New Techniques of Injection Locking in Communication Systems

A Thesis

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WONG, Kwok-wai

Department of Electronic Engineering

The Chinese University of Hong Kong

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DEDICATION

To my parents

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ABSTRACT

Four new techniques concerning injection locked oscillator utilization are investigated in this thesis. They are non-integral subharmonic locking, selective subharmonic locking range enhancement, locking range enhancement using feedback type injection locked oscillator, and technique of phase tuning beyond 180 degrees. Experimental results show that these techniques are superior to the current usage of injection locking.

The non-integral subharmonic locking behavior in injection locked oscillators, which has not been reported before, shows that an injection locked oscillator can lock to its non-integral subharmonic signals such as 2/3, 3/4, 2/5 and so on. The locking ranges for some non-integral subharmonic injections are comparable to some integral subharmonic injections. Therefore it is possible to use non-integral subharmonic locking signal to stabilize a high frequency oscillator and hence removing the limitation of using integral subharmonic signal only.

The second technique introduces a simple and practical way to enhance the subharmonic locking range without increasing the injection power. This technique avoids the need of determining the oscillator nonlinear characteristics which is difficult. At the same time, it leads to a wider subharmonic locking range. The crucial point is to introduce an additional feedback resonating at the subharmonic frequency. In addition, this technique also provides a simple way to control the enhancement by changing the feedback resistance.

The third technique improves the locking ranges on both fundamental and subharmonic locking by feedback type injection locked oscillator. Feedback type injection locked oscillator injects signal into the feedback network of the oscillator, in

contrary to its conventional counterpart in which injection signal is fed to the nonlinear network. The technique is concluded after comparative studies on the locking ranges at different injection points. Experimental results show that the locking ranges will be wider when using this new technique.

The fourth technique is a novel method of using fundamental injection locking to control the phase tuning range beyond 180 degrees. This method removes the current limitation of 180 degrees on phase tuning range. The method employs phase accumulation by cascaded fundamental injection locked oscillators. A graphical method which is innovative and original has been proposed to explain the locking range effect on the phase tuning range. There is a great potential in the application of phase tuning in phased array antenna.

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 STATEMENT OF PROBLEM

Locking range is a key characteristics of an injection locked oscillator. Wide locking range with low signal injection is desirable, particularly in subharmonic locking. Subharmonic locking suffers from narrower locking range compared with fundamental locking at the same injection power. Currently, wide locking range is obtained at the expense of high injection power.

1.2 GOALS OF RESEARCH

The goals of this research is to :

1) study any possible way to enhance the locking range, particular in subharmonic locking, without increasing the injection power

2) study any possible way to obtain phase tuning beyond 180 degrees by injection locking

1.3 METHODOLOGY

To study a nonlinear network like injection locked oscillator, there are two analysis methods. One is using nonlinear circuit theory while the other is using modeling approach. The former method involves many complicated mathematics; the latter offers a number of merits. It avoids complicated mathematics. Besides, circuit behavior can be more easily understood through modeling. The major advantage is the flexibility on choosing a specific model to suit a particular application. In view of the advantages, modeling approach is adopted for this analysis.

1.4 BACKGROUND

Injection-locked oscillator[6]-[10] is an oscillator with an input port. When there is no signal injected to the oscillator, the oscillator runs freely as a self-running oscillator. When a signal is injected at the input port, the oscillator tracks and locks to the injection signal provided that the injection signal falls into the locking range of the injection locked oscillator. This is fundamental injection locking. The locking range is proportional to the injection signal strength, and generally, the injection signal is much smaller than the output power level. Applications can be found on frequency tracking[11], signal amplification[12], and phase noise improvement[13]. An injection locked oscillator can lock to its subharmonic signal[9]-[10]. When an injection locked oscillator is locked to its subharmonic signal (i.e. the output frequency is a multiple of the input frequency), such process is called subharmonic injection locking. For subharmonic injection locking, when the oscillator is locked, the oscillator behaves as a frequency multiplier. As the signal is directly injected to the oscillator, the circuit is simpler than phase locked loop.

During the last decade, injection locking has been widely used in active phased array antenna[14]-[18]. Some applications have to do with optical control of the injection signal[19]-[29]. Injection locking can be found on phased array antenna for frequency synchronization where all array elements are locked to the injection signal. As the oscillators in the array elements are locked, the phase difference between the injection signal and the output signal can be electronically tuned. Therefore, the phase in each array element can be individually tuned to get the desired radiation pattern. Fig. 1-1 shows the block diagram of a phased array antenna using injection locking.

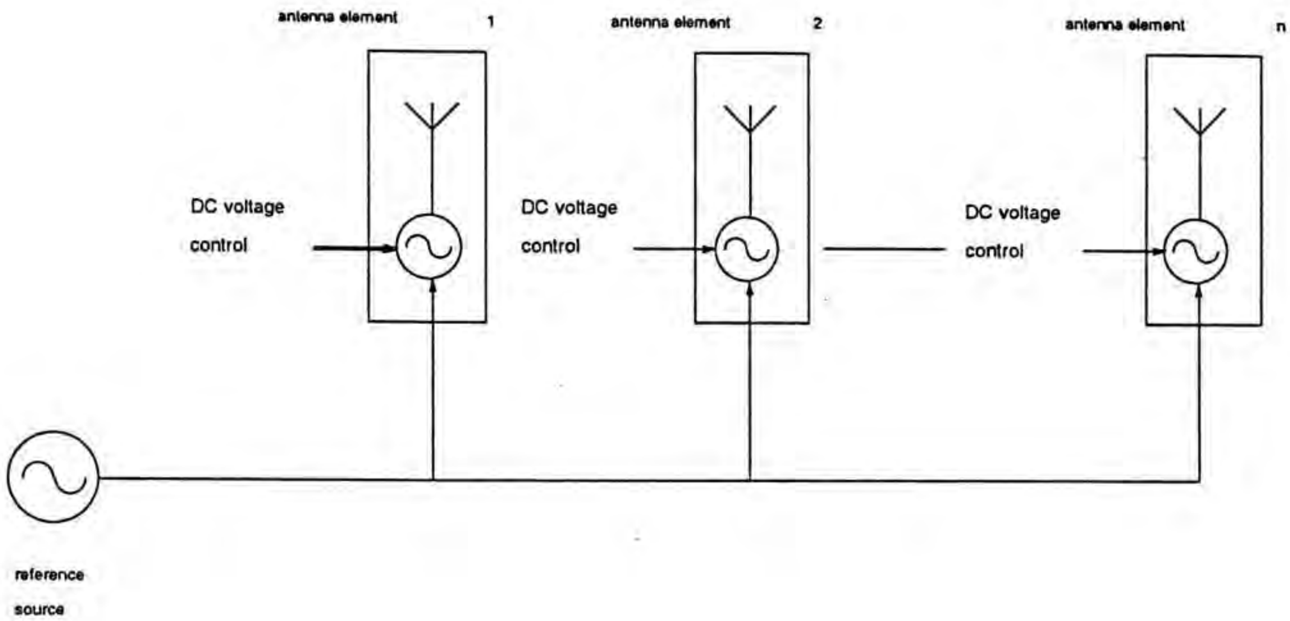


Fig. 1-1 Phased array with injection locking

When each antenna element is locked to the reference source, they are frequency coherent. The phases can then be electronically controlled by the DC voltages as shown in the figure. This method, however, is limited to 180 degrees of phase tuning.

1.5 OUTLINE OF THESIS

The outline of the thesis is as follows : Chapter 2 reviews the basic oscillator design, in which the oscillation criteria, feedback type oscillators such as Colpitt oscillator, Hartley oscillator, and Clapp oscillator are discussed. Chapter 3 discusses three fundamental injection locked oscillator models such as the Van del Pol model, the Adler model, and the Kurokawa model. Besides, two types of injection locked oscillator - the transmission type and the reflection type will be introduced. The last part of the chapter will discuss injection locking characteristics such as locking region, locking gain, and the three different stages of injection : unlocked state, locked state, and driven but unlocked state. Chapter 4 discusses subharmonic injection locking. Chien and Dalman model[10], and the Zhang *et al.* model[30] are discussed. The subharmonic locking characteristics are then introduced.

Chapter 5 consists of experimental investigations during this study. The investigations can be sub-divided into four parts. They are non-integral subharmonic injection locking; selective subharmonic locking range enhancement; locking range enhancment using feedback type injection locked oscillator; and phase tuning beyond 180 degrees by injection locking. The first three parts concentrate on improving the locking range, particular in the case of subharmonic injection. The last part concentrates on phase tuning beyond 180 degrees. Chapter 6 concludes the thesis.

CHAPTER 2

BASIC OSCILLATOR DESIGN

2.1 INTRODUCTION

Oscillator is a one port network which provides an output signal when a dc voltage is applied. In communication systems, sine wave oscillators are generally needed for the local oscillator. Sinewave oscillators is a circuit that, through amplification and feedback, generates a sinusoidal output. This chapter will review some design rules and methods of feedback oscillators. Oscillation criteria will be discussed first and different types of feedback oscillators such as Hartley oscillator, Colpitts oscillator, and Clapp oscillator will be introduced.

2.2 OSCILLATION CRITERIA

An oscillator contains a two port active device acting as an amplifier. Oscillation frequency is determined by the tune circuit in the feedback path. A feedback oscillator model is shown in the following figure.

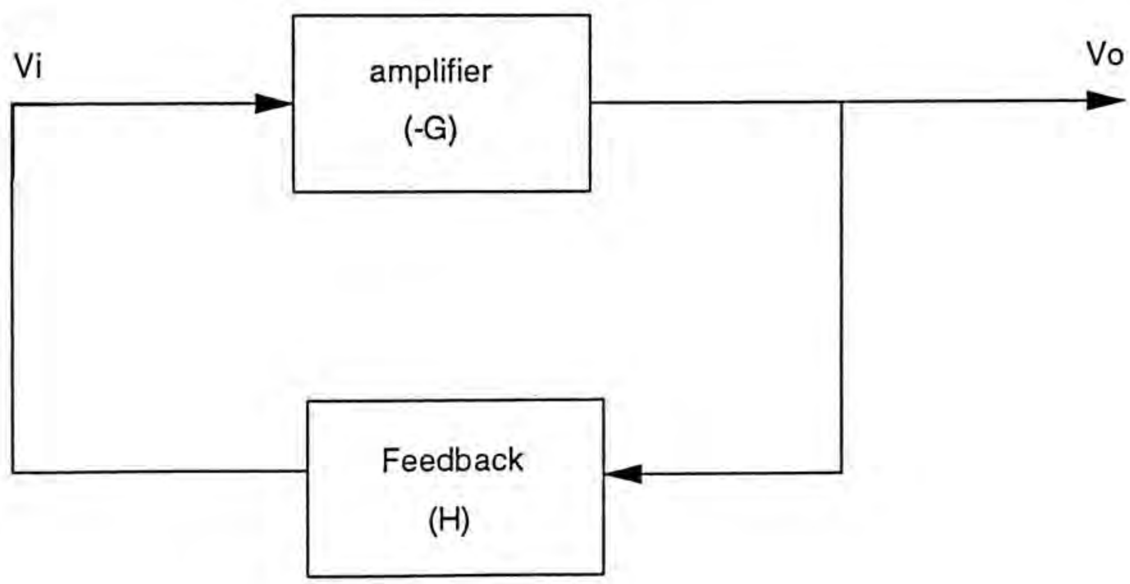


Fig. 2-1 Feedback oscillator model

The oscillator consists of an amplifier with gain (-G) and a feedback network with gain (H). The negative value of the amplifier gain means the output signal is 180 degrees out of phase with the input one. The feedback network determines the oscillation frequency. When there is a signal such as noise at the input (Vi), it is amplified by the amplifier and generates a signal at the output (Vo). The feedback path feed back part of the output signal to the input. If the feed-back signal is larger than, and in phase with, the input, oscillation begin. The oscillation signal grows linearly in amplitude until the active device goes into its saturation region. When the device goes into its saturation region, the gain around the feedback loop will decrease. The oscillation magnitude stops increasing when the loop gain approaches unity.

The Barkhausen criteria for oscillation states two conditions for a feedback circuit to oscillate.

1) The net gain around the feedback loop must not be less than one.
2) The phase shift must be a positive integral multiple of 2 π.

