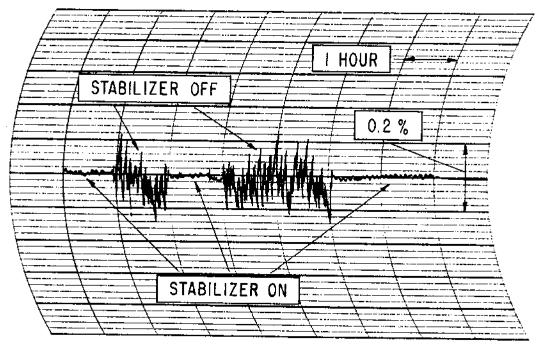

Fig. 5—Improvement in performance over an unstabilized klystron.

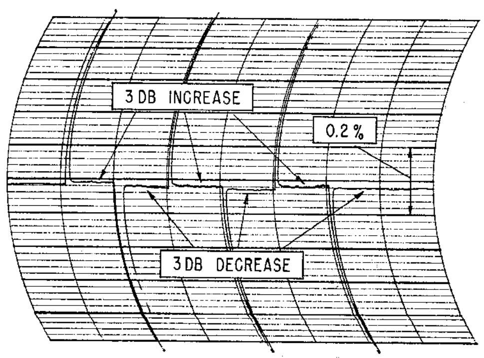

Fig. 6—Response of stabilizer to a 3-db change in input power.

These records also indicate a time constant for the stabilizer of about $\frac{1}{2}$ second. This could be reduced, if required, at the expense of the stabilization factor, but operating experience to date indicates that this value is satisfactory.

A Precision Attenuator

With suitable modification the instrument can also be used to produce known changes in power level, and thus serve as an attenuator, in the following manner. For definiteness, assume that the bolometer employed as power detector requires a total of 4 mw of power to bring it to the nominal operating resistance, and that the stabilizer has been so adjusted that this power is comprised of 3 mw of dc and 1 mw of rf. If a resistor is now shunted across the bridge as indicated by the dotted lines in Fig. 2, some of the dc power will be diverted from the bolometer and the action of the stabilizer will replace this with rf power. Thus by a proper choice of resistor the rf power can be made to increase from 1 mw to 2 mw or any other value within limits, and a load connected to the main arm of the directional coupler will experience a proportional increase in power. The accuracy of this result will depend in practice primarily upon the accuracy with which the initial conditions can be established and is expected to be of the order of 0.01 db for attenuations of 3 db with decreasing accuracy at larger values.

It should be noted that this accuracy is independent of the characteristics of the microwave components such as load vswr, etc. provided that these characteristics are independent of power level, and the frequency of the signal source remains constant. The accuracy is also independent, to a first approximation, of the bolometer substitution error.[6]

Conclusion

The amplitude or power stabilization technique has thus been shown to produce a variety of useful results. In conclusion, these are,

1) Stable amplitude—A stability of a few parts in 10^4 per hour is achieved.
2) Broad-band source match—A match of vswr ≤ 1.05 is obtained over an entire waveguide frequency band. This match may be further improved at a given frequency to a degree limited for practical purposes only by the state of the art in recognizing a matched load.
3) Constant source impedance—The technique holds the source impedance constant, regardless of its value, which is useful in certain applications.
4) Increased available power—In order to achieve a matched source it is common practice to pad the generator by 20 db or more, although ferrite isolators are finding a growing use for this purpose. The stabilizer to a large degree eliminates the need for this padding, although it does introduce a nominal 3-db loss in the control element. The generator padding cannot be entirely eliminated in general because of the possibility of pulling the oscillator frequency, although operating experience to date indicates that in practice this effect is usually negligible. The ultimate system would employ frequency stabilization of the oscillator and hence completely eliminate the need of padding. The power stabilizer can thus provide an effective increase in the available power of as much as 17 db or more over conventional dissipative pads.
5) Precision attenuator—Over a 0–10-db range or greater, the technique provides a precision attenuator which requires no calibration.

[6] The accuracy is independent of the bolometer dc-rf substitution error provided that the bolometer resistance law, at a constant ambient temperature can be expressed in the form $r=f(P_{dc}+KP_{rf})$ where K is constant and P_{dc} and P_{rf} are the dc and microwave power dissipated in the bolometer, respectively.

Appendix

A rigorous treatment of the effect of changes in magnitude of $\boldsymbol{b}_3$ in (2) is tedious, and in its place the following intuitive treatment will be supplied.

It has been observed in connection with (1) that $\boldsymbol{b}$ has in general a functional dependence in both amplitude and phase upon $\boldsymbol{a}$, while the phase of $\boldsymbol{b}$ is ordinarily of no interest. The existing state of the art is such, in fact, that the phases of the various quantities in (1) do not permit ready measurement; it is rather the magnitudes of these quantities which are usually observed.

