TABLE I
GLOW DISCHARGE TUBE AND DIODE SENSITIVITIES TO X-BAND RADIATION

Tube	V_n(μV)	A_r(mm^2)	I (mA)	R(V·mW^{-1})	NEP(pW·Hz$^{-1/2}$)	t_r(μs)
A059-2	40	8	2	4.45	1.44	2.1
NE-4	46	13	3	3.69	2.17	3.0
NE-76	50	8	3	3.10	2.23	2.0
A 215	153	5	2	15.4	3.25	1.3
T2-32-1	65	13	6	2.20	3.81	2.0
NE-3	39	9	3.4	3.81	6.20	2.4
NE-7	57	25	40.0	3.29	6.59	4.5
AR-9	84	12	2.5	4.26	7.51	2.5
NE-51-H	21	12	1.8	0.09	9.82	4.0
5AB-A	57	11	8.0	4.24	9.86	10.0
5AB-B	54	10	13.0	2.86	11.0	2.3
5AB	57	11	12.0	4.11	11.4	2.4
NE-81	73	14	15.0	3.67	15.9	2.0
LT2-24-2	52	6	10.0	0.33	19.1	0.8
A059-9	57	7	8.0	3.31	24.5	2.1
LT2-32-1	13	11	20.0	2.56	25.7	1.6
LT2-27-2	73	7	9.0	0.47	25.7	0.8
5AH-D	46	17	6.5	1.92	28.2	2.4
NE-2U	77	7	17.0	1.67	29.8	1.4
NE-84	137	7	4.2	2.32	30.7	1.0
AIB	72	6	17.0	4.46	34.9	0.8
5AHA	40	14	4.5	3.07	37.6	1.6
5AH	54	16	15.0	1.98	39.4	2.0
TRJ250	10	4	I_1 = 2, I_2 = 0.5	0.50	39.5	2.5
AIC	70	4	12	9.00	41.1	2.0
IN238 Crystal * Diode (Sylvania)	7	15	-	211.0	0.318	-
MA-40207 [12] Schottky-barrier diode	-	-	0.02	5.0	1.1	-

Note: I is current and t_r is rise time.
* Parameters measured in test setup.

Redesign of these indicator lamps for detector applications should improve their sensitivities and speed of response further.

ACKNOWLEDGMENT

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REFERENCES

[1] H. A. Burroughs and A. B. Bronwell, "High sensitivity gas tube detectors," *Tel.-Tech.*, vol. 11, p. 62, 1952.
[2] N. H. Farhat, "A plasma microwave power density detector," *Proc. IEEE* (Corresp.), vol. 52, pp. 1053–1054, Sept. 1964.
[3] D. C. McCain, "A plasma video detector," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-18, pp. 64–65, Jan. 1970.
[4] N. S. Kopeika, "Millimeter wave detection with glow discharge plasma and its application in holography," Ph.D. dissertation, Univ. Pennsylavania, Philadelphia, 1971.
[5] N. S. Kopeika and N. H. Farhat, "An economical, fast, and sensitive millimeter wave video detector," in *European Conf. Electrotechnics, Eurocon 1974 Conf. Dig.*, pp. C7-6(1)–C7-6(2).
[6] N. S. Kopeika and N. H. Farhat, "Viedo detection of millimeter waves with glow discharge tubes," *IEEE Trans. Electron Devices*, vol. ED-22, pp. 534–548, Aug. 1975.
[7] N. H. Farhat and N. S. Kopeika, "A low-cost millimeter-wave glow-discharge detector," *Proc. IEEE* (Lett.), vol. 60, pp. 759–760, June 1972.
[8] N. H. Farhat, "Optimization of millimeter-wave glow-discharge detectors," *Proc. IEEE* (Lett.), vol. 62 pp. 279–281, Feb. 1974.
[9] N. S. Kopeika, "On the mechanism of glow discharge detection of microwave/millimeter wave radiation," *Proc. IEEE* (Lett.), vol. 63, pp. 981–982, June 1975.
[10] G. F. Weston, *Cold Cathode Glow Discharge Tubes.* London: Iliffe Books Ltd., 1968.
[11] W. G. Miller, *Using and Understanding Miniature Neon Lamps*, Indianapolis, Ind.: H. W. Sams & Co., Inc., The Bobs Merrill Co., Inc., 1972.
[12] Bulletin 4201, "Schottky barrier detector diodes. . . ," Microwave Associates, Inc., Burlington, Mass., Jan. 1973.
[13] N. S. Kopeika, "The influence of external electrodes in millimeter wave video detection with glow discharge plasmas," in *1974 IEEE Nat. Telecommunications Conf. Rec.*, pp. 1069–1073.
[14] Catalog SF4–2, "Signalite neon glow lamps. . . ," Signalite, Division of General Instrument, Inc., Neptune, N. J., Jan. 1973.
[15] Glow Lamps Catalog 3–6254, "Glow lamps-indicator and circuit components," Miniature Lamp Products Dep., General Electric Corp., Jan. 1973.
[16] A. D. MacDonald, *Microwave Breakdown in Gases.* New York: Wiley, 1966.