The overall gain with feedback is given by

$$A_v = \frac{G}{1 - G \cdot H} \tag{2.1}$$

where A_V = overall circuit complex gain
G = forward open loop gain
H = feedback path gain

With the equation, an amplifier is designed to achieve sufficient gain, and the feedback network is designed to resonate at the desired oscillation frequency.

2.3 TYPES OF FEEDBACK OSCILLATORS

In VHF range, tuned L-C elements are often used in oscillator for frequency tuning. There are three common tuned L-C oscillators. They are :

1) Hartley oscillator ;
2) Colpitts oscillator ;
3) Clapp oscillator.

The oscillators have a common configuration having three reactance elements in the feedback network.

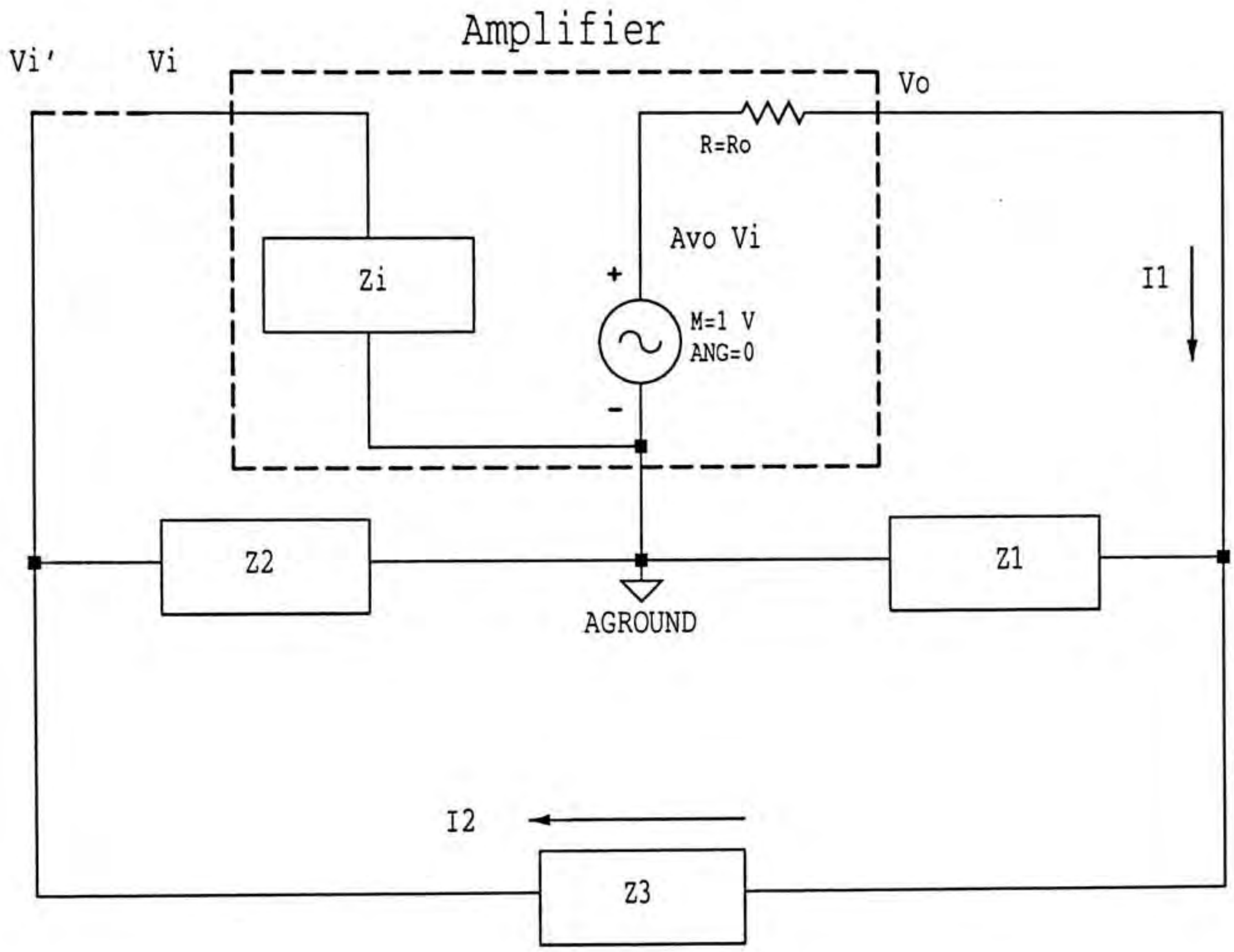


Fig. 2-2 General tuned LC oscillator (Z1, Z2, Z3 are reactive elements)

By circuit analysis

$$A_{vo}V_i = I_1(R_o + Z_1) - I_2 Z_1$$

and $$|A_{vo}| = 1$$

$$I_2 = -A_{vo} \cdot \frac{Z_1 Z_2}{Z_1^2 - (Z_1 + Z_2 + Z_3)\cdot(R_o + Z_2)}$$

loop gain $$A_v = \frac{V_o'}{V_i}$$

$$= -A_{vo} \cdot \frac{Z_1 Z_2}{Z_1^2 - (Z_1 + Z_2 + Z_3)\cdot(R_o + Z_2)}$$

At resonance, $Z_1 + Z_2 + Z_3$ becomes zero.

thus, $$A_v = -A_{vo}\frac{Z_2}{Z_1}$$

By Barkhausen criteria, $$|A_{vo}| \geq 1$$

and at steady $$|A_{vo}| = 1$$

Circuit identification

Oscillator	Z1	Z2	Z3
Hartley	L	L	C
Colpitts	C	C	L
Clapp	C	C	series LC

When the reactance elements are selected to be different L-C elements, different types of oscillator can be identified. Hartley oscillator utilizes a tapped-inductor or two inductors to provide the correct level and phase of the feedback to the input circuit. The Colpitts oscillator makes use of a tapped-capacitor or two capacitors in the output tuned circuit to provide the correct feedback. The Clapp oscillator is a variation of the Colpitts circuit with the tank coil in the Colpitts oscillator replaced by a series combination of L3 can C3. Tuning is done with the capacitor C3 which varies the net inductive reactance of the L-C branch. Since C1 and C2 are not varied, the feedback ratio is independent of tuning.

1) Hartley Oscillator

resonance frequency : $$f = \frac{1}{2\pi\sqrt{(L_1 + L_2)\cdot C_3}}$$

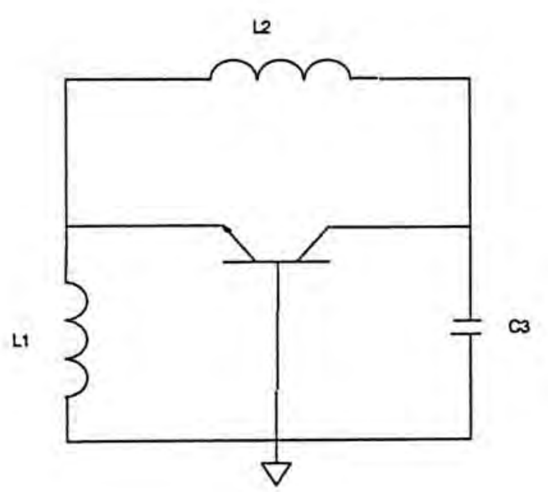


Fig. 2-3 Hartley Oscillator

2) Clapp Oscillator

resonance frequency : $f = \dfrac{1}{2\pi\sqrt{LC}}$

where $C = \dfrac{1}{\dfrac{1}{C_1} + \dfrac{1}{C_2} + \dfrac{1}{C_3}}$

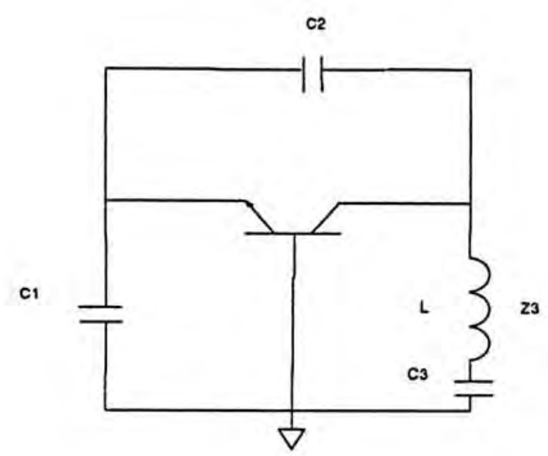


Fig. 2-4 Clapp Oscillator

3) Colpitts Oscillator

resonance frequency : $f = \dfrac{1}{2\pi\sqrt{L_3 C}}$

where $C = \dfrac{C_1 \cdot C_2}{C_1 + C_2}$

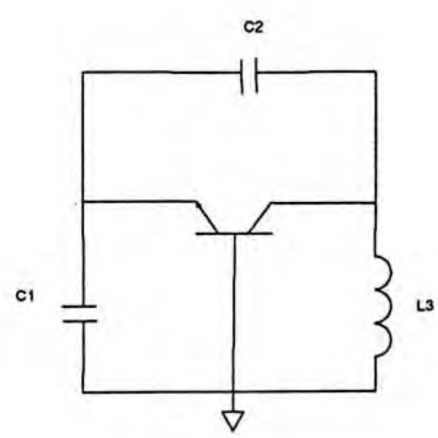


Fig 2-5 Colpitts Oscillator

Among the oscillators, the Hartley oscillator is characterized by a tapped coil LC tank circuit. The colpitts oscillator is characterized by tapped capacitor while the Clapp oscillator is a variation of the Colpitts oscillator characterized by an additional capacitor in series with the L in the tank. Tapped capacitor gives more flexibility for frequency tuning, therefore Colpitts oscillator is more often used than Hartley oscillator.

2.4 CONCLUSION

Basic feedback oscillator designed is reviewed. The criteria for a feedback circuit to oscillate is to have an amplifier with gain greater than unity and a feedback network so that there is zero phase shift between the input and the output. The feedback network also couples the output signal to the input. Three types of feedback oscillators are discussed. They are Hartley oscillator, Clapp oscillator, and Colpitts oscillator.

CHAPTER 3

FUNDAMENTAL INJECTION LOCKING

3.1 INTRODUCTION

Injection locked oscillator modeling has been studied by different researchers. In this chapter, three different models will be discussed[6]-[8]. The first model discussed here is proposed by B.Van del Pol[6] who did some pioneering works in the 1920's when he used appropriate approximations and solved a second-order differential equation to nonlinear oscillations. Many nonlinear oscillation behaviors, including injection locking, can be traced back to Van del Pol description. Van del Pol named injection locking as "oscillation with external electromotive force". By solving the 2nd order differential equation, Van del Pol showed the solution graphically, and it showed that the existence of the solution (injection-locked) depends on the signal injection level.

In 1946, R.Adler[7] used a linear model to derive the locking range for an oscillator, in which most complications of nonlinear analysis are avoided. The model assumed that the nonlinearities are not important for small perturbations around the resonant frequency. Although the model is simple, the model does provide a good insight toward the locking range. Adler also found that the locking range is dependent on the injection signal level.

The next model was proposed by K.Kurokawa[8] who used a negative resistance model, in which he found it better for microwave oscillator analysis. Kurokawa introduced the concept of complex plane with impedance locus and device line. For injection locking, Kurokawa used injection vector which depends on the injection signal magnitude. The injection vector relates the impedance locus to the device line, and the complex plane showed graphically that the locking range is dependent on the magnitude of the injection vector.

