late at two discrete fundamental frequencies,[2] 618 Mc and 11,480 Mc, at a bias voltage of 215 mv. These frequencies were detected using a Polarad RW-T receiver and a SA-84WA spectrum analyzer. The detected and H.P.-X532B wavemeter-dipped oscillation at 11,480 Mc is shown in Fig. 2. Plots of frequency vs bias voltage for the observed oscillations are presented in Figs. 3 and 4. The 11.5-kMc oscillation was verified with the shorting plunger (see Fig. 5). From this experiment the average waveguide half-wavelength was determined to be 0.625 inches, which corresponds to a frequency of 11,493 Mc.

The first nine harmonics of the 618-Mc fundamental were detected using a coaxial probe, and are presented in column A of Table I. From this data the average fundamental was determined to be 614 Mc. Using this average fundamental, the harmonics were calculated and are presented in column B. The observed 11,480-Mc oscillation does not fall within the range of the theoretical harmonics of the 614-Mc fundamental. Even when the equipment detection error is accounted for, the error analysis still indicates that the 11,480-Mc oscillation is not harmonically related to 614 Mc. Also, an analysis of frequency deviation with bias voltage indicates that 11,480 Mc does not fall within the harmonic range of 614 Mc.

Thus, microwaves have been generated with a low-frequency, large capacitance, inexpensive tunnel diode.

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[2] K. Ishii and C. C. Hoffins, "Oscillation frequency of microwave tunnel diodes," PROC. IEEE (*Correspondence*), vol. 51, pp. 485–486; March, 1963.

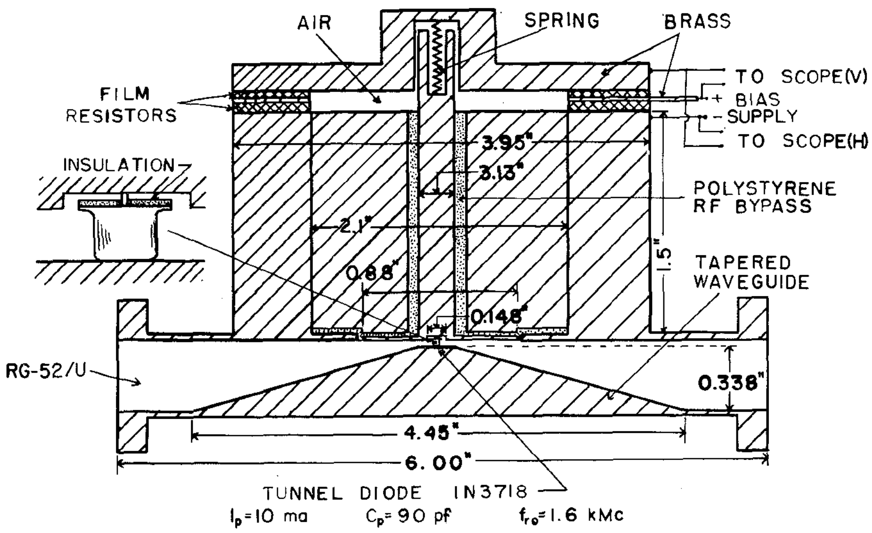

Fig. 1—1N3718 Tunnel Diode mounted in impedance transformation waveguide mount.

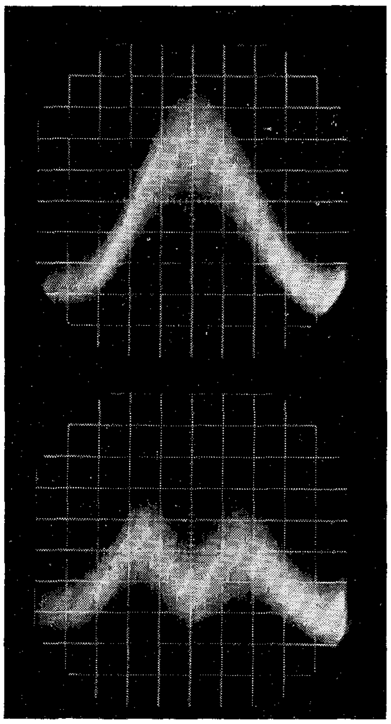

Fig. 2—Detected output of 1N3718 with a dc bias of 215 mv and at a frequency of 11,480 Mc.

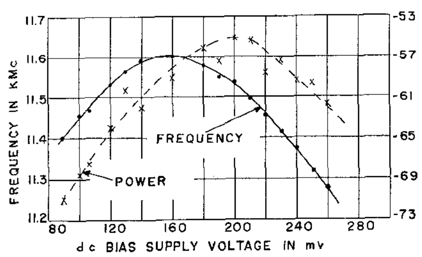

Fig. 3—Effect of dc bias voltage on the *X*-band oscillation and output power.