Light Transmittance and Microwave Attenuation of a Gold-Film Coating on a Plastic Substrate

SAM Y. LIAO, MEMBER, IEEE

***Abstract*—Light transmittance and microwave attenuation of a gold-film coating on a plastic substrate is investigated. The dependence of the transmittance of visible light upon the thickness or resistivity of a gold-film coating on a plastic substrate is analyzed numerically. The microwave attenuation produced in the far field over the frequency range of 100 MHz–30 GHz by the gold film is calculated and compared with experimental data. An optimum condition is established between the light transmittance and the microwave attenuation. The results are applicable to any transparent glass coated with any thin metallic film.**

I. INTRODUCTION

In certain engineering applications, it is often desirable to use a metallic-thin-coated glass to transmit optimum light intensity at visible-light frequencies and also to attenuate as much of the EM radiation as possible at microwave frequencies. For example, the head of a missile may be formed of a plastic–glass dome coated on its concave surface by a gold film which is designed so that the optimum amount of light be transmitted into the dome for picture taking by cameras while, at the same time, the microwave radiation is attenuated sufficiently to eliminate its interference with the electronic systems inside the dome.

The microwave attenuation of a metallic-film-coated glass was investigated by several workers in the near field [1], [2]. Their work was carried out at a distance of 1 in away from the power source. This is not a complete treatment of the problem. This short paper presents the microwave attenuation in the far field.

II. OPTICAL PROPERTIES OF GOLD FILM

The optical properties of materials are usually characterized by two parameters, the index of refraction n and the extinction coefficient k. The complex refractive index is given by

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The author is with the School of Engineering, California State University at Fresno, Fresno, Calif. 93740, and works for the Naval Weapons Center, China Lake, Calif. 93555 during the summer.

$$N = n - jk. \qquad (1)$$

It is assumed that light is normally incident upon a thin absorbing film N_1 of thickness t_1, and that it is transmitted through an absorbing substrate of complex refractive index N_2, and then emerges into the air. The incidence and emergence media are dielectrics of refractive index n_0. The reflection loss between the substrate and the air is small and, for convenience, is taken as zero. Fig. 1 shows light transmittance, reflection, and absorption through a thin absorbing film and a substrate.

The reflection loss R and the transmittance T are given by [3], respectively, as

$$R = \frac{a_1 e^{\sigma} + a_2 e^{-\sigma} + a_3 \cos v + a_4 \sin v}{b_1 e^{\sigma} + b_2 e^{-\sigma} + b_3 \cos v + b_4 \sin v} \qquad (2)$$

$$T = \frac{16 n_0 n_2 (n_1^2 + k_1^2)}{b_1 e^{\sigma} + b_2 e^{-\sigma} + b_3 \cos v + b_4 \sin v} \qquad (3)$$

where a_1, a_2, a_3, a_4, b_1, b_2, b_3, and b_4 are determined by the index of refraction n and the extinction coefficient k, σ is the attenuation constant of the film coating, and v is the phase angle in the film coating. The absorption loss A is then given by

$$A = 1 - R - T. \qquad (4)$$

The total attenuation loss L is given by

$$L = A + R. \qquad (5)$$

However, when the concave surface of a plastic dome is uniformly coated with an EM interference shield of gold film, the light is normally incident into the plastic substrate N_2, and transmits through the thin gold-film N_1, and then emerges into the air n_0. From the EM theory of luminous transmission in transparent media, the light transmittance is the same regardless if the light is normally incident upon the substrate medium N_2 or upon the absorbing film N_1. Hence the total attenuation loss is the same in both cases.