3.2 NONLINEAR OSCILLATOR MODELS

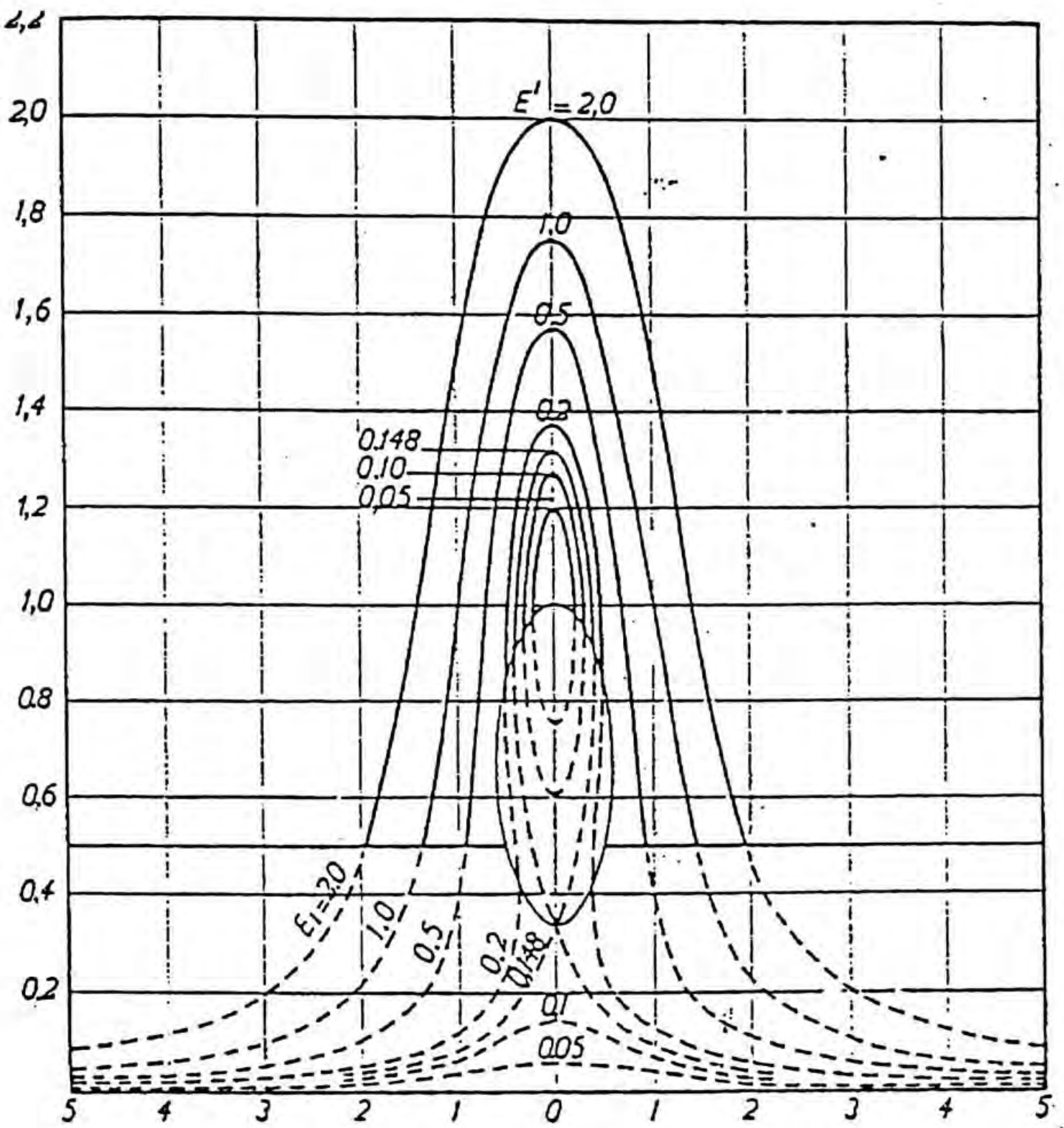
Van Del Pol Model[6]

Van del Pol found that most of typical oscillation phenomena considered can be investigated and explained with the aid of a simple anti symmetrical characteristics of the form $i = \alpha v - \gamma v^3$. Van del Pol used the following differential equation to describe the oscillator with signal injected.

$$V'' - (\alpha - \gamma V^2)V' + \omega_o^2 V = \omega_i E \sin \omega_i t \qquad (3.1)$$

Van del Pol found the solution graphically as shown in Fig 3-1. The abscissa represents the offset frequency of the injected signal relative to the natural frequency of the oscillator. The ordinate represents the magnitude of output voltage. The different curves are corresponding to the different levels of injection E. The graph can also be divided into full line region and dotted lines region. The full lines represent the area where solution exist (locked) while dotted lines represent the area where solution does not exist (unlocked). It means that a stable solution to the equation is not always existed. It depends on the injection signal magnitudes. In other words, the injection magnitude determines the different states of locking : locked; unlocked; driven but unlocked states, of the oscillator.

output mangitude



normalized offset frequency

Fig. 3-1 Graphical solution of Van del Pol equation under different voltage (E1) injection

Adler Model[7]

Adler model avoids most of the complications of nonlinear analysis. It is described by a differential equation. The locking range and the locking condition can be obtained from the equation. The Adler's oscillator circuit model was shown in Fig. 3-2.

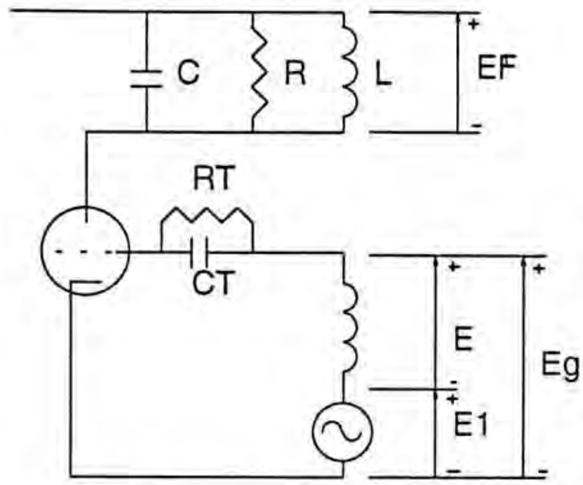


Fig. 3-2 Adler's circuit model

angular frequency :

ω_o = free running frequency

ω_i = injection signal frequency

$\Delta\omega_o$ = $\omega_o - \omega_i$
= free running and injection frequency difference

ω = instantaneous frequency

$\Delta\omega$ = $\omega - \omega_i$
= instantaneous beat frequency

voltages :

E_p = voltage across plate load

E = voltage induced in gird coil

E1 = voltage of injection signal

Eg = resultant grid voltage

Q = figure of merit of plate load L,C,R

In Adler's model the $C_T R_T$ form an amplitude control mechanism with short time constant compared to one beat cycle.

$$\text{beat cycle} \qquad T << \frac{1}{\Delta\omega}$$

Where a signal ω_i is injected into an oscillator with free running frequency ω_o, a beat frequency $\Delta\omega$ is produced. The value of ω is a signal which is frequency modulated with a beat frequency $\Delta\omega$. To have a clear insight, a mathematical model is presented with the help of a vector diagram.

For injection, E_1 generally is small comparing to E ($E_1 << E$).

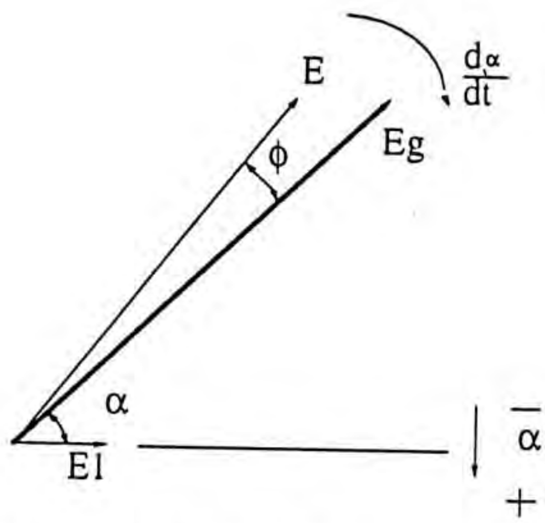


Fig 3-3 Vector diagram of the output and input signal

beat frequency $$\Delta\omega = \frac{d\alpha}{dt} \tag{3.2}$$

by sine rule

$$\frac{E_1}{\sin\phi} = \frac{E}{\sin(-\alpha)}$$
$$\sin\phi = \frac{E_1}{E}\sin(-\alpha) \tag{3.3}$$

because $E_1 << E$

$\Rightarrow$ ϕ is very small

$\therefore$ $$\phi = -\frac{E_1}{E}\sin\alpha \tag{3.4}$$

Assuming the phase Φ versus frequency for the tuned circuit at the frequency range be linear.

i.e. $$\frac{d\phi}{dt} = \text{A (say, a constant)}$$

$$\Rightarrow \quad \phi = A(\omega - \omega_o) = -\frac{E_1}{E}\sin\alpha \tag{3.5}$$

$$\therefore \quad \omega = \omega_o - \frac{E_1}{AE}\sin\alpha \tag{3.6}$$

The above equation shows that the instantaneous frequency of oscillation deviated from the free running frequency by :

$$\frac{E_1}{AE}\sin\alpha.$$

To analyze further, for a tuned circuit, phase shift and frequency are related by the Q value of the tuned circuit.

$$\tan\phi = 2Q\frac{\omega - \omega_o}{\omega_o} \tag{3.7}$$

for small angle $$\phi \approx 2Q\frac{\omega - \omega_o}{\omega_o} \tag{3.8}$$

$$\therefore \quad A = \frac{2Q}{\omega_o} \tag{3.9}$$

and instantaneous frequency

$$\omega = \omega_o - \frac{\omega_o E_1}{2QE}\sin\alpha \tag{3.10}$$

or instantaneous beat frequency

$$\Delta\omega = \Delta\omega_o - \frac{\omega_o E_1}{2QE}\sin\alpha \tag{3.11}$$

With the above equation, the locking condition and the locking range can be derived. When locking is achieved, the instantaneous beat frequency goes to zero.

i.e.
$$\Delta\omega_o - \frac{\omega_o E_1}{2QE}\sin\alpha = 0 \tag{3.12}$$

$\Rightarrow$
$$\Delta\omega_o = \frac{\omega_o E_1}{2QE}\sin\alpha \tag{3.13}$$

$\Rightarrow$
$$\sin\alpha = \frac{2QE}{E_1}\frac{\Delta\omega_o}{\omega_o} \tag{3.14}$$

This is the basic condition for locking, as $|\sin\alpha| \leq 1$, the locking condition is valid only if

$$\left|\frac{2QE}{E_1}\frac{\Delta\omega_o}{\omega_o}\right| \leq 1 \tag{3.15}$$

$\Rightarrow$
$$|\Delta\omega| \leq \frac{E_1}{2QE}\omega_o \tag{3.16}$$

$\Rightarrow$
$$|\omega_o - \omega_i| \leq \frac{1}{2Q}\frac{E_1}{E}\omega_o \tag{3.17}$$

Therefore, the maximum one-side locking range is

$$\Delta\omega_{o\max} = \frac{1}{2Q}\frac{E_1}{E}\omega_o \tag{3.18}$$

and the two-side locking range is

$$2\Delta\omega_{o\max} = \frac{1}{Q}\frac{E_1}{E}\omega_o \tag{3.19}$$

which is the locking range of the injection-locked oscillator.

Kurokawa Model[8]

Kurokawa used a negative resistance model with impedance locus and device line to study the oscillator behavior. When an oscillator oscillates at its steady state, the active device behaves as a negative resistance delivering power which in turn is the power dissipated by the load. The equivalent circuit of a free running microwave oscillator is shown in Fig 3-4.

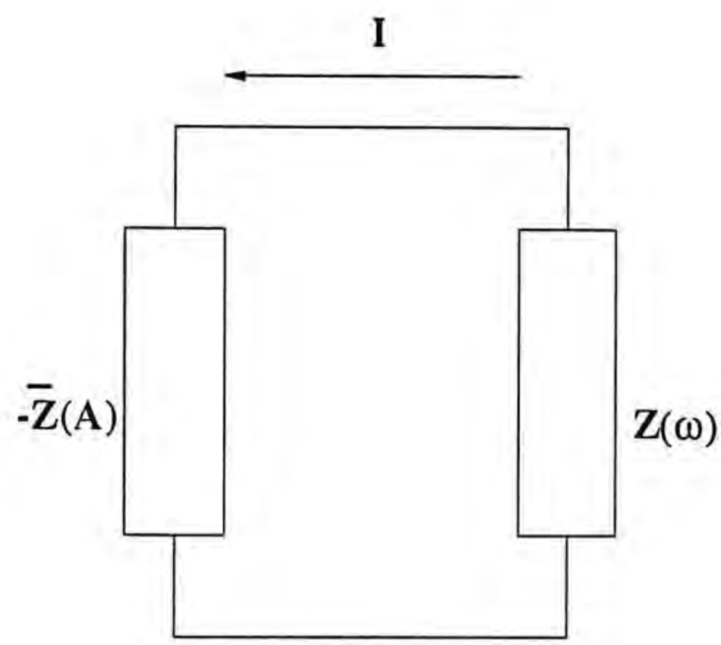


Fig. 3-4 Kurokawa oscillator model

where $Z(\omega)$ is the circuit impedance seen from the active device, $\overline{Z}(A)$ is the device impedance, and I is the current flow. The device impedance is a function of the RF current amplitude A. The circuit impedance is a function of frequency ω. From the model, the equation of free oscillation is given by :

$$\left[Z(\omega)-\overline{Z}(A)\right]I=0 \tag{3.20}$$

The loci of the circuit impedance and device impedance can be drawn on a complex plane by varying ω and A respectively as shown in Fig. 3-5 .

