CHAPTER 4

RESONANT-CAP GUNN OSCILLATORS FOR 75-110 GHz BAND

4.1 Introduction

As discussed in chapter 1, the 75-110GHz frequency band is also an atmospheric transmission window for ground based radio astronomical observations. The rotational transitions of several astrophysically important molecules e.g. acetaldehyde (CH_3CHO-79.150 GHz), silicon monoxide (SiO-86.243 GHz), methyl alcohol (CH_3OH-96.741 GHz), silicon monosulphide (SiS-108.924 GHz) etc. lie In this frequency band. Solid-state sources for this frequency range are required for providing a reliable alternative to the klystron local oscillators presently being employed in radio astronomy receivers. Gunn diodes have been used in the development of these solid-state sources due to their low noise characteristics.

75-110 GHz band Gunn oscillators have been realized in the past using a resonant-cap circuit in a rectangular waveguide (Ruttan, 1975; Ondria, 1979; Barth, 1981). The resonant-cap circuit was first developed for millimetre-wave IMPATT diodes (Lee et al, 1968). In this circuit, a metal cap of about half-wavelength diameter is placed directly 'above the diode in a section of rectangular waveguide. The oscillation frequency of this type of circuit is mainly determined by the dimensions'of the resonant-cap.

In this chapter, a new design for the 75-110 GHz band Gunn oscillators using a resonant-cap circuit in a circular waveguide

(Arora and Sarma, 1984) is presented. The circular waveguide Gunn oscillator is simpler in construction as compared to the conventional rectangular waveguide designs which involve a number of precise milling operations. The effect of various circuit parameters on the oscillation frequency and power is investigated experimentally. An empirical relation has been obtained for the prediction of oscillation frequency based on the physical dimensions of the resonant-cap. Comparison of this circuit with a conventional resonant-cap circuit in a rectangular waveguide has also been carried out by observing the performance of the same Gunn diode in both the circuits.

4.2 Resonant-cap Gunn oscillator in a circular waveguide

4.2.1 Design and construction

A cross-sectional view of the Gunn oscillator is shown in figure 4.1 and a photograph is shown in figure 4.2. The Gunn diode is mounted on a massive copper plug and inserted into a section of circular waveguide of 3mm diameter which is-chosen so that the cutoff frequency of the circular waveguide for the dominant mode (TE_{11}) is nearly the same as that of the dominant mode (TE_{10}) in the W-band (75-110 GHz) rectangular waveguide. The D.C. bias for the Gunn diode is provided through a metal post which has a resonant-cap at its end. The post also contains a 5-section co-axial low pass filter for RF choking. The resonant cap-Gunn diode assembly can be moved up and down in the waveguide by a mechanical arrangement. A vernier driven noncontacting backshort is also provided in the waveguide section behind the Gunn diode.

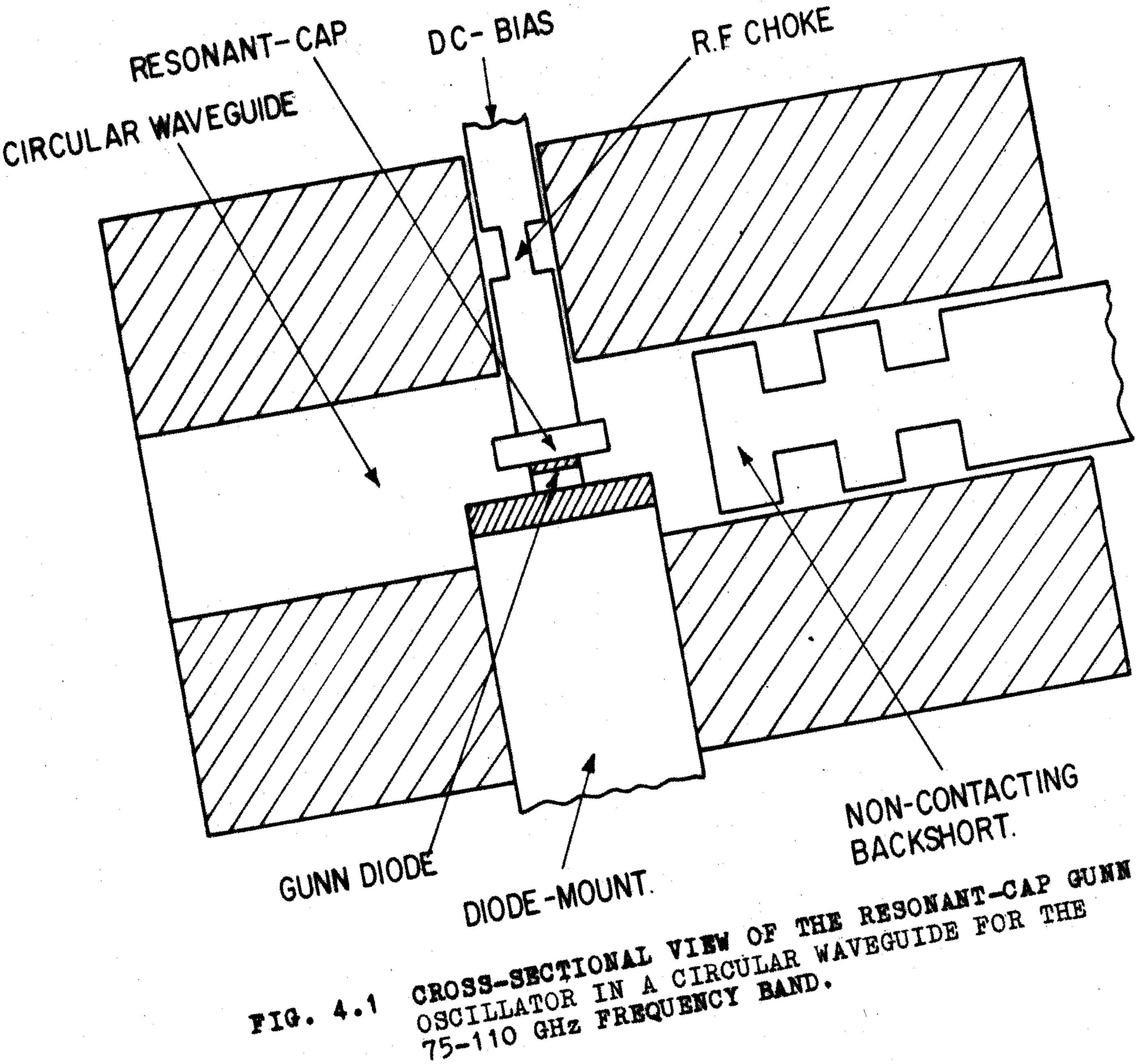
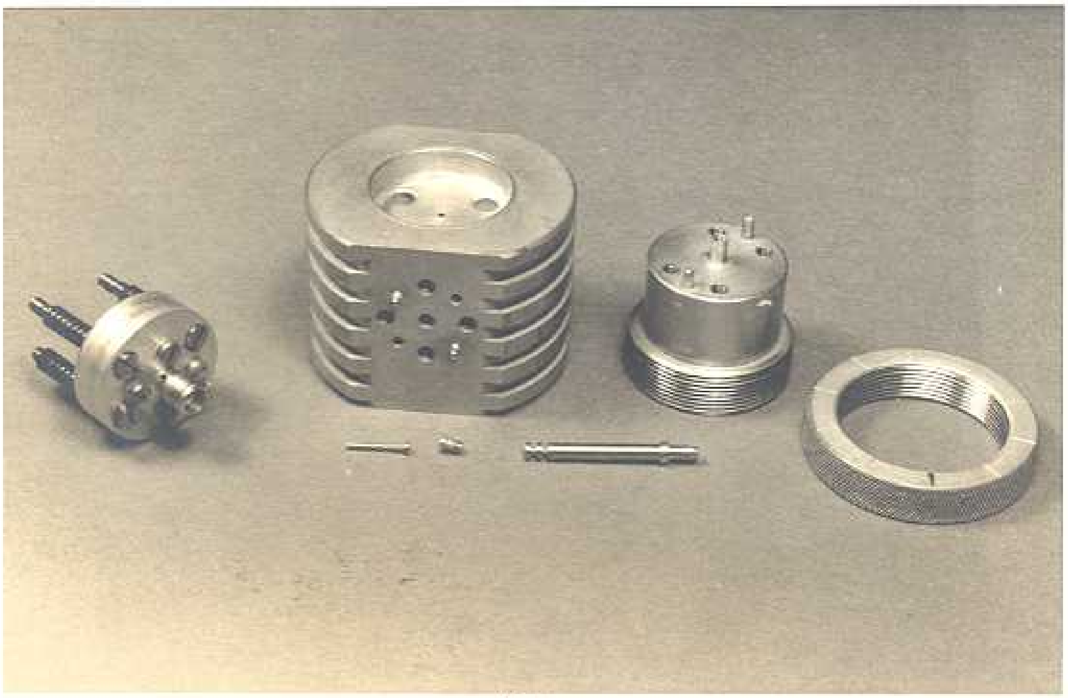


FIG. 4.1 CROSS-SECTIONAL VIEW OF THE RESONANT-CAP GUNN OSCILLATOR IN A CIRCULAR WAVEGUIDE FOR THE 75-110 GHz FREQUENCY BAND.