The refractive index n_0 of air or vacuum is unity. The substrate material of a plastic dome is assumed to be nonabsorbing plastic–glass and its refractive index n_2 is taken as 1.50. For the visible-light region, the values of the refractive index n and of the extinction index k of a gold-film coating deposited in a vacuum are taken from tabulated data [4]. The thickness t_1 of the gold-film coating is assumed to be in the range of 10–100 Å. A computer program was written for computing (2) and (3) for the light transmittance T and the reflection loss R. From the values of T and R, the absorption loss A and the total attenuation loss L are calculated. The results are graphically presented in Fig. 2.

III. RESISTIVITY OF GOLD FILM

Very thin metal films have a much higher resistivity than the bulk metal because of the scattering of the electrons from the surface of the film. If the film thickness is very large compared to the electron mean-free path, the resistivity is expected to be nearly the same as that of a bulk metal. When the film thickness is of the order of the electron mean-free path, then the role of surface scattering becomes dominant. Fuchs [5] and Sondheimer [6] considered the general form of the solution of the Boltzmann equation for the case of a conducting film and found the film conductivity in terms of the bulk conductivity σ_0, the film thickness t, and the electron mean-free path p_0 as given by

$$\sigma = \frac{3t\sigma_0}{4p_0}\left[\ln\left(\frac{p_0}{t}\right) + 0.4228\right], \qquad \text{for} \quad t \ll p_0. \qquad (6)$$

The electron mean-free path of bulk gold at room temperature is 570 Å [7]. The resistivity of bulk gold at room temperature is $2.44 \times 10^{-6}\ \Omega \cdot \text{cm}$, and its corresponding conductivity is $4.1 \times 10^5\ \text{mho} \cdot \text{cm}^{-1}$ [8]. The surface resistance of conducting films is normally quoted in units of ohms per square. The resistivity of gold film for thicknesses from 10 to 100 Å is presented graphically in Fig. 3.

The resistivity is decreased as the thickness of the coated film is increased. However, the luminous transmittance is decreased as the resistivity of the film is decreased. Fig. 4 illustrates the relationship of light transmittance versus wavelength for a given resistivity of

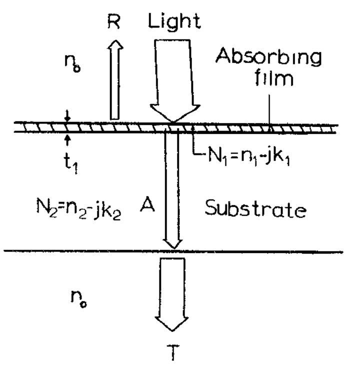

Fig. 1. Light transmittance, reflection, and absorption through thin film coated on a glass substrate.

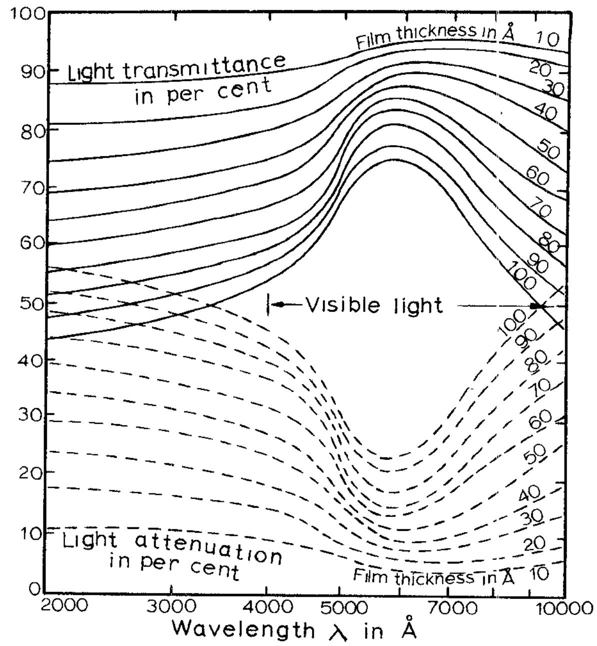

Fig. 2. Light transmittance T and light attenuation loss L versus wavelength λ with film thickness t as a parameter.