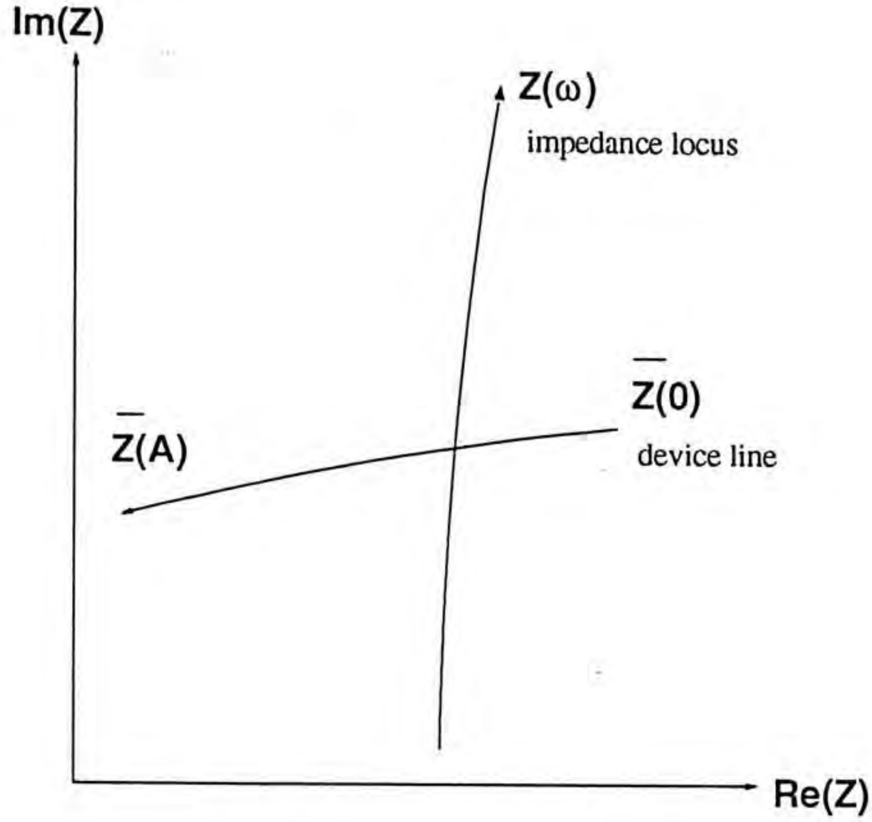


Fig. 3-5 Impedance locus and device line

The locus of circuit impedance $Z(\omega)$ is the impedance locus and the locus of the device impedance $\overline{Z}(A)$ is the device line. The arrowheads attached in the locus and the lines indicate the direction of increasing ω and increasing A respectively. The intersection of these loci corresponds to $Z(\omega)=\overline{Z}(A)$. It is the steady-state oscillation point of the oscillator.

When a signal with its frequency close to the free running frequency is injected to an oscillator, the oscillator is synchronized or locked to the injected signal. An equivalent negative resistance circuit diagram is shown in Fig. 3-6.

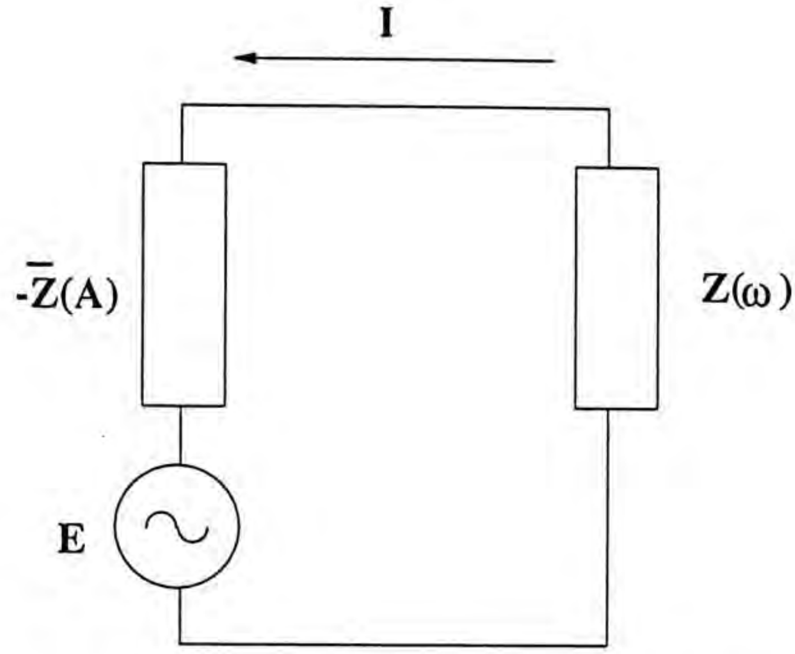


Fig. 3-6 Kurokawa oscillator model with signal injection

The corresponding equation is given by

$$\left[Z(\omega_i)-\overline{Z}(A)\right]I = E \tag{3-21}$$

where E represents the injection signal voltage seen by the device, and ω_i is the injection frequency. If $I = A_o e^{j\phi}$, the equation becomes

$$Z(\omega_i)=\overline{Z}(A)+\frac{|E|}{A_o}e^{-j\phi} \tag{3.22}$$

where ϕ is the phase difference between I and E.

The arrow joins from $\overline{Z}(A)$ to $Z(\omega_i)$ in the complex plane is called the injection vector with magnitude given by $|E|/A_o$ as shown in Fig. 3-7.

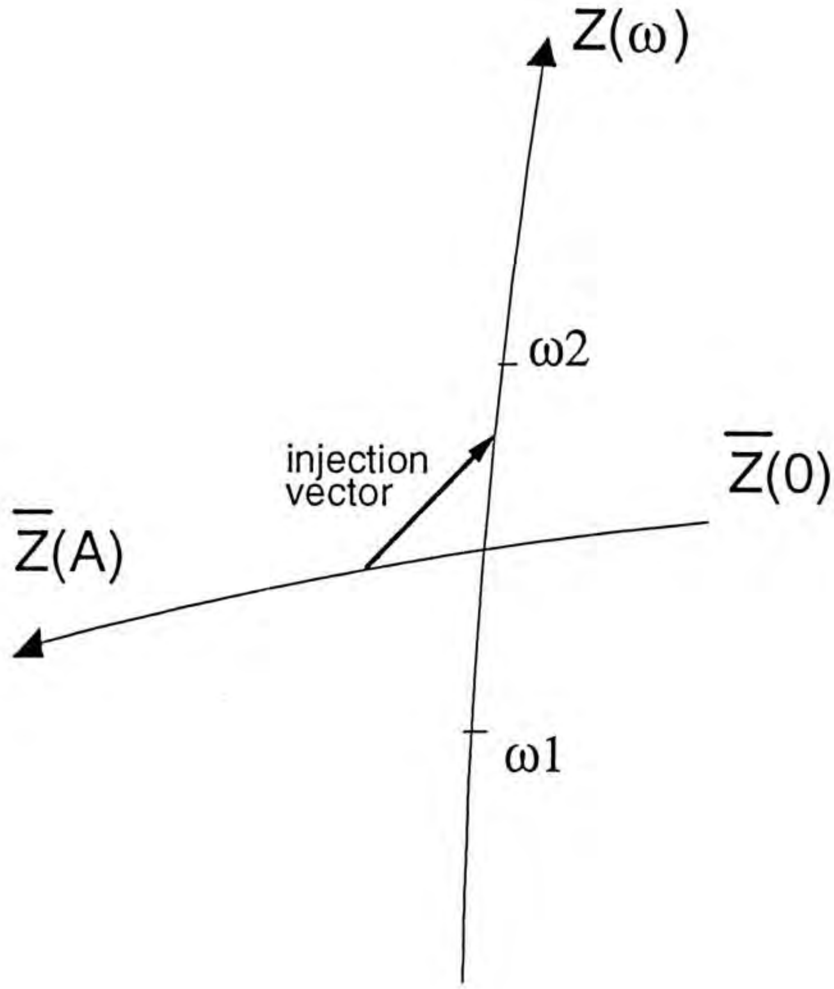


Fig. 3-7 Relation of injection vector, impedance locus, and device line

It can be seem from the locus that by varying ω_i and keeping $|E|$ constant, the vector moves as shown in Fig. 3-8, with upper and lower boundaries at ω_1 and ω_2. For the frequency below ω_1 and aboveω_2, the distance to the device line is longer than the injection vector. When the vector relation is not satisfied, it indicates that no locking takes place. Between ω_1 and ω_2, the locking takes place and the locking range is $|\omega_1 - \omega_2|$.

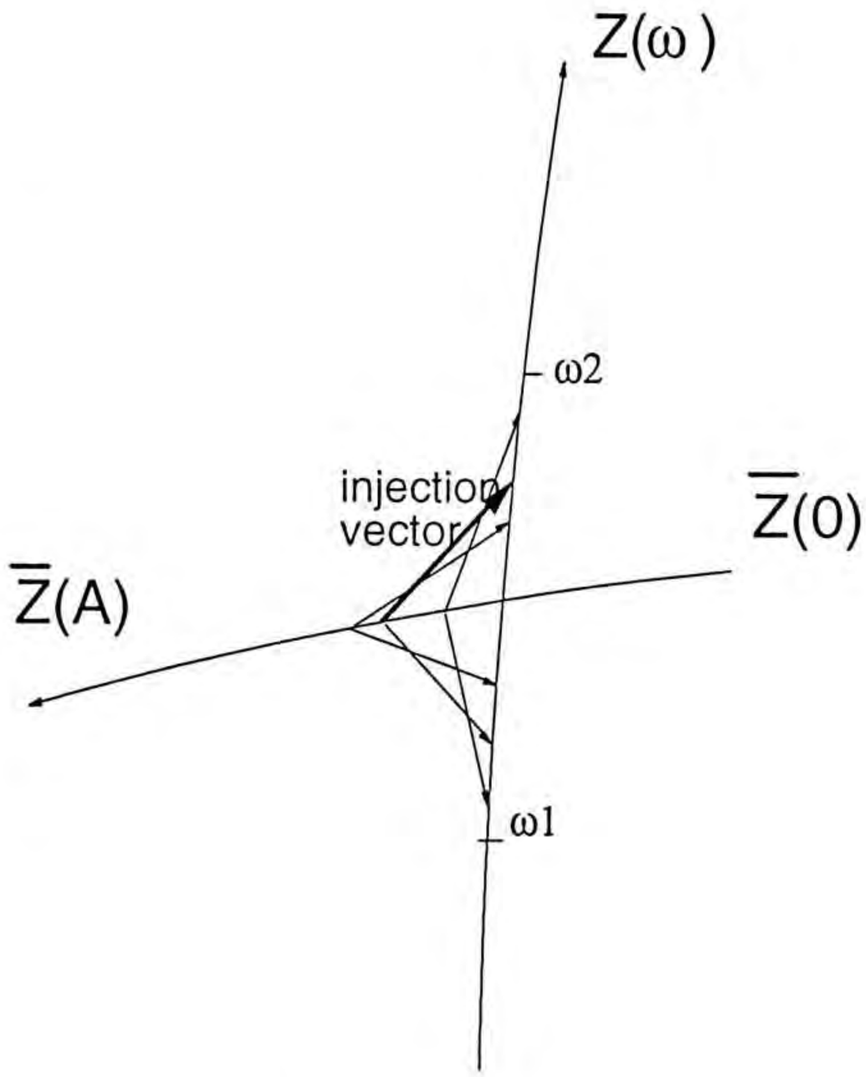


Fig. 3-8 Variation of the injection vector as the injection frequency is swept from ω_1 to ω_2. Locking is not possible below ω_1 or above ω_2.