(a)



(b)

FIG. 4.2 PHOTOGRAPH OF THE 75-110 GHz BAND GUNN OSCILLATOR IN A CIRCULAR WAVEGUIDE. (a) ASSEMBLED VIEW, (b) EXPLODED VIEW.

4.2.2 Oscillator performance

The Gunn oscillator performance was evaluated in a standard W-band (75–110 GHz) rectangular waveguide measuring set-up consisting of a precision variable attenuator, a frequency meter and a power meter. A photograph of the measurement setup is shown in figure 4.3. The oscillator was connected to the measurement system through a circular to rectangular waveguide transition. Sufficient attenuation was always ensured between the oscillator and the measuring system to avoid load-pulling of the oscillator. However, no significant load-pulling effects on oscillation frequency were observed even when all attenuation was removed. In order to study the effect of various cap parameters, D, t, d and ℓ, shown in figure 4.4, on oscillator performance a number of resonant-caps of varying dimensions were fabricated. The procedure adopted for measurement was to select a particular resonant-cap and note the oscillation frequency and power output as the cap position is varied inside the waveguide. The backshort position was adjusted each time for maximum power output. The backshort position, however, was found to have negligible effect on the oscillation frequency. The results are presented in table 4.1 which gives the oscillation frequencies and output powers obtained for a large number of resonant-caps of varying dimensions.

More than 10mW CW power was achieved with this circuit over 75–90 GHz frequency range using a Varian Gunn diode type VSB-9222S2 which is specified for 10mW output at 87 GHz. The d.c.

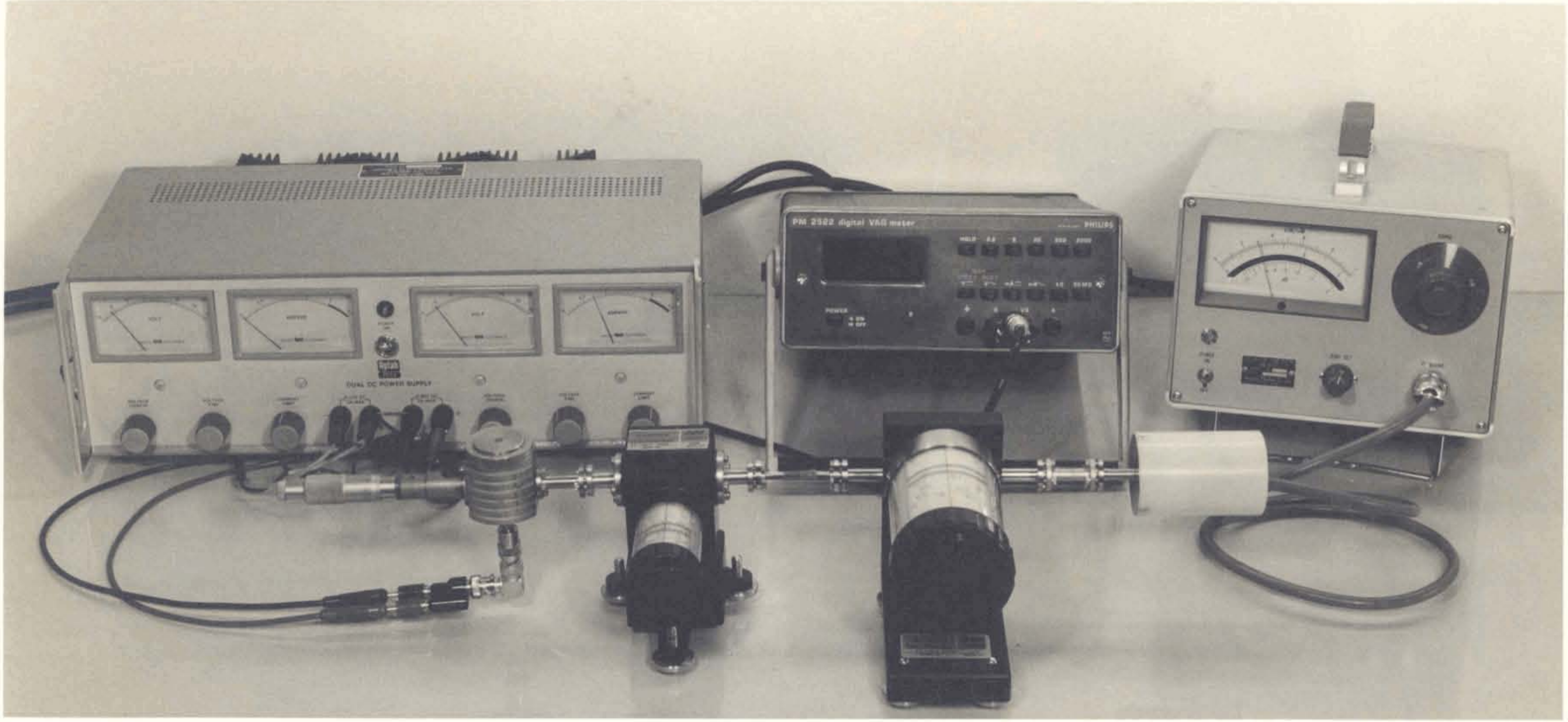


FIG. 4.3 PHOTOGRAPH OF THE MEASURING SETUP FOR THE 75-110 GHz FREQUENCY BAND GUNN OSCILLATORS.

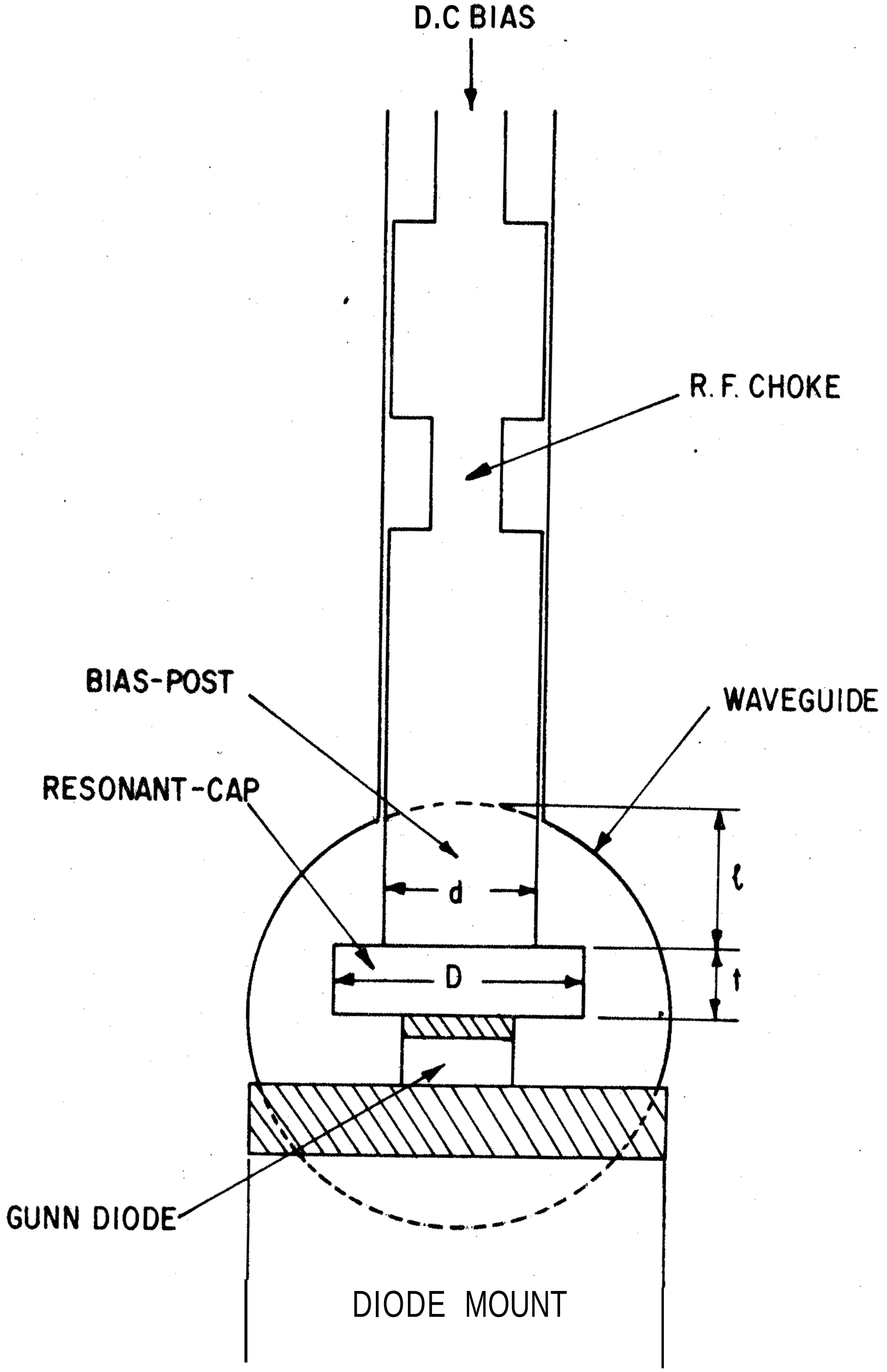


FIG. 4.4 DIMENSIONAL PARAMETERS OF THE RESONANT-CAP GUNN OSCILLATOR IN A CIRCULAR WAVEGUIDE.