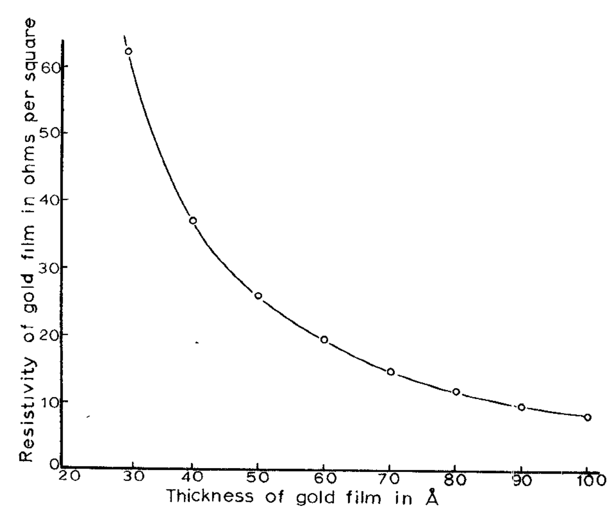

Fig. 3. Resistivity of gold film versus thickness of gold film.

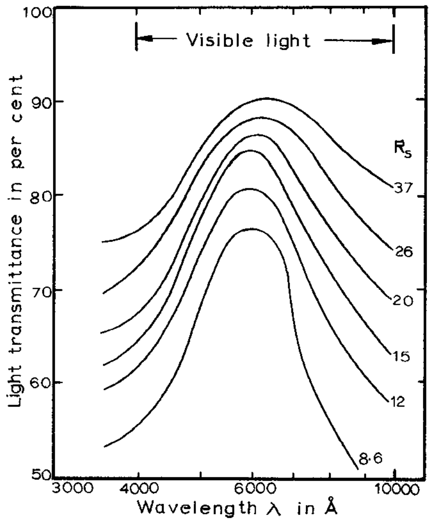

Fig. 4. Light transmittance versus wavelength with resistivity R_s as a parameter.

the coated film. If a power dissipation of 5 W/sq is allowed for deicing and defogging by the conducting coating on a plastic dome and a light transmittance of 80 percent is desired for picture taking by cameras, the resistivity of the gold film must be 12 Ω/sq while the film coating is designed so that its effective area must be 13 in^2 and the voltage applied to the coating terminations should be 28 V. The power dissipation can be calculated [9]

$$P = \frac{V^2}{RA} = \frac{(28)^2}{(12)(13)} = 5.0 \text{ W/sq.} \tag{7}$$

IV. MICROWAVE ATTENUATION

A conductor of high conductivity and low permeability has low intrinsic impedance. When a radio wave propagates from a medium of high intrinsic impedance into a medium of low intrinsic impedance, the reflection coefficient is high. From the plane-wave theory of attenuation in the far field, high microwave attenuation occurs in a shield made of material of high conductivity and low permeability. Next to copper, which is a standard material for EM shielding, gold has a higher conductivity. Since the electrical conductivity of a coated gold film is uniformly distributed, gold film is an ideal material for application to microwave attenuation where visible-light transmittance is required.

In general, the microwave attenuation M of a gold-film coating on a glass substrate is expressed by [10]

$$M = A + R + C \text{ dB} \tag{8}$$

where

- A absorption or penetration loss in decibels inside the shield;
- R reflection loss in decibels from the multiple boundaries of the shield;
- C correction term in decibels required to account for multiple internal reflections when the absorption loss A is much less than 10 dB for electrically thin film.

The absorption loss A is given by [10]

$$A = 8.686t(\mu\pi f\sigma_f)^{1/2} \text{ dB} \tag{9}$$

where

- t thickness of the film coating in meters;
- μ permeability of the film in henrys per meter;
- f frequency in hertz;
- σ_f conductivity of the coated film in mhos per meter.

Since the thickness of the coated film is very thin, for example 100 Å at most, the absorption loss A is very small and can be ignored.