3.3 TYPES OF INJECTION LOCKED OSCILLATOR

There are two main types of injection locked oscillator. They are the transmission type and the reflection type. The difference between these two type of oscillator mainly lies on the different points of injection.

Reflection type

Reflection type injection locked oscillator was named by Tajima and Mishima[31] in 1979. Injection locked oscillator was widely used in the millimeter wave range in which the fundamental injection signal was injected at the output by means of a circulator as shown in Fig. 3-9. The circulator is used to isolate the input and output port.

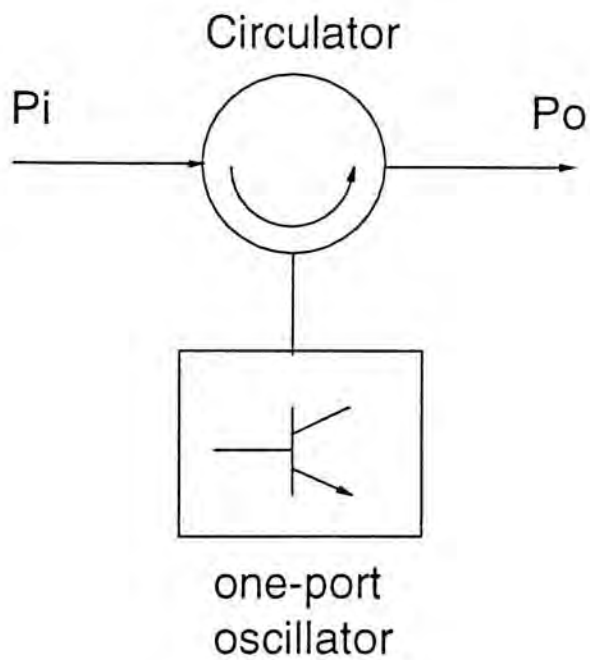


Fig. 3-9 Reflection type injection locked oscillator

Transmission type

Transmission type injection locked oscillator is equipped with separate signal input and power-output ports as shown in Fig. 3-10. The transmission type can retain high gain within a locking frequency range which is wider than that of reflection types, but does not necessarily require the use of a circulator to isolate the input and output ports. Tajima and Mishima[31] experimentally showed that an injection-locked GaAs FET oscillator gave a 1.8 times wider locking range than with reflection type.

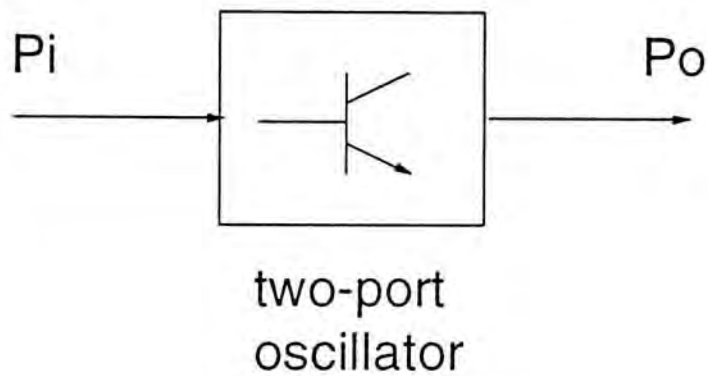


Fig. 3-10 Transmission type injection locked oscillator

3.4 INJECTION LOCKING CHARACTERISTICS

Locking range

Locking range is a key figure of merit to describe an injection locked oscillator. It is the frequency region in which the oscillator tracks and locks to the injection signal. The Van del Pol model, the Kurokawa model, and the Adler model also shows that the locking range of an injection locked oscillator depends on the output magnitude and the input magnitude. From Adler model the locking range (Δf) is given by

$$\Delta f = \frac{f}{Q}\frac{V_{inj}}{V_{out}} \tag{3.23}$$

where f = oscillator natural frequency
Q = Q-factor
Vinj = Injection voltage
Vout = oscillator output voltage

The equation shows that locking range is directly proportional to the injection voltage strength. That means the locking range depends on the input signal strength. For a higher signal level injection, the locking range is higher.

Locking Gain

The locking gain of an injection locked oscillator is generally defined in terms of dB as shown in the equation below.

$$\text{Locking gain (dB)} = 10\log_{10}\left(\frac{Pout(mW)}{Pin(mW)}\right) \tag{3.24}$$

where Pout is the output power level of the oscillator measured in milli-watt (mW)and Pin is the input power level measured in milli-watt (mW). If the powers are measured in terms of dBm, the locking gain is defined as shown in the following equation.

$$\text{Locking gain (dB)} = \text{Pout (dBm)} - \text{Pin (dBm)} \tag{3.25}$$

When an injection locked oscillator oscillates at its steady state giving a saturated power, the output (Pout) is almost the same, i.e., Pout is constant. Therefore, locking gain is a function of the injection power level (Pin).

Three stages of injection

When there is no injection signal injected to the injection locked oscillator, the oscillator is in its free running state giving its natural frequency fo and power Po. When there is a signal injected to the oscillator, there are 3 stages of injection of an injection locked oscillator. They are the 1) locked state, 2) unlocked state, and 3) driven but unlocked state.

i) Locked state

When an injection locked oscillator is locked to an injected signal, the oscillator is in its locked state giving the output frequency equal to the injection one but the power remains equal to Po. When a signal is injected to an injection locked oscillator and falls into the locking range. The oscillator is in its locked state.

ii) Unlocked state

When the injection signal is far from the locking range and does not affect the natural frequency of oscillation, the injection locked oscillator is in the unlocked state. In this case, the ILO operates as a self-oscillating mixer[32].

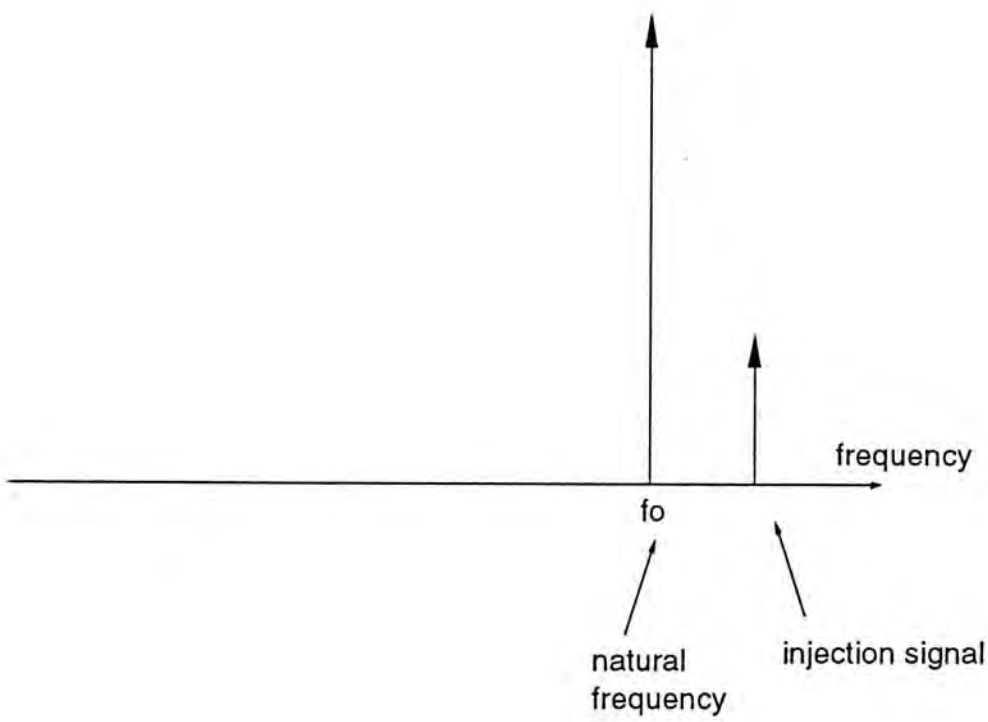


Fig. 3-11 Frequency spectrum with fundamental injection (unlocked state)

iii) Driven but unlocked state

Prior to locking or after unlocking, the output spectrum of an ILO shows an asymmetrical side band as shown in Fig. 3-12. This is the driven but unlocked state. The ILO is nearly locked.

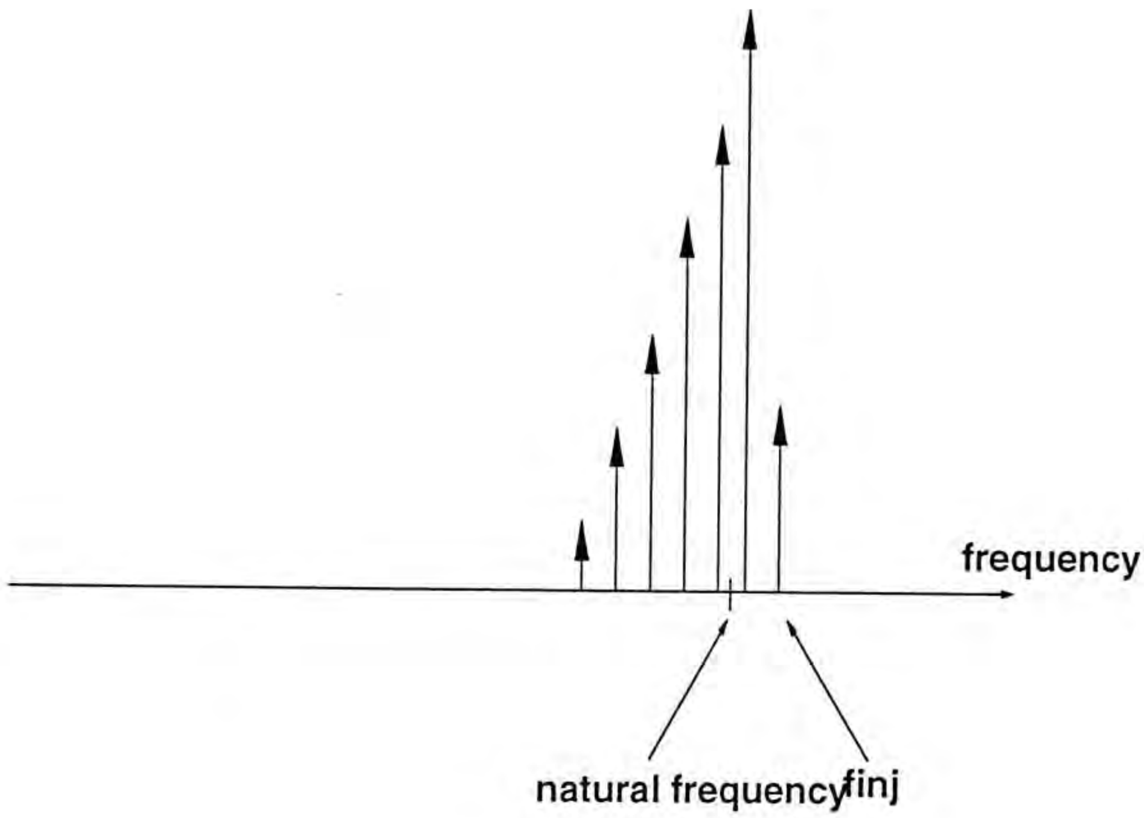


Fig. 3-12 The driven but unlocked of an injection locked oscillator.

The asymmetrical side band has been explained successfully by Stover[33], Armand[34]. When an injection locked oscillator is on its driven but unlocked stated, it be expected that when either by increasing the injection signal strength or by varying the frequency closer to the natural free running frequency, the ILO will lock to the input signal. This state is important for determining the lock-in points.

Transfer characteristics

When an ILO is measured using a network analyzer, in which the injection signal frequency is continuously swept. The transfer characteristics of the ILO can be obtained as shown in Fig. 3-13.