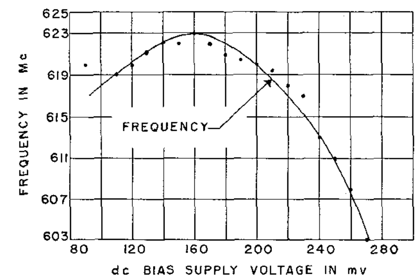

Fig. 4—Effect of dc voltage on the UHF oscillation.

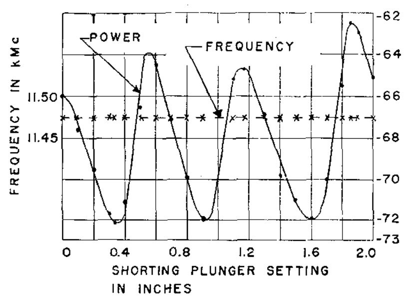

Fig. 5—Effect of the shorting plunger on the 11,480 Mc frequency of oscillation and the output power.

TABLE I
OBSERVED AND THEORETICAL FREQUENCIES OF OSCILLATION

Harmonics	A Experimental Frequencies	B Theoretical Frequencies
Fundamental	618	614
2	1240	1228
3	—*	1842
4	2434	2456
5	3050	3070
6	3652	3684
7	4265	4298
8	4863	4912
9	5495	5526
10	—*	6140
11	—*	6754
12	—*	7368
13	—*	7982
14	—*	8596
15	—*	9210
16	—*	9824
17	—*	10438
18	—*	11052
19	—*	11666
20	—*	12280

Bias = 215 mv.
* Not experimentally detected.

An Improved Mode-Selecting Coupler

A mode-selecting coupler which couples two orthogonally oriented rectangular waveguides into circular or square waveguide for simultaneous orthogonal transmission has been previously reported by Ohm.[1] It has been found that by adding an additional septum to the coupler configuration the bandwidth can be substantially improved.

As shown in Fig. 1, rectangular guide is coupled to square guide through a reso-

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[1] E. A. Ohm, "A broad-band microwave circulator," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-4, pp. 210–217; October, 1956.

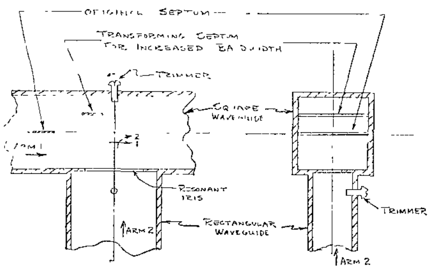

Fig. 1—Mode-selecting coupler.

nant iris. Placement of a septum in the square guide perpendicular to the electric field of arm 1 and parallel to the electric field of arm 2 provides the required degree of isolation between the two arms.

Ohm reported a match for the side-arm 2 input of greater than 35 db return loss (VSWR = 1.036:1) for the 8.94 per cent band of 10.7 to 11.7 Gc. He did not report performance outside this band as it was not then of current interest.

It has been found that the bandwidth can be improved by adding an additional septum, as shown in Fig. 1. In the model developed coupling WR-187 rectangular guide (1.872×0.872) into square guide (1.55×1.55), a match of 34 db return loss (VSWR = 1.04:1) was obtained for a 14.6 per cent band. This was better than 30 db return loss (VSWR = 1.065:1) over a 22.0 per cent band.

It is believed that the improved performance is due to a transforming action between the rectangular guide impedance and the square guide impedance. For the model evaluated, at 4.7 Gc the rectangular guide has an impedance of 520 ohms. The square guide has an impedance of 1280 ohms. Considering the guide below the added septum as partial height square guide, it has an impedance proportional to the square guide impedance. The performance reported was obtained with this added septum at 3/4 height which would produce an impedance of 960 ohms. Thus without the added septum the impedance ratio is 2.44:1, and with the added septum it is 2.44:1.83:1.

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A New Formula for Attenuation in Coaxial Cables

Attenuation in matched coaxial cables is expressed by the formula for 100 feet (db),[1] $A = 4.34 R_t/Z_0 + 2.78 f\epsilon^{1/2} F_p$ with $R_t = 0.1(1/d + 1/D_i)\sqrt{f \cdot \rho/\rho Cu}$. This attenuation, however, deviates heavily from the measured values, as it does not consider the skin effect with its changes over the frequency range. In the cable RG-58-U, for example,[2] the error reaches 47 per cent at 3000 Mc. Before setting up a new, empirical formula, the author has taken averages from hundreds of measurements on coaxial cables between 0.2 and 3000 Mc. The inner conductors had diameters from 0.012 to 0.036 inch.