The reflection loss R can be analyzed by means of conventional transmission-line theory. From Fig. 1 described previously, the reflection loss due to the multiple boundaries of the plastic dome coated with gold film is expressed by [11]

$$R = -20 \log \frac{2|Z_g|}{|Z_a + Z_g|} - 20 \log \frac{2|Z_f|}{|Z_g + Z_f|} - 20 \log \frac{2|Z_a|}{|Z_f + Z_a|}$$

$$= 20 \log \frac{|Z_a + Z_g||Z_g + Z_f||Z_f + Z_a|}{8|Z_g||Z_f||Z_a|} \text{ dB} \tag{10}$$

where

- Z_g intrinsic impedance of the glass substrate;
- Z_f intrinsic impedance of the coated gold film;
- Z_a intrinsic impedance of air or free space.

The intrinsic impedance of air or free space in the far field is 377 Ω. The intrinsic impedance of the glass substrate is about 194 Ω where the conductivity of the glass substrate σ_g is taken to be 10^{-12} mho/m and the relative permittivity of the glass substrate ϵ_r is taken as 3.78 for the frequency range of 100 MHz–30 GHz. The intrinsic impedance of the conducting film is given by [11]

$$Z_f = \left(\frac{j\mu\omega}{\sigma_f}\right)^{1/2} = (1 + j)\left(\frac{\mu\omega}{2\sigma_f}\right)^{1/2}. \tag{11}$$

Then the reflection loss R (10) simplifies to

$$R = 88 + 20 \log \left(\frac{\sigma_f}{f}\right)^{1/2} \text{ dB}. \tag{12}$$

When the value of the absorption loss A is smaller than 10 dB for very thin film, the correction term C [10] is accordingly reduced to

$$C = -48 + 20 \log [t(f\sigma_f)^{1/2}] \text{ dB}. \tag{13}$$

Finally, the total microwave attenuation M in the far field becomes

$$M = 40 - 20 \log (R_s) \text{ dB} \tag{14}$$

in which the surface resistivity R_s has been replaced by $1/t\sigma_f$.

It is very interesting to note that the microwave attenuation due to the coated gold film in the far field is independent of frequency and it is related only to the surface resistivity of the gold film. Fig. 5 shows graphically the microwave attenuation versus the surface resistivity of the gold-film coating. For a coated gold film which has a surface resistivity of 12 Ω/sq, the microwave attenuation is about 19 dB. The results agree with Hawthorne's conclusion [12].

V. CONCLUSION

As described at the beginning, maximum light transmittance and maximum microwave attenuation are required of the gold-film coating on the dome. The optimum condition which is determined by the power dissipation of the film coating and the 80 percent of light transmittance occurs at a surface resistivity of about 12 Ω/sq. In order to obtain 80-percent light transmittance, the thickness of the gold-film coating must be about 80 Å. For the frequency range

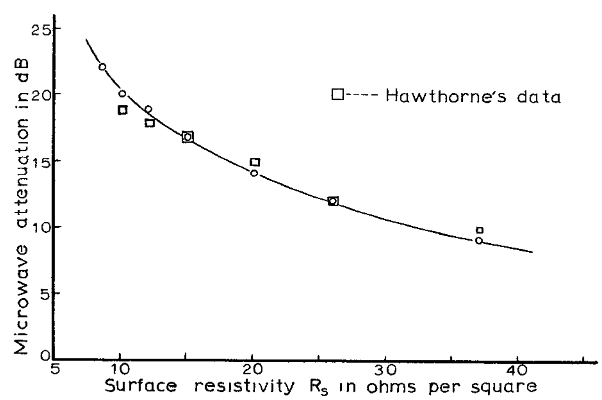

Fig. 5. Microwave attenuation versus resistivity of gold film in the far field.

of 100 MHz–30 GHz, the microwave attenuation is about 19 dB. The results of this study are applicable to any transparent glass coated with any thin metallic film.