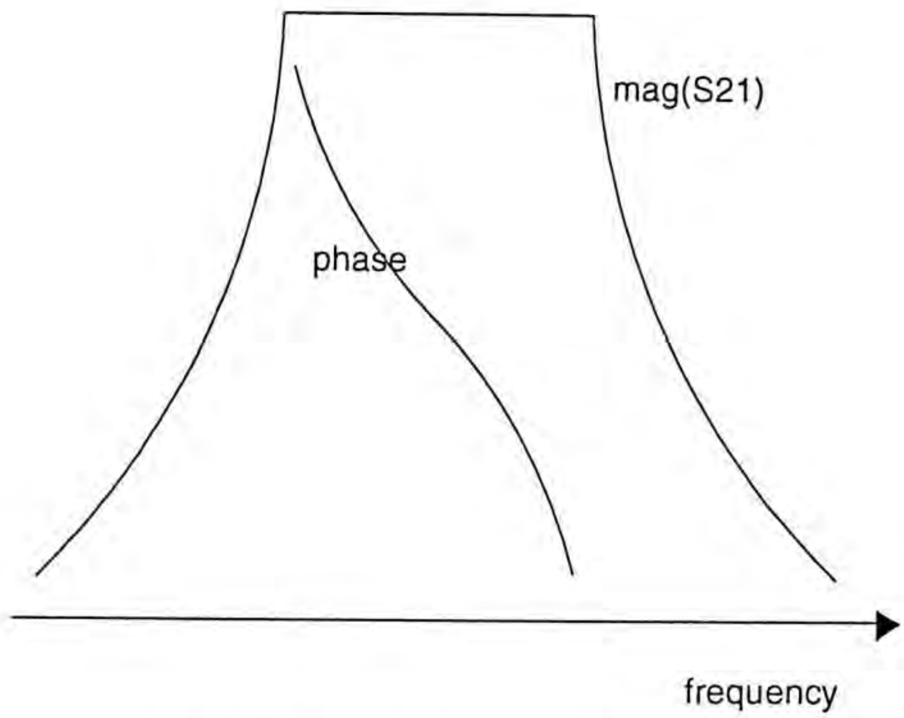


Fig. 3-13 Transfer characteristic of an ILO

It shows both the magnitude and the phase of S21. For the magnitude of S21, there is a flat top region corresponding to the locked state. The width of the flat top region is the locking range of the ILO. The other regions (the lower and upper regions) are the driven but unlocked regions. The flatness of the S21 curve in the locking region indicates that the active device of the ILO operates at its saturated region giving saturated output power. For the phase, it gives a continuos phase change with ±90° (180° in total) range.

3.5 CONCLUSION

In this chapter, three injection locked oscillator models, two types of injection locked oscillator, and some injection locking characteristics are discussed. The models are the Van del Pol model, the Adler model, and the Kurokawa model. Those models showed that the locking range of an injection locked oscillator depends on the signal injection level.

For the two types of injection locked oscillator, they are the transmission type and the reflection type. The transmission type injection locked oscillator gives a larger locking range than that of the reflection type. Besides, transmission type is simpler than reflection type as no circulator is needed for signal injection.

For injection locking characteristics, the locking range, the locking gain, the three stages of injection, and the transfer characteristics are discussed. In the three stages of injection, there are locked stage, unlocked state, and driven but unlocked stage.

CHAPTER 4

SUBHARMONIC INJECTION LOCKING

4.1 INTRODUCTION

In this chapter, the Chien and Dalman theory[10] will be discussed first. Although, their discussion was limited to qualitative descriptions, it can be further elaborated using a block diagram oscillator model. Their theory forms the foundation of subharmonic injection works.

After the Chien and Dalman theory, the feedback nonlinear model from Zhang *et al.*[30] will then be discussed, in which a feedback nonlinear model with power series is used to predict the subharmonic locking.

4.2 SUBHARMONIC INJECTION LOCKING

Chien and Dalman Model

Chien and Dalman put forward a theory that subharmonic locking phenomenon is caused by the nonlinearities in the active device, which creates the appropriate harmonic of the subharmonic injection signal. The harmonic signal then acts as the fundamental locking signal and forced the oscillator to be synchronized. This idea can be represented by the model shown in Fig. 4-1.

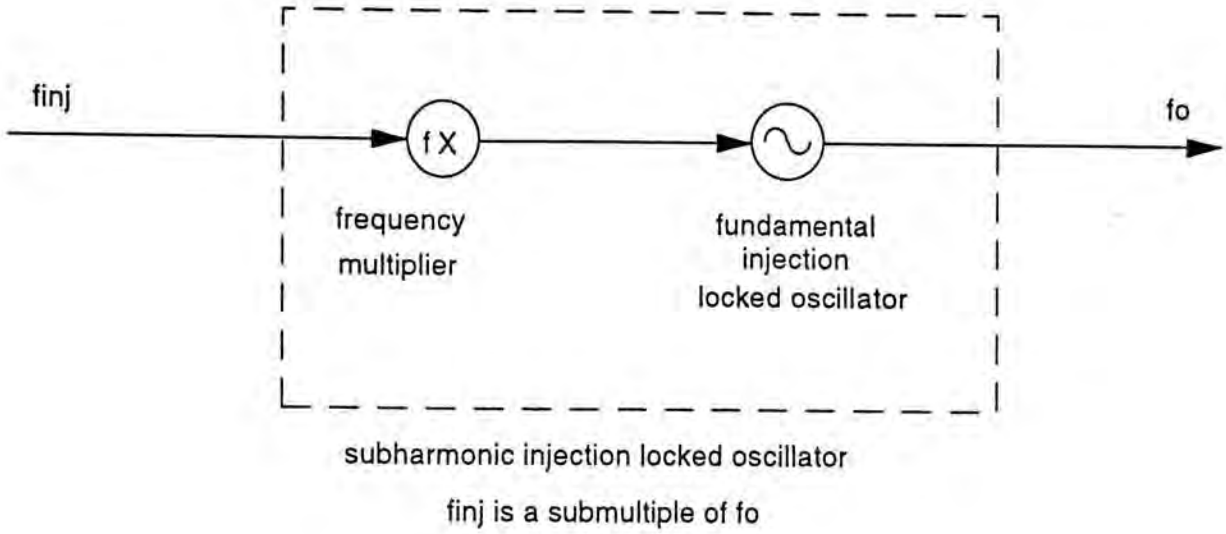


Fig. 4-1 Block diagram of Chien and Dalman model

The model consists of a frequency multiplier and a fundamental injection oscillator. When an oscillator is operating at steady state, it is a nonlinear device. If a signal is injected to the oscillator, harmonics are generated. It acts like a frequency multiplier. The appropriate harmonic is then injected to the oscillator as fundamental injection locking. There is power loss in the frequency conversion process in the "frequency multiplier". The fundamental signal power level generated by the "multiplier" and injected to the "oscillator" is lower. This explains why subharmonic locking give a smaller locking range in comparing with fundamental injection locking. Besides, the subharmonic locking is no longer directly proportional to the injection voltage. It depends on both the injection power level and the nonlinear characteristic of the oscillator for up conversion process.

Feedback Nonlinear Model

A new way of analyzing subharmonic injection-locked oscillator was proposed by Zhang *et al*[30], which is based on a general nonlinear input-output model for the subharmonic synchronized oscillator. The results show that the n-th order subharmonic injection locked oscillator is locked primarily by the n-th harmonic output of injected signal that is generated by the current-voltage nonlinearity of the active device. The feedback model is shown in Fig. 4-2.

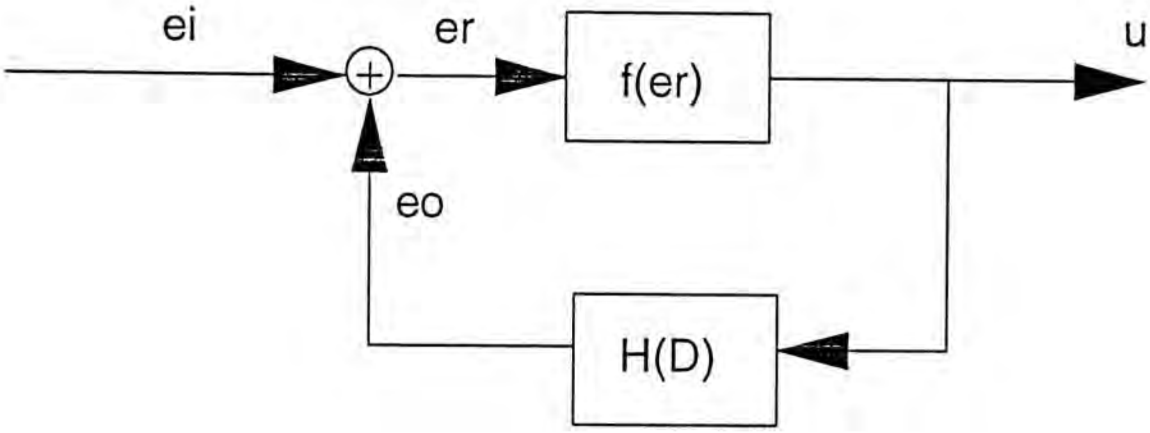


Fig. 4-2 Conceptual diagram model of subharmonically synchronized oscillator

The feedback model consists of a nonlinear network $f(e_r)$ and a linear feedback network H(D). The output of the oscillator, u, feeds back to the input via H(D). The signal is injected to the nonlinear network with the input signal e_i.

The input signal e_r for the nonlinear network is :

$$e_r = e_o + e_i = \frac{E}{2}(e^{j\omega t} + e^{-j\omega t}) + \frac{E_i}{2} e^{j\frac{\omega}{n}t}$$

where $\omega = n\omega_{inj}$ is the synchronized frequency after injection locking, and ω_{inj} is the injection frequency. Ei is the injected signal amplitude and phase θ. n is an integer for the subharmonic factor, and E is the oscillation signal amplitude at input port. The output of the oscillator can be expanded into a Fourier Series :

$$u = f(e_r) = \sum_{m=-\infty}^{\infty} \dot{U}_m e^{jm\frac{\omega}{n}t} \tag{4.1}$$

To simplify the analysis, f(er) is expressed approximately by

$$u = f(e_r) = \sum_{i=1}^{\infty} \alpha_i e_r^{\ i} \tag{4.2}$$

where α_i is considered to be real for simplicity.

Substituting eqn. (4.2) to eqn. (4.1), for subharmonic injection at a factor of n, the output signal with oscillation frequency $n\omega_{inj}$ is given :

$$\dot{U}_n = \left(\sum_{j=0}^{\infty} \sum_{k=0}^{\infty} \frac{1}{2^{N-1}} \cdot \frac{N!}{(j!)^2 \cdot (k+1)! \cdot k!} \cdot \alpha_N \cdot |E_i|^{2j} \cdot E^{2k} \right) \cdot E$$
$$+ \left(\sum_{m=0}^{\infty} \sum_{p=0}^{\infty} \frac{1}{2^{M-1}} \cdot \frac{M!}{(m!)^2 \cdot (p+n)! \cdot p!} \alpha_M \cdot |E_i|^{2p} \cdot E^{2m} \right) \cdot E_j^n$$
$$+ \text{higher order terms} \tag{4.3}$$

where $N = 2j + 2k + 1$ and $N = 2m + 2p + n$. The first term is the oscillation signal amplitude U_{out}, and the second term represents the response U_{outn} of injected signal *Ei* when it goes through the nonlinear network together with the oscillation signal *E*.

$$\dot{U}_n \approx U_{out} + U_{outn} \tag{4.4}$$

The subharmonic injection locking range can be expressed in terms of Q and ω_o as follows :

$$\Delta\omega_{1/n} \approx \frac{\omega_o}{2Q} \cdot \frac{U_{outn}}{U_{out}} = \frac{\omega_o}{2Q} \cdot \sqrt{\frac{P_{outn}}{P_{out}}} \tag{4.5}$$

4.3 SUBHARMONIC INJECTION LOCKING CHARACTERISTICS

Subharmonic locking range

Similar to fundamental injection locking, subharmonic locking range is a key parameter describing a subharmonic injection locked oscillator. Subharmonic locking range is the frequency region that the output frequency of the oscillator is a multiple of the injection frequency. The difference between the highest locked frequency and the lowest locked frequency is the subharmonic locking range.

Locking gain

Locking gain for subharmonic injection is the same as defined in fundamental injection locking. It is defined as

$$\text{Locking gain (dB)} = 10\log_{10}\left(\frac{Pout(mW)}{Pin(mW)}\right) \tag{4.6}$$

or , Locking gain (dB) = Pout (dBm) - Pin (dBm) (4.7)

eqn. (4.6) is defined if the powers are in milli-watt (mW), and eqn. (4.7) is defined if the powers are in dBm.