A skin factor F_s in Table I (allowing interpolation) takes care of the skin effect and of the ensuing inductance change. Thus the attenuation, in decibels per 100 feet, is

$$A = F_s 8.4 \sqrt{f} R/Z_0.$$

Here $f \cdots$ frequency in Mc, Z_0 = characteristic impedance in ohms; the attenuation A of matched coaxial cables for 100 feet is based on the dc resistance of 100 feet inner conductor (R). In the metric system, R for 100 meters is listed in manuals; accordingly, attenuation for 100 meters will be obtained by the same formula, using this different R. The new formula is tried out for nonmagnetic conductors, tinned, blank or silver-plated, and with shields of tinned copper-braid.

For frequencies from 0.2–1 Mc, the true R of a composite conductor enters. Thus, for stranded copper-covered steel, take R as listed by the maker for a single strand but divided by the number of strands. For frequencies above 1 Mc, take R of copper from the right-hand column of Table I, filling the diameter solid.

In most cases, the error against average measurement is smaller than 5 per cent. While the attenuation of rectangular pulses with duty-cycle $\Delta = 0.5$ is practically the same as that of those with sine waves, correction factors F_Δ should be empirically found for other duty cycles. Extrapolations might be misleading. Table II gives an example for the investigation of F_Δ in a 100 kc–200 kc range of pulse cycles per second ("repetition rate").

TABLE I

Skin Factor F_s

Conductor diameter in mils	Take composite R		Take R of outer metal solid			
	0.2 Mc	1 Mc	10 Mc	140–400 Mc	3000 Mc	$R/100$, Ω_ω
7/38 AWG = 12	1.6	1.1	1.02	1.2		9.8
solid 12	1.4	1.05	1.02	1.2		6.3
12.6	1.4	1.05	1.02	1.2		6.5
15		1.05		1.4		4.4
15.9		1.05		1.4		4.08
7/34 AWG = 19	2.0	1.17		1.8		2.7
20	2.15	1.25		1.9		2.57
23	2.25	1.43		2.1	2.45	1.9
25		1.55		2.2		1.6
28.5				2.3	2.8	1.28
19/34 AWG = 32	2.3	1.97	2.2	3.5	4.0	1.01
27/36 AWG = 35		2.25		4.3		0.84
35.9	2.35	2.35	3.28	4.4	6.2	0.805
96				16		0.11

TABLE II

Correction Factor F_Δ for Attenuation of Rectangular Pulses with a Repetition Rate of 100–200 kc

Δ	F_Δ at 35–36 mil conductor	F_Δ at 19–23 mil conductor	F_Δ at 12 mil conductor
0.5	1.0	1.0	1.0
0.4	1.086	1.08	1.025
0.2	1.32		1.08
0.1	1.33		1.115
0.05	1.57	1.55	1.4

Δ = pulse width/pulse cycle.

Examples

Example 1

A cable of $Z_0 = 75$ ohms has a conductor made of a copper alloy, 90 per cent conductivity of copper, 7 strands of AWG 38. Over-all conductor diameter: 12 mils. Attenuation at 1 Mc:

$$A = 1.1 \times \frac{8.4 \times 1}{75} \times 9.8/0.90$$
$$= 1.34 \text{ db}/100 \text{ ft}.$$

Attenuation at 400 Mc:

$$A = 1.2 \times \frac{8.4 \times 20}{75} \times 6.3/0.90$$
$$= 18.85 \text{ db}/100 \text{ ft}.$$

Example 2

A cable of $Z_0 = 50$ ohms has a copper conductor of 19 AWG 34 strands, tinned. Over-all conductor diameter: 32 mils. Attenuation at 10 Mc:

$$A = 2.2 \times \frac{8.4 \times 3.16}{50} \times 1.01$$
$$= 1.17 \text{ db}/100 \text{ ft}.$$

Attenuation at 1 Mc:

$$A = 1.97 \times \frac{8.4 \times 1}{50} \times 1.01$$
$$= 0.331 \text{ db}/100 \text{ ft}.$$

Interpolation: Attenuation at 5 Mc; the interval between 1 and 10 Mc is 9 Mc, and 1.17db − 0.331 db = 0.839 db.
$A = 0.331 - 0.839 \times 4/9 = 0.704$ db/100 ft.

Manuscript received November 14, 1963; revised February 3, 1964.

[1] "Reference Data for Radio Engineers," International Telephone and Telegraph Corp., New York, N. Y., p. 574; 1956.

[2] *Ibid.*, p. 614.