TABLE 4.1: OSCILLATION FREQUENCIES AND OUTPUT POWERS OBTAINED WITH VARIOUS RESONANT CAPS FOR THE 75-110 GHz GUNN OSCILLATOR IN A CIRCULAR WAVEGUIDE

	D= 1.6mm																	
	d= 0.7mm						d= 0.9mm						d= 1.1mm					
	t= 0.25mm		t= 0.50mm		t= 0.75mm		t= 0.25mm		t= 0.50mm		t= 0.75mm		t= 0.25mm		t= 0.50mm		t= 0.75mm	
ℓ mm	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW
1.0			85.3	2.0	82.0	5.0					86.6	3.2					91.0	7.8
1.2			85.1	5.4	82.2	13.0			89.6	8.5	85.4	4.0			90.6	2.0	89.1	10.0
1.4	88.5	4.0	84.5	7.8	81.6	15.6	91.3	3.1	87.7	2.6	83.5	8.0	94.0	2.6	90.4	8.5	86.7	9.1
1.6	88.0	4.2	83.2	11.0	79.7	18.2	90.2	7.0	85.6	10.4	81.4	8.5	93.0	4.0	88.8	7.8	84.1	8.8
1.8	87.2	1.4	83.2	13.0	78.0	20.8	89.1	8.0	85.2	9.1	79.5	13.0	90.6	3.8	86.5	8.5	82.2	10.4
2.0	86.3	2.0	80.1	10.7			87.8	2.6	82.9	2.6			88.5	4.0	83.9	8.5		
2.2	84.9	1.2					86.4	1.5					86.6	3.6				

TABLE 4.1 contd.

	D = 1.8mm																	
	d = 0.7mm						d = 0.9mm						d = 1.1mm					
	t = 0.25mm		t = 0.50mm		t = 0.75mm		t = 0.25mm		t = 0.50mm		t = 0.75mm		t = 0.25mm		t = 0.50mm		t = 0.75mm	
a mm	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW
1.0					78.3	16.0			84.5	11.2	82.5	18.2					86.0	11.7
1.2			80.2	8.5	77.4	16.9			83.6	10.4	81.3	8.5			87.7	15.0	84.0	14.5
1.4	83.7	9.0	79.7	19.0	75.8	18.2	86.6	9.1	82.3	4.0	80.1	17.0	89.4	8.5	85.6	20.8	81.4	14.3
1.6	83.4	14.5	76.7	15.6	74.4	16.9	85.5	13.0	81.5	12.5	78.5	17.0	87.7	10.4	83.5	18.2	79.5	18.5
1.8	82.2	4.5	76.6	23.5			84.3	10.4	80.1	19.5	75.5	17.0	85.9	14.3	81.8	13.0	78.0	13.0
2.0	82.0	3.0	76.1	13.0			82.7	4.0	78.8	12.5			83.8	5.2	79.8	11.7		
2.2	81.3	4.0					81.3	3.5					82.1	4.0				

TABLE 4.1 contd.

	D = 2.0mm																	
	d = 0.7mm						d = 0.9mm						d = 1.1mm					
	t = 0.25mm		t = 0.50mm		t = 0.75mm		t = 0.25mm		t = 0.50mm		t = 0.75mm		t = 0.25mm		t = 0.50mm		t = 0.75mm	
ℓ mm	f GHz.	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW	f GHz	P mW
1.0			74.4	11.0	74	16.0			79.7	6.0	76.6	12.0			85.3	11.7	81.2	14.0
1.2			76.0	18.2					79.1	3.3	75.8	20.5			83.2	15.6	79.0	20.0
1.4	78.4	3.0	75.7	23.4			82.0	6.0	78.3	16.9	74.0	15.6	84.2	11.0	81.0	13.0	76.9	19.5
1.6	78.2	4.0	75.0	20.8			81.0	4.5	76.5	18.2			82.4	17.0	79.0	16.9	74.9	17.0
1.8	77.7	10.4					80.2	13.0	74.6	9.1			80.5	12.0	77.8	20.8		
2.0	77.2	13.0					78.9	15.6					79.1	4.0	74.4	13.0		
2.2	76.8	6.5					77.7	6.5					77.7	5.5				

bias voltage required for maximum power varied between 4 and 5 volts depending on the oscillation frequency-higher frequencies requiring lower voltage. Continuous mechanical tuning of about 8 GHz was obtained by varying the position of the resonant cap-Gunn diode assembly across the waveguide (This corresponds to an effective variation of the parameter 'ℓ'). The power variation over this range is less than 3dB, but the backshort position requires readjustment every time the cap position is changed. Bias-tuning sensitivity of about 300 MHz/volt was also observed. The variation of oscillation frequency with bias voltage was utilized for frequency stabilization of the Gunn oscillator using the phase-lock system described in detail in chapter 6.

4.2.3 Effect of the cap parameters on the oscillation frequency

A systematic investigation of the effect of various cap parameters D, t, d and ℓ on the oscillation frequency was carried out. The effect of these parameters is discussed below.

4.2.3.1 Effect of cap diameter 'D'

The effect of increasing cap diameter on the oscillation frequency is shown in figure 4.5 for a number of resonant-caps with diameters ranging from 1.6 to 2.0mm. The oscillation frequency monotonically decreases with increasing cap diameter indicating that the cap acts as a capacitive reactance. The frequency variation with cap diameter is found to be almost linear with a sensitivity of about 25 GHz/mm.