However, it should be reminded that the power levels, Pout and Pin, refer to different frequencies although the frequencies are harmonically/subharmonically related.

Three stages of subharmonic injection

i) Locked state

When an injection locked oscillator is locked to its subharmonic injection signal, i.e. the output frequency is a multiple of the injection frequency, the oscillator is in subharmonically locked state. Unlike fundamental injection locking, the subharmonic signal co-exists in the frequency spectrum as shown in Fig. 4-3.

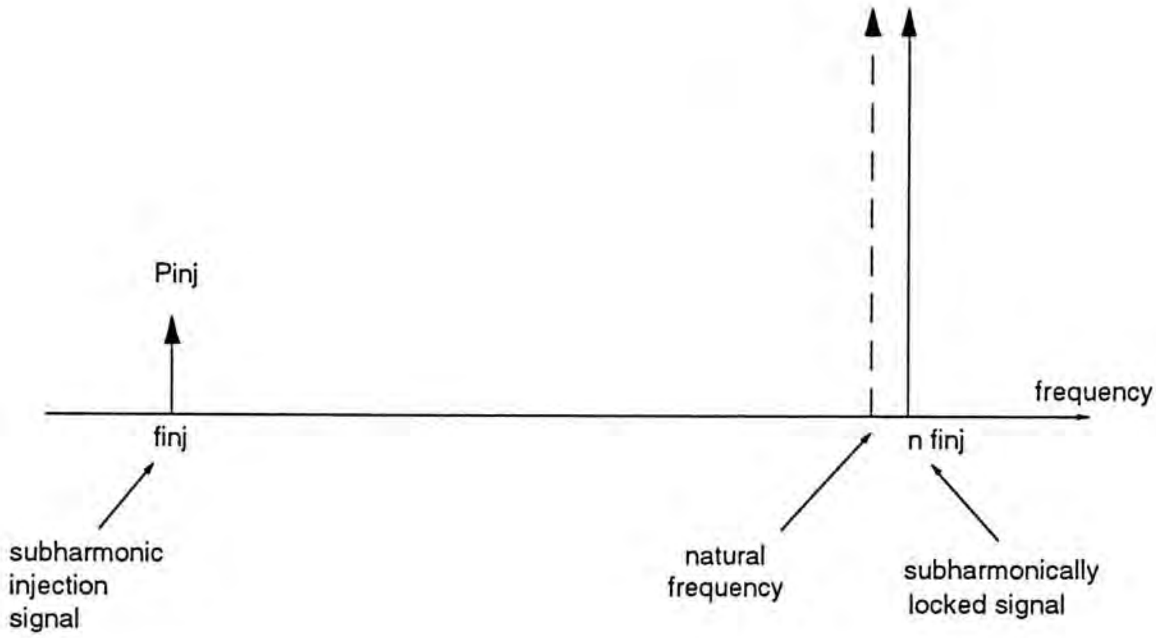


Fig. 4-3 Output spectrum of the locked state by subharmonic injection

2) Unlocked state

When the injection signal is far from the fundamental locking range and the subharmonic locking ranges, it does not affect the oscillator natural frequency. The injection locked oscillator is in its unlocked state. The oscillator behave as a self oscillating mixer. The output spectrum is shown in Fig. 4-4 The natural frequency does not change and the injection signal is mixed up to give an upper and a lower side band at the oscillator natural frequency band.

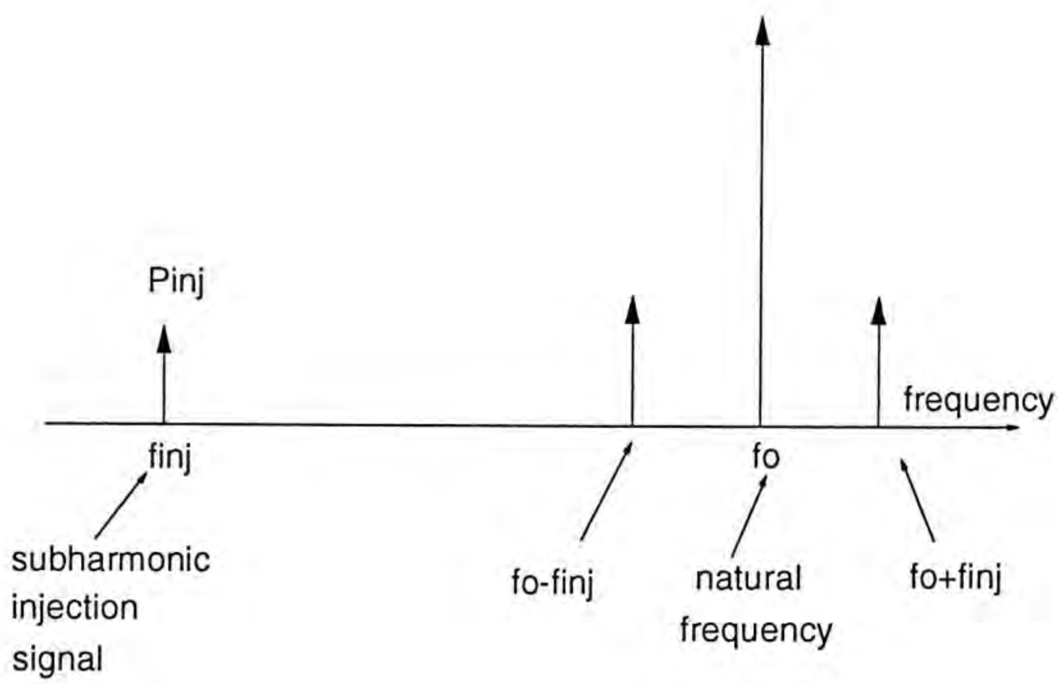


Fig. 4-4 Output spectrum of unlocked state by subharmonic injection

3) Driven but unlocked state

When the injection signal is closed to the subharmonic frequency of the natural frequency, the appropriate harmonic of the injection frequency caused an unlocked but driven state. An asymmetrical side band is also observed as shown in Fig. 4-5.

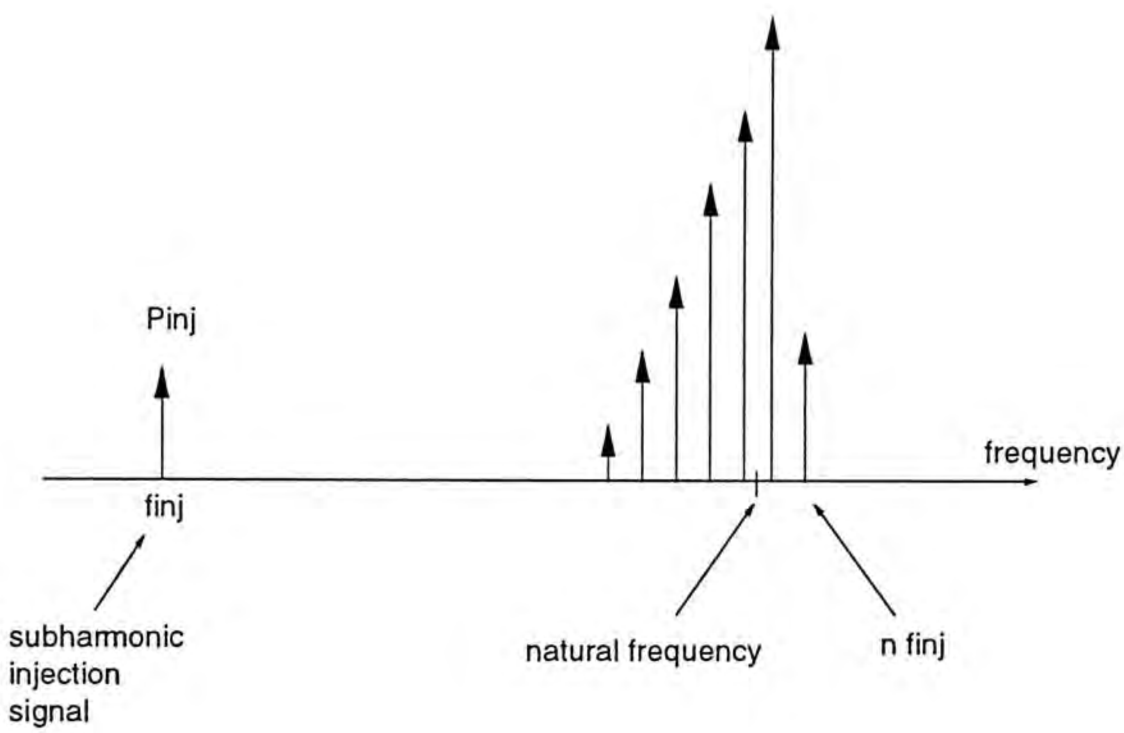


Fig. 4-5 Output spectrum of driven but unlocked state by subharmonic injection

4.4 CONCLUSION

In this chapter, two models for subharmonic injection locking are discussed. They are the Chien and Dalman model and the Zhang *et. al* feedback model. The basic theory of subharmonic injection locking is the appropriate harmonic generation when a subharmonic is injected to an injection locked oscillator. The appropriate harmonic signal is then injected to the oscillator as fundamental injection locking. Due to the power loss in the frequency conversion process, the locking range for subharmonic locking is smaller than the fundamental locking range with same power level of injection. Subharmonic locking range can be predicted by the feedback model proposed by Zhang *et al.* if the nonlinear characteristics of the oscillator can be determined.

CHAPTER 5

EXPERIMENTAL INVESTIGATIONS ON INJECTION LOCKING

5.1 INTRODUCTION

In this chapter experimental findings on injection locking will be presented. They are sub-divided into four parts : 1) non-integral subharmonic injection locking, 2) selective subharmonic locking range enhancement, 3) comparison on different points of injection, and 4) phase tuning beyond 180 degrees by injection locking.

Traditionally, subharmonic locking is limited to integral subharmonic signal locking. However, the subharmonic injection signal can be non-integrally related to the natural frequency of the oscillator, which will also provide locking behavior. Two BJT oscillators were implemented using different transistors to demonstrate the behavior. This behavior can be explained by the nonlinear feedback model.

The second part emphasizes on subharmonic locking range enhancement. Usually, higher injection power is required to obtain certain locking range for subharmonic locking than that required for fundamental. Zhang *et al.*[30] proposed a two port nonlinear feedback model to predict the subharmonic locking range by considering the device nonlinearities. With this approach, the subharmonic locking range can be optimized by optimizing the nonlinearity of the device. In real design practice, however, determining the nonlinear network parameters is difficult. This part shows that introducing an additional feedback path for the desired subharmonic frequency can enhance the subharmonic locking range. An oscillator with an additional feedback path resonating at 1/3 subharmonic was built to demonstrate the effect. Experimental results show that the subharmonic locking range can be enhanced and controlled by the resistor in the additional feedback path.

The third part shows a comparison study on the locking range with two different points of injection in an oscillator. A signal is injected directly to a terminal of the BJT and the other is injected via the feedback path. Both the fundamental and 1/2 subharmonic injection locking ranges were measured. Significant improvement was found for the one injected via the feedback path.

The phase characteristic within the locking range of injection locked oscillator is studied in the last part. With linear analysis, the phase change in the locking range of an injection locked oscillator is limited to 180 degrees. Even if the nonlinear reactance is taken into account, the phase change is limited to around 190 degrees only[8]. Using cascaded fundamental injection locking one can increase the phase change within the locking range. Theoretically, it can be 360 degrees for two injection locked oscillators cascaded together.

Some experimental characteristics of injection locking are presented before the detail discussions of the investigation results.

5.2 EXPERIMENTAL CHARACTERISTICS

The simulation results of a 900MHz oscillator and the circuit diagram are shown in Fig. 5-1 and Fig. 5-2 respectively. The oscillator is a Colpitts oscillator with the BJT in common base configuration. The oscillator is simulated using HP Microwave Design System (MDS) before implementation. The oscillator prototype is shown in Fig. 5-3 and Fig. 5-4. The oscillator was implemented with lump elements and most elements are surface mount type components. Semi-rigid SMA connectors are used for the input and output ports. Variable capacitors are used in the circuit so that the oscillator frequency can be adjusted. The free running frequency spectrum observed from a spectrum analyzer is shown in Fig. 5-5. The oscillator under fundamental injection locking is shown in Fig. 5-6. The oscillator is locked to the input signal. Notice from the figures that the phase noise is improved when the oscillator is under injected locked. Two driven but unlocked states observing from a spectrum analyzer are shown in Fig. 5-7 and Fig. 5-8. The asymmetric side band is observed. The transfer characteristics of the oscillator observing from a network analyzer is shown in Fig. 5-9. The flat-top region at the top is corresponding to the locking range of the oscillator. The phase change within the locking range is within ± 90°.