If the generator is connected to a passive load of reflection coefficient Γ_l, then $\boldsymbol{a}=\boldsymbol{b}\Gamma_l$ and (1) becomes:

$$\boldsymbol{b}(1-\Gamma_l\Gamma_g)=\frac{e}{2}(1-\Gamma_g)$$

from which it follows:

$$\frac{\left|\frac{e}{2}(1-\Gamma_g)\right|}{1+|\Gamma_l\Gamma_g|}\leq|\boldsymbol{b}|\leq\frac{\left|\frac{e}{2}(1-\Gamma_g)\right|}{1-|\Gamma_l\Gamma_g|}.$$

Thus if the load is matched ($\Gamma_l=0$), and

$$|\boldsymbol{b}|=\left|\frac{e}{2}(1-\Gamma_g)\right|$$

while for $\Gamma_l\neq 0$ there is an uncertainty in the magnitude of $\boldsymbol{b}$ by the factor $1/1\pm|\Gamma_l\Gamma_g|$. In practice the interest in Γ_g stems from the role it plays in determining the uncertainty in $|\boldsymbol{b}|$. Define $\delta\boldsymbol{b}_1$ and $\delta\boldsymbol{b}_2$ such that

$$|\boldsymbol{b}_0|+|\delta\boldsymbol{b}_1|=\frac{|\boldsymbol{b}_0|}{1-|\Gamma_l\Gamma_g|}$$

and

$$|\boldsymbol{b}_0|-|\delta\boldsymbol{b}_2|=\frac{|\boldsymbol{b}_0|}{1+|\Gamma_l\Gamma_g|}$$

where $\boldsymbol{b}_0$ is the value of $\boldsymbol{b}$ when $\Gamma_l=0$. $|\delta\boldsymbol{b}_1|$ and $|\delta\boldsymbol{b}_2|$ thus represent the uncertainty in $|\boldsymbol{b}|$ when the generator is connected to other than a matched load. Solving for $|\Gamma_g|$ yields:

$$|\Gamma_g| = \frac{1}{|\Gamma_l|}\,\frac{|\delta b_1|}{|b_0| + |\delta b_1|},$$

$$|\Gamma_g| = \frac{1}{|\Gamma_l|}\,\frac{|\delta b_2|}{|b_0| - |\delta b_2|},$$

or if Γ_g is small $|\delta b_1| \ll |b_0|$, $|\delta b_1| = |\delta b_2| = |\delta b|$, and

$$|\Gamma_g| \approx \frac{1}{|\Gamma_l|}\,\frac{|\delta b|}{|b_0|}. \tag{3}$$

An upper limit to $|\Gamma_g|$ due to noninfinite gain of the feedback loop may be obtained by the following experimental technique. First a matched load is connected to the stabilized output and the magnitude of b_3 (2) observed. The matched load is then replaced by a sliding short which is adjusted to produce the maximum change in $|b_3|$.

Since b_2 is a linear function of b_3, the value of $|b_3|$ and $|\delta b_3|$ as thus obtained may be substituted in (3) to obtain an upper limit to the equivalent $|\Gamma_g|$ due to finite gain.

Application of this technique to the stabilizer yielded a corresponding vswr of less than 1.001 which indicates this term is negligible in comparison with

$$\left(S_{22} - \frac{S_{12}S_{23}}{S_{13}}\right).$$

Acknowledgment

The author acknowledges the contributions of R. W. Beatty who proposed the application as a precision attenuator, and thanks him for his valuable criticism in the preparation of the manuscript.

A Simple Artificial Anisotropic Dielectric Medium*

R. E. COLLIN†

Summary—**The anisotropic properties of an infinite stack of thin dielectric sheets separated by another set of thin sheets with a different dielectric constant is investigated. It is shown that the anisotropic properties are brought about because of the two distinct modes of propagation which can exist in such a stacked array of sheets. The limiting forms of the wave solutions and second-order results for the equivalent dielectric constants are given.**

Introduction

ELECTROMAGNETIC wave propagation in homogeneous anisotropic dielectric media is well understood and discussed in most text books on optics.[1] At optical frequencies, one has to rely on naturally occurring crystalline media with anisotropic properties. At microwave frequencies where the wavelength is much greater, it is possible to construct artificial dielectric media having either isotropic or anisotropic properties. For example, nonsymmetrical metallic obstacles arranged in a cubical array or symmetrical (also unsymmetrical) obstacles arranged in a noncubical array in a suitable binder will produce an artifical dielectric with anisotropic properties.[2] However, this paper will consider only the anisotropic properties of an infinite stack of dielectric sheets as illustrated in Fig. 1. Each sheet of thickness t and relative dielectric constant κ_a is separated by a sheet of thickness d and relative dielectric constant κ_b. In order to behave essentially as a homogeneous medium, the spacing S must be small in comparison with the wavelength λ_0 of the radiation. Conditions on S will be given later. Because of the similar disposition of the sheets with respect to the y and z axis, it can be anticipated that this medium will have the same effective dielectric constant along the y and z axis, but a different effective dielectric constant in the x direction and therefore corresponds to a uniaxial crystalline medium.

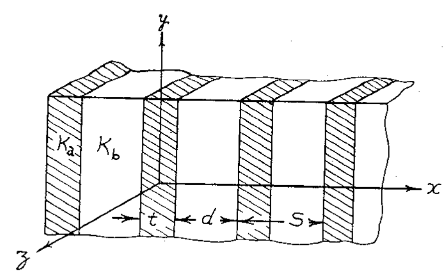

Fig. 1—An artificial anisotropic dielectric medium.

Before considering propagation in this stacked dielectric sheet medium, the theory of wave propagation in a homogeneous uniaxial crystalline medium will be briefly reviewed for later comparison.

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† Elec. Eng. Dept., Case Institute of Technology, Cleveland, Ohio; formerly with Canadian Armament Res. and Dev. Estab., Valcartier, P. Q., Can.

[1] G. Joos, "Theoretical Physics," Blackie and Son, Ltd., London, 2nd ed., ch. 19; 1951.

[2] G. Estrin, "The effects of anisotropy in a three-dimensional array of conducting disks," Proc. IRE, vol. 39, pp. 821–826; July, 1951.