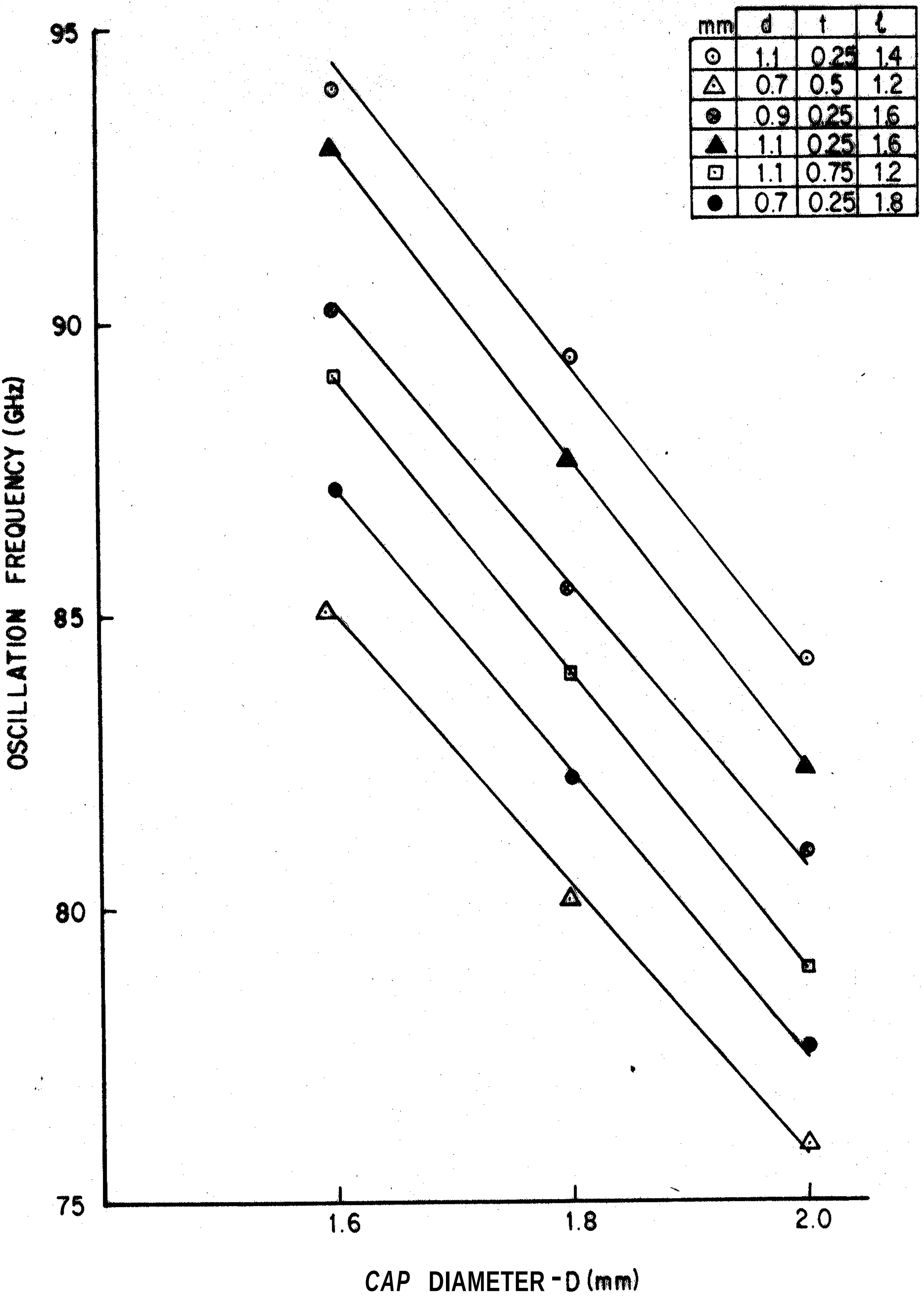


FIG. 4.5 OSCILLATION FREQUENCY vs. CAP DIAMETER D FOR THE CIRCULAR WAVEGUIDE RESONANT-CAP GUNN OSCILLATOR.

4.2.3.2 Effect of cap thickness 't'

Effect of varying cap thickness 't' on the oscillation frequency is shown in figure 4.6 for cap thickness varying from 0.25 to 0.75mm. The oscillation frequency decreases with increasing cap thickness, indicating once again that the cap behaves like a capacitor. Frequency variation with cap thickness is also approximately linear with an average sensitivity of about 15 GHz/mm.

4.2.3.3 Effect of post dia 'd'

Variation of oscillation frequency with post diameter 'd' is shown in figure 4.7 for post diameters varying from 0.7 to 1.1mm. The oscillation frequency increases with increasing post diameter indicating that the post provides an inductive circuit reactance. Frequency variation with 'd' is also almost linear with an average sensitivity of about 15 GHz/mm.

4.2.3.4 Effect of post length 'ℓ'

Effect of post length 'ℓ' on the oscillation frequency is shown in figure 4.8 for post lengths varying from 1.0 to 2.2mm. The frequency decreases with increasing post length indicating once again that the bias-post acts as an inductor, The sensitivity of oscillation frequency to post length 'ℓ' depends on the post diameter 'd'. For thinner posts (0.7mm dia), the frequency variation with post length is only about 3 GHz/mm, while for thicker posts (1.1mm dia) it is about 12 GHz/mm.

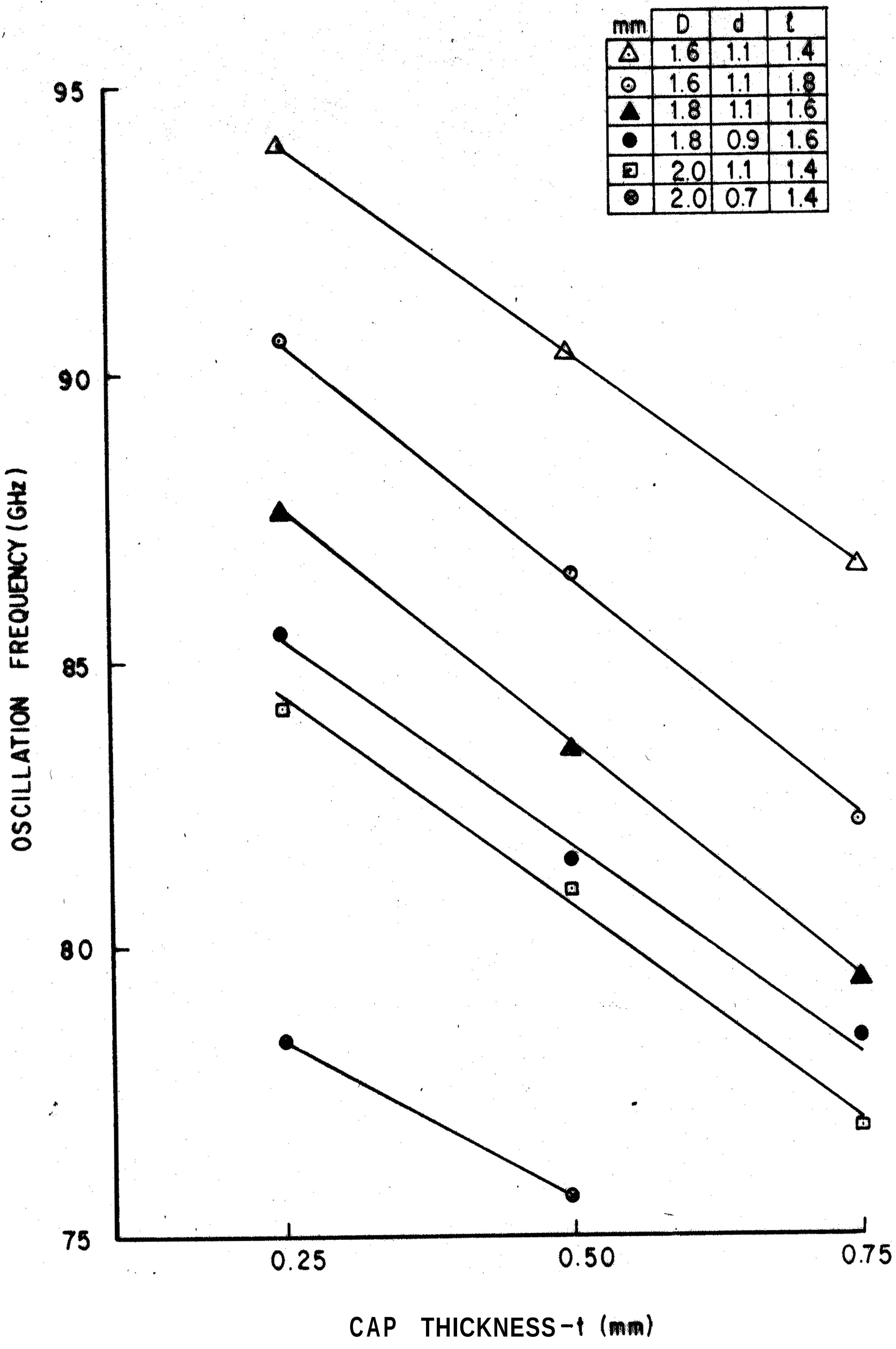
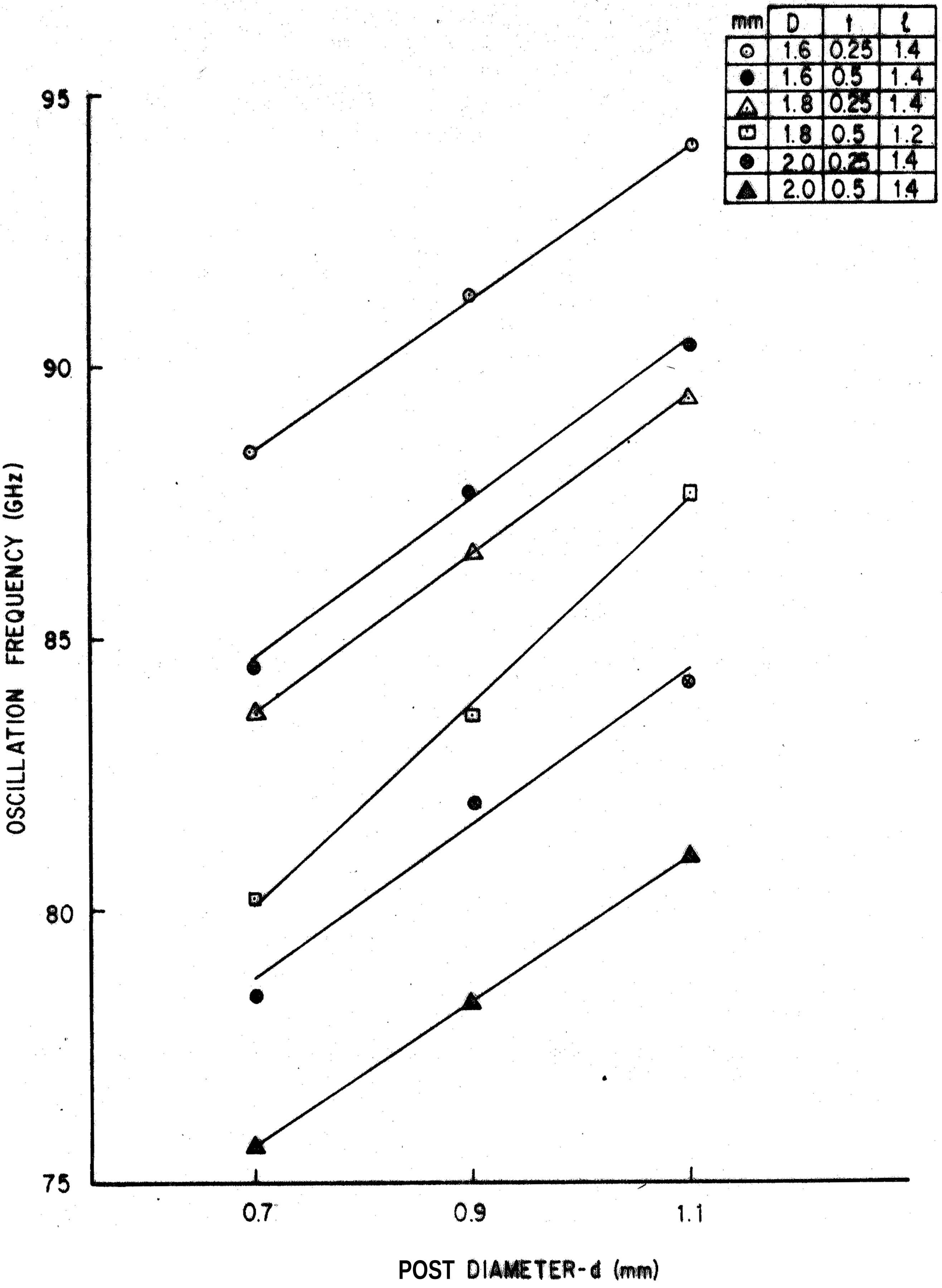