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REFERENCES

[1] H. A. Lasitter, "Low-frequency-shielding effectiveness of conductive glass," *IEEE Trans. Electromagn. Compat.*, vol. EMC-6, pp. 17–30, July 1964.
[2] Genisco Test Rep. TR 10670, Feb. 1968.
[3] D. E. Gray, Ed., *American Institute of Physics Handbook*, 3rd ed. New York: McGraw-Hill, 1972, pp. 6-119–6-121.
[4] ——, *American Institute of Physics Handbook*, 3rd ed. New York: McGraw-Hill, 1972, p. 6–138.
[5] K. Fuchs, "The conductivity of thin film metallic films according to the electron theory of metals," *Proc. Cambridge Phil. Soc.*, vol. 30, p. 100, 1938.
[6] E. H. Sondheimer, "The mean-free path of electrons in metals," *Advan. Phys.*, vol. 1, p. 1, 1952.
[7] C. Kittel, *Introduction to Solid State Physics*, 2nd ed. New York: Wiley, 1962.
[8] *ITT Reference Data for Radio Engineers*, 5th ed., 1972.
[9] *Sierracin Intrex—Electrically Conductive Film Components*, Sierracin Corp., Sylmar, Calif., 1974.
[10] C. S. Vasaka, "Problems in shielding electrical and electronic equipments," U. S. Naval Air Development Center, Johnsville, Pa., Rep. NADC-EL-N5507, June 1955.
[11] S. A. Schelkunoff, *Electromagnetic Waves*. New York: Van Nostrand, 1943, pp. 83 and 226.
[12] E. I. Hawthorne, "Electromagnetic shielding with transparent coated glass," *Proc. IRE*, vol. 42, pp. 548–553, Mar. 1954.

Computer Program Descriptions

NOVA (Network Optimization Via Adjoints)

PURPOSE: Least pth optimization of reflection coefficients and/or transducer gain of two-port microwave networks.

LANGUAGE: Fortran IV; 1145 cards, including comments.

AUTHORS: D. L. Herrick was with the Department of Electrical Engineering, University of Maine at Orono, Orono, Me. 04473. He is now with the Department of Electrical Engineering, Montana State University, Bozeman, Mont. 59715. J. C. Field is with the Department of Electrical Engineering, University of Maine at Orono, Orono, Me. 04473.

AVAILABILITY: ASIS/NAPS Document No. 02628. This document includes a program listing, flow charts, and user's guide including examples illustrating input data format. A deck may be obtained from J. C. Field, price furnished upon request.

DESCRIPTION: NOVA employs a least pth objective function [1] based on the following network responses: (1) input reflection coefficient, (2) output reflection coefficient, (3) transducer gain, or (4) a weighted combination of the first three responses. This objective function is minimized by the Fletcher–Powell algorithm [2], which was selected for its rapid, second-order convergence. The response gradients required by Fletcher–Powell are evaluated by means of adjoint network techniques [3].

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See NAPS document No. 02628 for 63 pages of supplementary material. Order from ASIS/NAPS c/o Microfiche Publications, 440 Park Ave. S., New York, N. Y., 10016. Remit in advance for each NAPS accession number, $9.95 for photocopies, $1.50 for microfiche. Outside of the U. S. and Canada, postage is $2.00 for a photocopy or $.50 for a microfiche. Make checks payable to Microfiche Publications.

The allowed network configuration for NOVA is a cascade arrangement of two-port circuit elements, with the possibility of a single parallel path.

Seven basic types of circuit elements are available. They include transmission lines, open- and short-circuited shunt stubs, resistors, capacitors, and inductors. The distributed elements may be lossy or lossless, the amount of loss being specified in decibels per wavelength. Additionally, a general two-port element type is provided. This element is characterized by its measured S parameters and is useful for representing transistors or any element for which experimental data must be used. With the exception of the general element, the user may select which of the network parameters are to be varied during optimization. Since the general element is represented empirically, it is never optimized.

To avoid using excessive computer storage, a maximum of 30 network parameters and 30 frequency points were selected for NOVA. Larger networks may be accommodated by simply redimensioning the appropriate arrays. Most of the input data is in NAMELIST format to help identify each variable on a data card. The program is presently running on an IBM SYS370/145 computer and requires $42K_8$ of core.

To illustrate program usage, an example involving the design of a 1–2-GHz amplifier is included. The goal was to achieve a flat 14-dB transducer gain over the 1–2-GHz range. The configuration of the amplifier is shown in Fig. 1, and the initial parameter values are

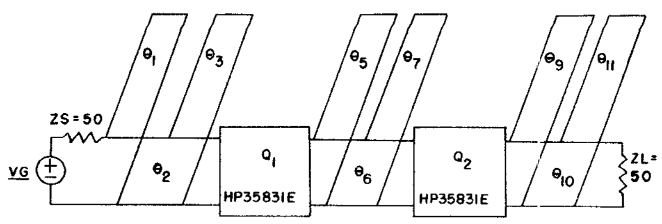

Fig. 1.