FIG. 4.6 OSCILLATION FREQUENCY vs. CAP THICKNESS t FOR THE CIRCULAR WAVEGUIDE RESONANT-CAP GUNN OSCILLATOR.



mm	D	t	ℓ
⊙	1.6	0.25	1.4
●	1.6	0.5	1.4
△	1.8	0.25	1.4
⊡	1.8	0.5	1.2
●	2.0	0.25	1.4
▲	2.0	0.5	14

FIG. 4.7 OSCILLATION FREQUENCY vs. POST DIA d FOR THE CIRCULAR WAVEGUIDE RESONANT-CAP GUNN OSCILLATOR.

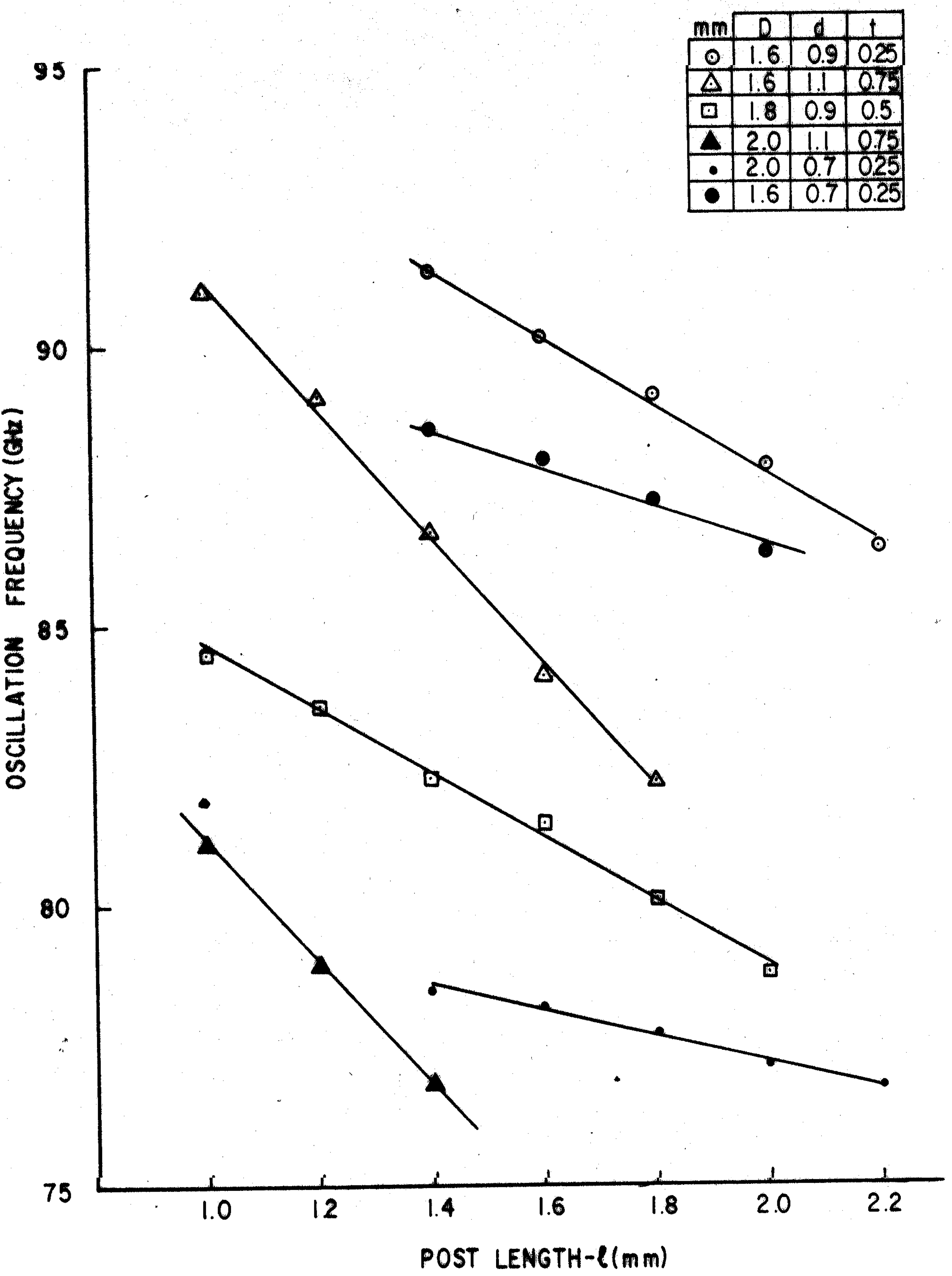


FIG. 4.8 OSCILLATION FREQUENCY vs. POST LENGTH ℓ FOR THE CIRCULAR WAVEGUIDE RESONANT-CAP GUNN OSCILLATOR.

4.2.4 An empirical relation for determining the oscillation frequency

It has been shown in section 4.2.3 that the oscillation frequency of the resonant-cap Gunn oscillator in a circular waveguide is a well behaved function of the four dimensional parameters D, t, d and ℓ. The following empirical relation connecting the wavelength of oscillation to the physical dimensions of the resonant-cap has bean obtained:

$$\lambda_{osc.} = D-d + 0.3\ell + 0.6t + \frac{d-1}{d+2}(\ell-t) + 2.05 \qquad (4.1)$$

where $\lambda_{osc.}$ is the wavelength in mm corresponding to the oscillator output frequency and D, t, d and ℓ are the physical dimensions of the resonant-cap circuit as shown in figure 4.4, all expressed in millimetres. The constant term on the right hand side of equation 4.1 also has the dimensions of millimetres. Equation 4.1 is valid over the frequency range 75–95 GHz with the following constraints on the physical dimensions:

> $a < D < 1.4a$; $0.4a < d < 0.75a$; $0.15a < t < 0.5a$ and $0.6a < \ell < 1.5a$
>
> where a is the radius of the circular waveguide.

More than 75% of the experimentally observed values tabulated in table 4.1 agree with that obtained from equation 4.1 within a maximum error of ± 1%, while the rest show slightly larger deviation. In an attempt to determine the general validity of the equation, several Gunn diodes were tested in the oscillator circuit described above. In most cases the measured oscillation frequency agrees with that obtained from the equation to about ± 1%. The larger deviations seen for a few diodes may be attributed to slight variations in the package parasitics.

4.2.5 Effect of cap parameters on the oscillator power output

The effect of various cap parameters D, t, d and ℓ on the oscillation frequency has been described in the earlier sections. These parameters also affect the output power of the oscillator. The plot of figure 4.9 was obtained using caps of varying dimensions, D, t and d and noting frequency and power output as the position of the cap is varied across the waveguide (variation of 'ℓ'). Cap diameter D determines the frequency of power maximum, which shifts towards lower frequency as the cap diameter is increased. This is understandable, since the cap along with the flange of the Gunn diode package acts as a radial-line transformer for matching the Gunn diode impedance to the waveguide output. The radius of the cap should therefore be approximately a quarter wavelength at the oscillator output frequency. However, the optimum cap radius is slightly different from quarter wavelength because of the effect of fringing capacitance due to finite cap thickness.

Around the frequency of power maximum determined by cap diameter 'D', optimum performance is obtained by adjusting the dimensions d and t. Large variations in output power are observed for d of 0.7 and 0.9mm and t of 0.25 and 0.5mm as the frequency is varied by moving the position of the resonant-cap. However, for d

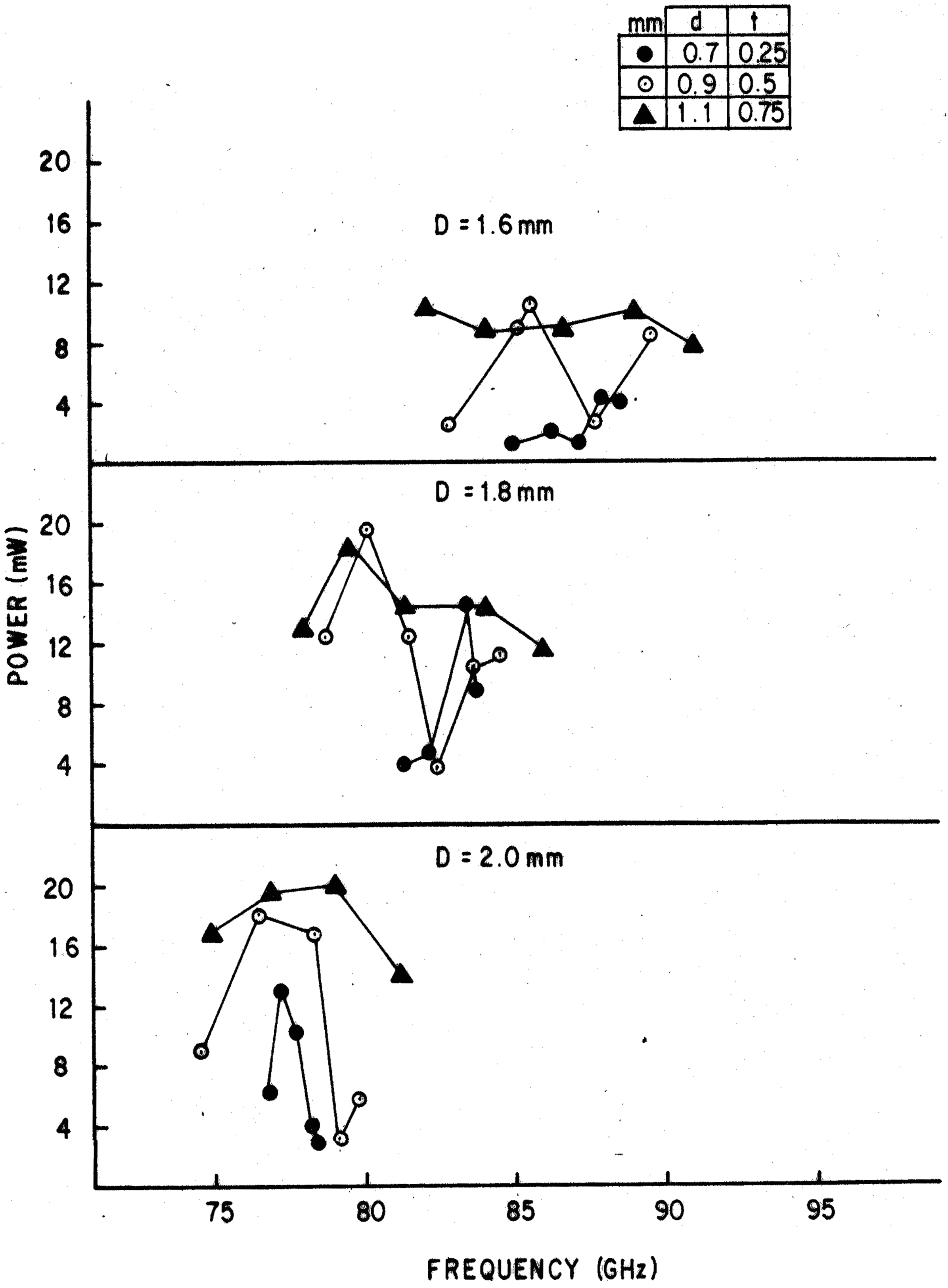


FIG. 4.9 POWER vs. FREQUENCY CHARACTERISTICS OF THE CIRCULAR WAVEGUIDE GUNN OSCILLATOR FOR SEVERAL RESONANT CAPS.

of 1.1mm and t of 0.75mm, relatively lesser variation of power with frequency is observed. Maximum power is also obtained for caps with d of 1.1mm and t of 0.75mm over most of the tuning range except at certain isolated frequencies where caps of 0.5mm thickness yield maximum powers.

In addition to the cap parameters, the d.c.-bias-voltage also sharply affects the oscillator power. The bias-voltage for maximum power output is a function of operating frequency. For the Gunn diode used here (Varian type VSB-9222S2) this Voltage varies from 5 volt at 75 GHz to about 4 volt at 90 GHz.

The position of the backshort also has a very sharp effect on the oscillator output power. Several power maxima and minima are observed as the backshort is moved away from the Gunn diode. Backshort position for maximum power changes when any of the four resonant-cap parameters D, t, d and ℓ is changed.

4.3 Resonant-cap Gunn oscillator in a rectangular waveguide

A resonant-cap Gunn oscillator circuit of conventional design was constructed in a standard W-band (75-110 GHz) rectangular waveguide mount for performance comparison with the circular waveguide Gunn oscillator. A photograph of the oscillator is shown in figure 4.10. A waveguide channel of 2.54mm width and 1.27mm height is milled in a brass split-block. The diode is mounted on a separate copper block and attached to the main waveguide block through spring loaded screws which control the position of the

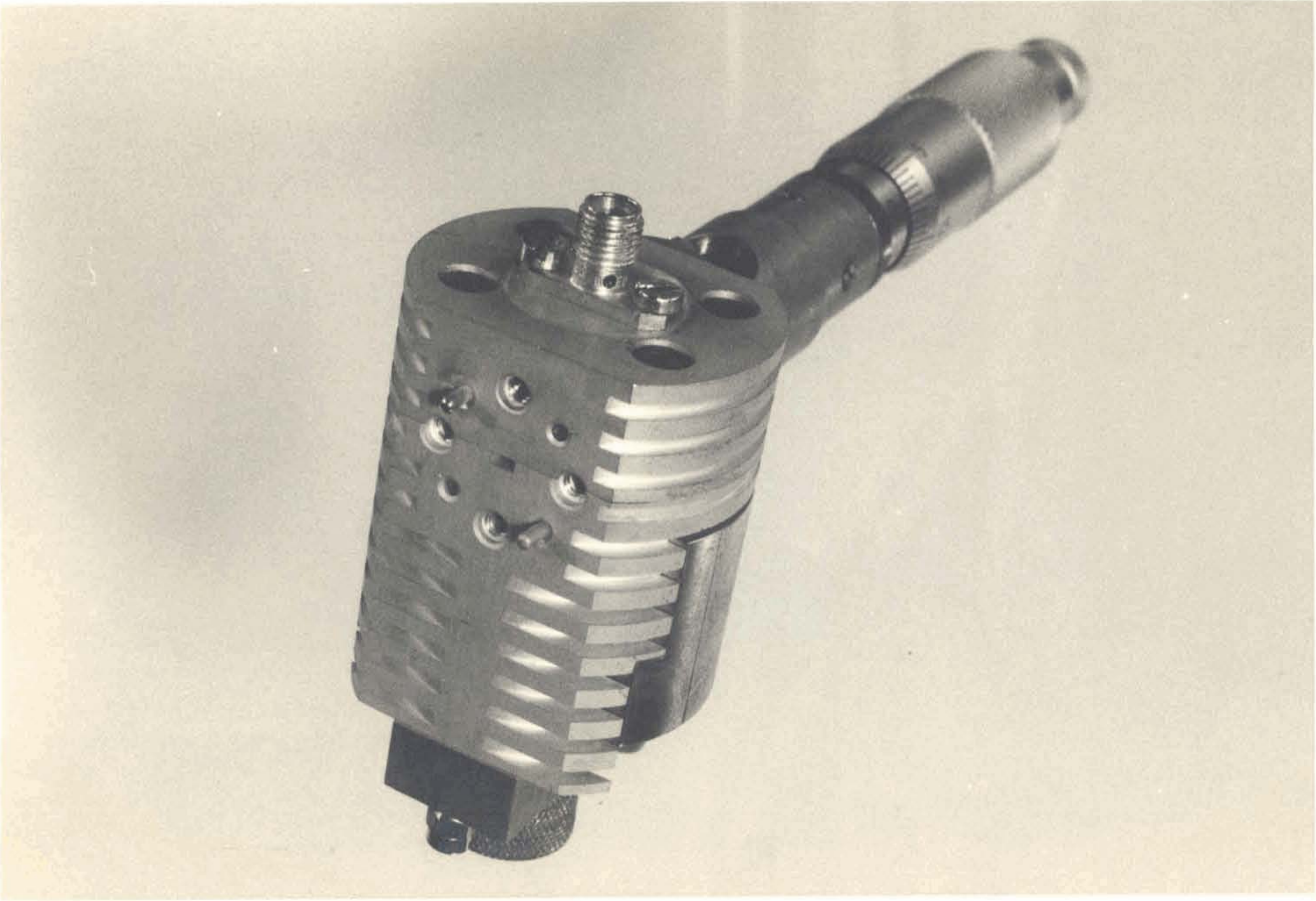


FIG. 4.10 PHOTOGRAPH OF THE RESONANT-CAP GUNN OSCILLATOR IN A W-BAND (75-110 GHz) RECTANGULAR WAVEGUIDE.

Gunn diode across the waveguide. Since the diode package has a flange diameter of 3mm, the waveguide section was locally widened by drilling a hole of 3mm diameter to allow the passage of the Gunn diode across the waveguide. The D.C. bias for the Gunn diode was provided through the resonant-cap which also contains a co-axial low pass filter for RF isolation, similar to the one used in the circular waveguide design. A noncontacting vernier driven backshort was provided in this case also for optimization of the oscillator output power.

Three resonant-caps of varying dimensions D, t and d were used. The cap dimensions were chosen so that the oscillation frequency could be made to lie in the 75-90 GHz range and CW powers were maximized in this range. Output frequency and power were noted for each of the resonant-caps as the cap position is varied across the waveguide height (variation of post length ℓ). The results are tabulated in table 4.2. Figure 4.11 shows the effect of post length ℓ variation on the oscillation frequency. As may be seen from the figure, about 8-10 GHz mechanical tuning is obtained by changing the post length ℓ by varying the position of the Gunn diode across the waveguide. However, the sense of frequency change with post length ℓ is opposite to that observed in the case of the circular waveguide Gunn oscillator. This may be due to the proximity of the top waveguide wall to the resonant-cap in this case. The parallel plate capacitance of the top surface of the resonant-cap with the top waveguide wall swamps the effect of post inductance when the cap is close to the top

TABLE 4.2: OSCILLATION FREQUENCIES AND OUTPUT POWERS OBTAINED WITH VARIOUS RESONANT CAPS FOR THE 75-110 GHz GUNN OSCILLATOR IN A W-BAND RECTANGULAR WAVEGUIDE

	D = 1.6mm d = 0.3mm t = 0.3mm		D = 1.8mm d = 0.5mm t = 0.3mm		D = 1.8mm d = 0.6mm t = 0.3mm	
ℓ mm	f GHz	P mW	f GHz	P mW	f GHz	P mW
0.2	76.1	10.0	75	2.6	77.7	11.0
0.3	81.4	11.7	78.1	10.4	83.8	9.1
0.4	83.9	8.5	80.6	12.0	85.9	8.8
0.5	85.8	8.8	82.5	13.0	87.2	10.4
0.6	86.9	10.0	83.6	13.0	87.4	10.4
0.7	87.4	10.0	83.8	11.0	87.3	13.0
0.8	87.5	7.2	83.7	9.1	86.7	11.7
0.9	87.0	5.2	83.2	9.3	86.0	7.8

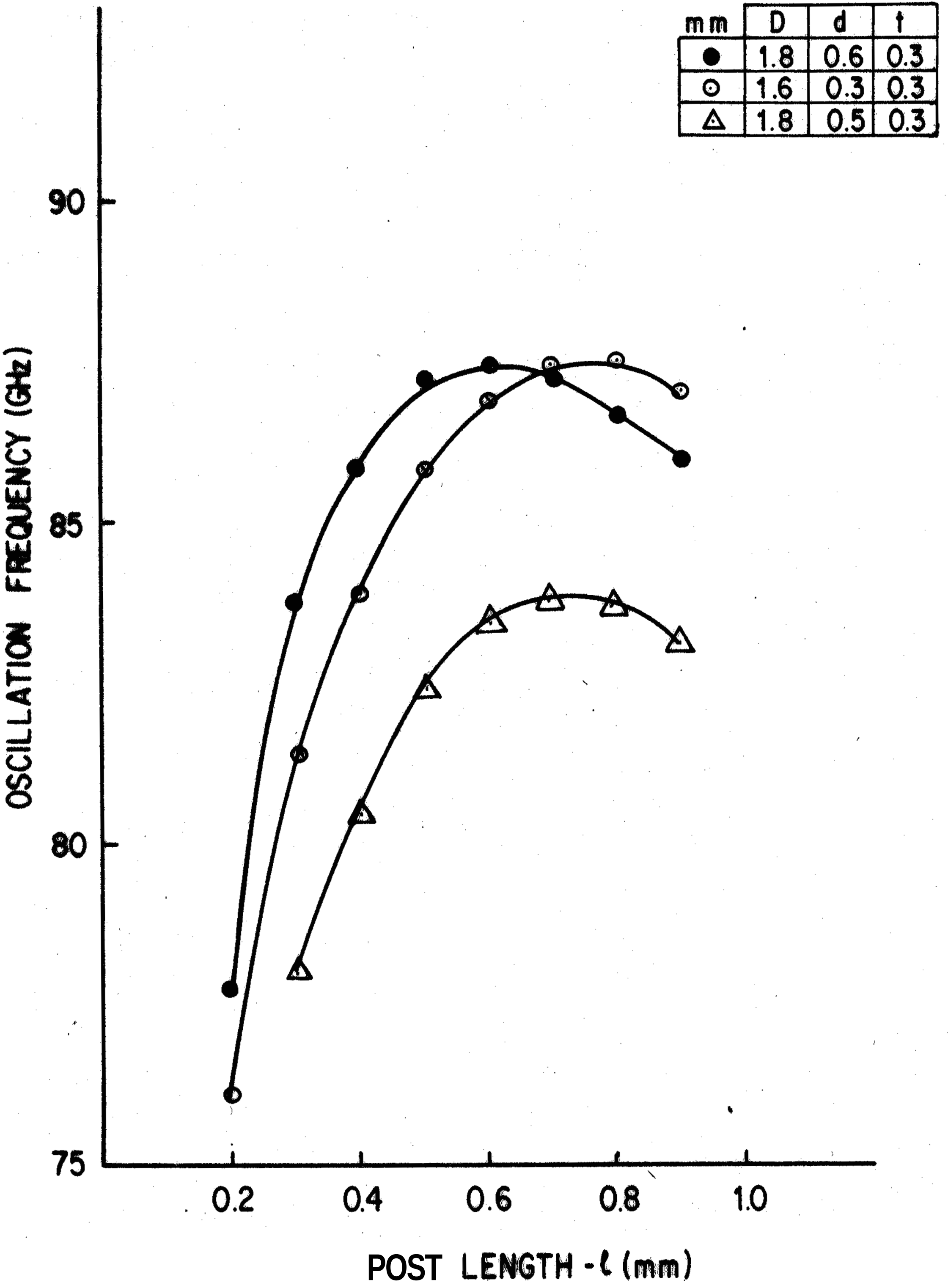


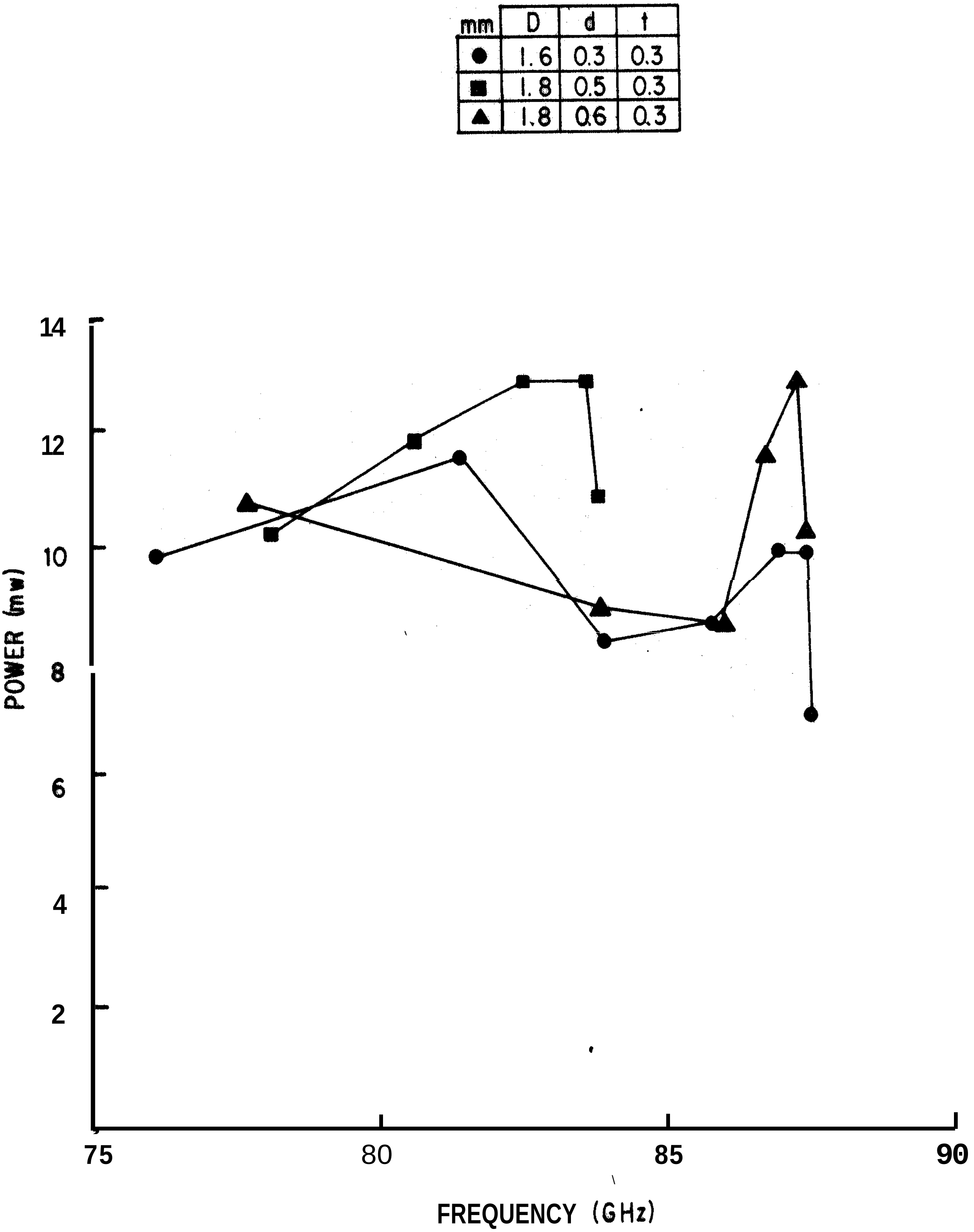
FIG. 4.11 OSCILLATION FREQUENCY vs. POST LENGTH ℓ FOR THE RECTANGULAR WAVEGUIDE RESONANT-CAP GUNN OSCILLATOR.

waveguide wall. When the post length is more than 0.8mm, the sense of frequency change with post length is the same as that observed in the circular waveguide case because the inductive reactance of the post now predominates. Effect of the other dimensional parameters D, t, d on oscillation frequency was found to be similar to that obtained in the circular waveguide case. The effect of these parameters on the oscillation frequency of resonant-cap oscillators realized in 75-110 GHz band rectangular waveguide has also been studied recently by Haydl (1983). The experimental observations of Haydl agree quite well with the ones described here.

The CW powers obtained with this design using the Varain Gunn diode type VSB-9222S2 are shown in figure 4.12. A comparison with figure 4.9 shows that the powers obtained with the circular waveguide design are comparable and sometimes even better than those obtained with the rectangular waveguide design over the frequency range 75-90 GHz.

4.4 Discussion

The realization of resonant-cap Gunn oscillators for the 75-110 GHz frequency band has been described in the foregoing sections. A new oscillator circuit configuration using circular waveguide has been developed which is comparatively simple to construct at millimetre wavelengths. Experimental investigation of the various cap parameters on the oscillator frequency shows a behaviour similar to that observed for W-band (75-110 GHz) resonant-cap Gunn oscillators in conventional rectangular waveguides which



mm	D	d	t
●	1.6	0.3	0.3
■	1.8	0.5	0.3
▲	1.8	0.6	0.3

FIG. 4.12 **POWER vs. FREQUENCY CHARACTERISTICS OF RECTANGULAR WAVEGUIDE GUNN OSCILLATOR FOR SEVERAL RESONANT CAPS.**

operate in a harmonic extraction mode (Eddison and Brookbanks, 1981; Haydl, 1981).

The resonant cap with diameter D and thickness t seems to behave like a capacitor while the post above it with diameter d and length ℓ behaves like an inductor. The cap and the post together form a fundamental frequency resonant circuit below the cutoff frequency of the waveguide. The cap also acts as a radial line transformer for efficient coupling of the harmonic frequency power to the waveguide output. An increase in D or t increases the capacitance of the fundamental resonant circuit thereby decreasing the oscillation frequency. On the other hand, an increase in d or a decrease of ℓ decreases circuit inductance and results in an increase of the oscillation frequency.

Harmonic operation of the circular waveguide resonant-cap Gunn oscillator circuit is indicated by the fact that the backshort position has practically no effect on the oscillation frequency while it sharply affects the power output. A similar effect of the backshort position on the oscillation frequency has also been observed in the W-band (75-110 GHz) resonant-cap Gunn oscillators of conventional design. Since the resonator frequency which is determined by the dimensions of the cap and the post lies below the cutoff frequency of the waveguide, the backshort does not contribute to the resonant circuit impedance. Another consequence of the fundamental oscillation frequency lying below the waveguide cutoff is that the resonant circuit does not 'see' the output load. This results in an extremely high value of external quality factor for resonant-cap Gunn oscillators. An incidental advantage of these harmonic oscillators is the elimination of expensive ferrite isolators since load isolation is provided 'naturally'.

Theoretical analysis of the resonant-cap Gunn oscillators operating in a harmonic extraction mode is highly complex. However, a simulation study of the harmonic oscillators has recently been carried out (Solbach, 1982). The model proposed by Solbach assume a simple cubic I-V characteristic for the active device and separat embedding impddances for the fundamental and harmonic frequencies. The model seems to explain several observed characteristics of the resonant-cap Gunn oscillators. A more exact analysis would require an accurate knowledge of the diode embedding impedance at the fundamental and harmonic frequency provided by the cap structure which may be extremely difficult to obtain theoretically. Therefore, most investigations of the resonant-cap Gunn oscillator circuit have been carried out experimentally (Haydl et al, 1982; Solbach et al, 1983b; Haydl, 1983).

A simple empirical relation obtained here for determining the oscillation frequency of the resonant-cap Gunn oscillator in a circular waveguide may be of considerable help for a systematic design of millimetre-wave (75-110 GHz) Gunn oscillators which have so far relied on cut-and-try methods. The performance of the circular waveguide oscillator has been found to be comparable to the conventional rectangular waveguide designs. 10-20mW CW powers have been obtained over the frequency range 75-90 GHz using a packaged Gunn diode specified for 10mW output at 87 GHz. Constructional simplicity of the circular waveguide oscillator is a great advantage at millimetre wavelengths where the realization of rectangular waveguide oscillator mount involves a number of precise milling operations. However, the maximum operating frequency of this circuit is limited to just above 90 GHz due to the unavoidable use of longer post-lengths in the circular waveguide geometry. Higher frequency operation may be possible by reducing the diameter of the circular waveguide but the waveguide size cannot be reduced arbitrarily due to the constraints imposed by the size of the Gunn diode package. No specific effects due to the presence of the higher order modes, usually the inhibiting factor in the use of circular waveguides, have been observed in the case of the Gunn oscillator. It is believed that the presence of the Gunn diode-resonant-cap structure inside the waveguide restrains the excitation of the first higher order mode (TM_{01}).

The power output of both the circular and the rectangular waveguide resonant-cap Gunn oscillators falls off rather steeply above 95 GHz. This may be due to the frequency limitation of the GaAs packaged Gunn diode used in the oscil'lators. Higher output powers beyond 95 GHz might be possible with the same circuits using better quality Gunn diodes.