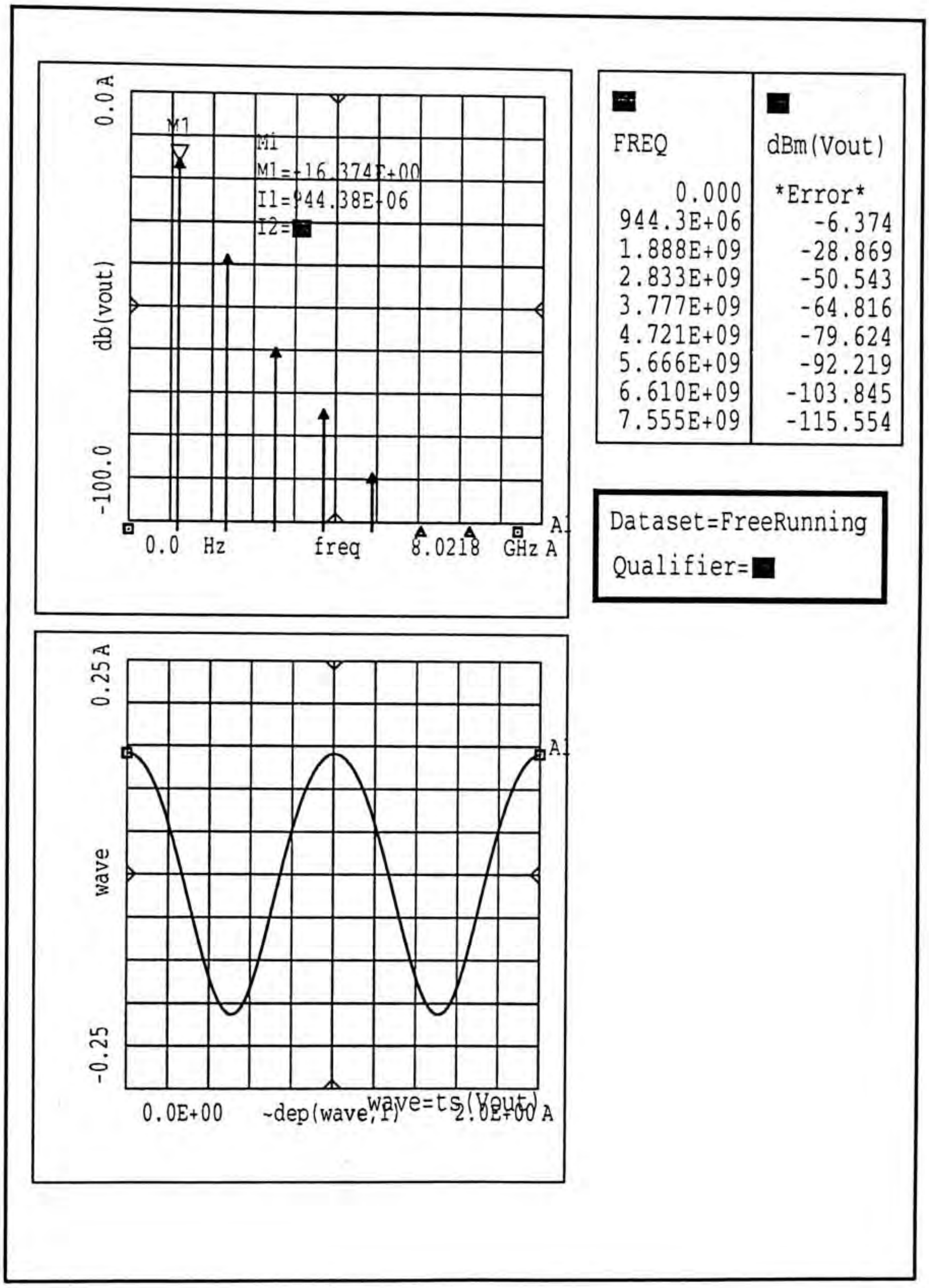


Fig. 5-1 Simulation results of the 900MHz oscillator

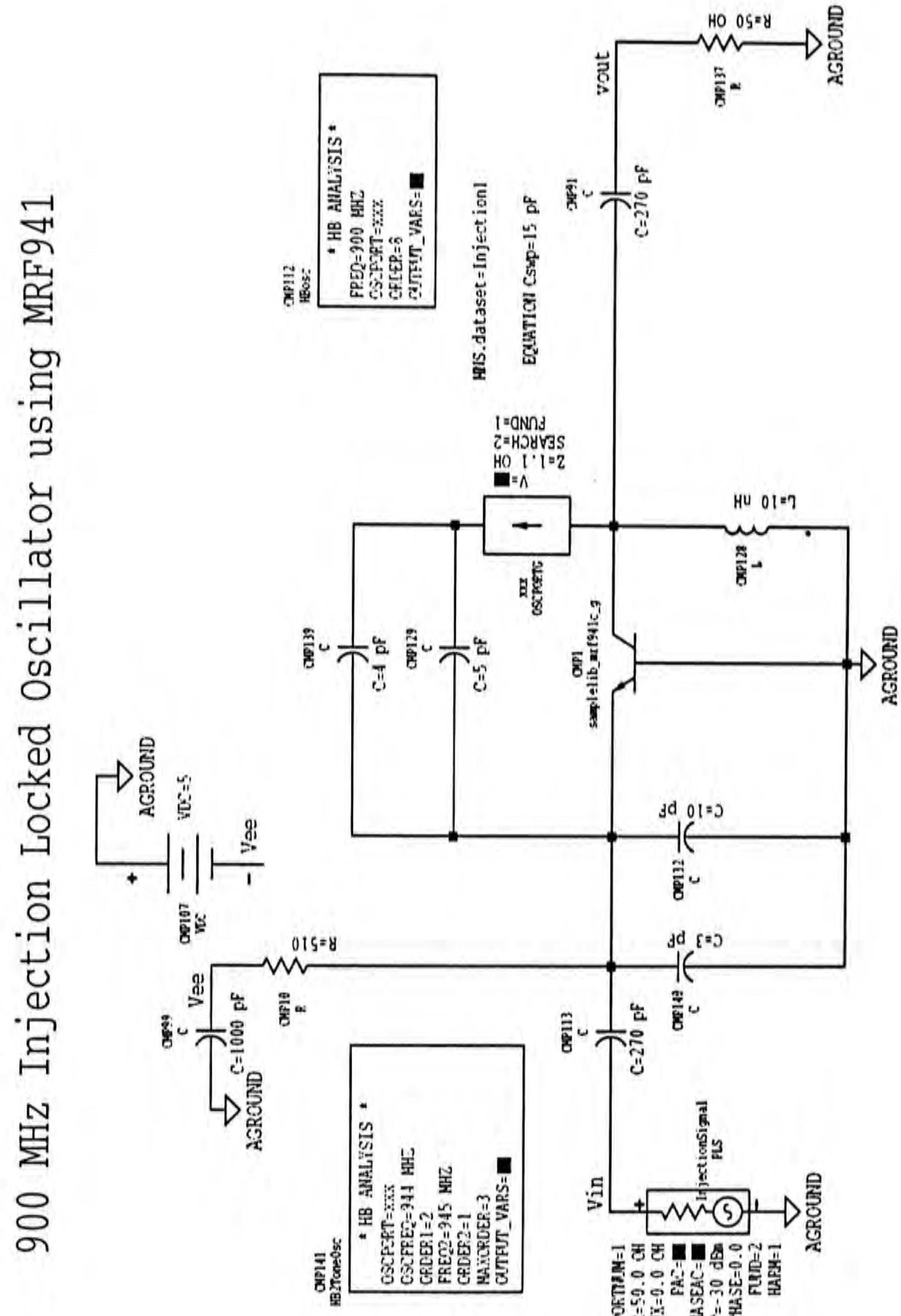


Fig. 5-2 Schematic diagram of the 900MHz oscillator

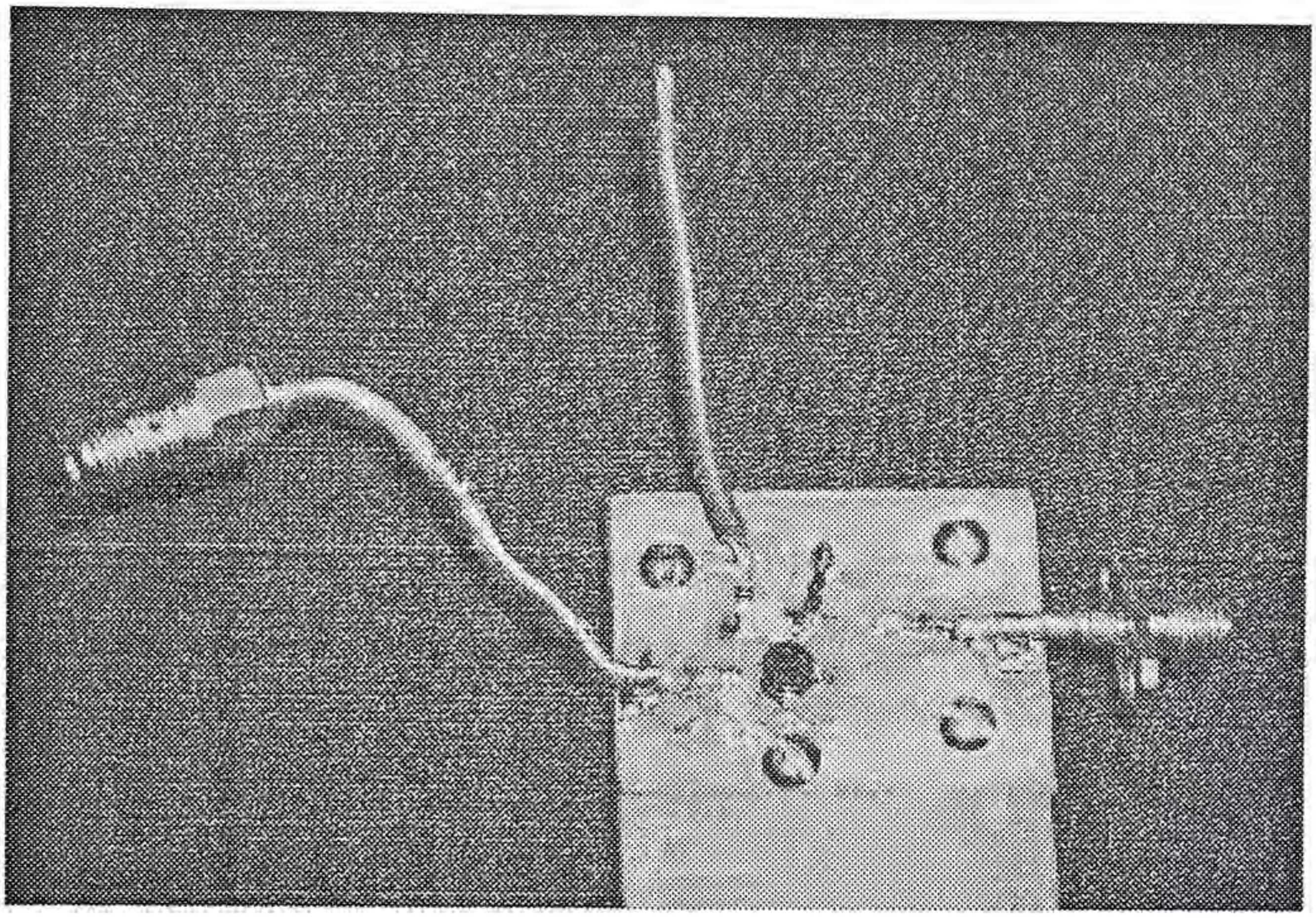


Fig. 5-3 Real circuit prototype of the 900MHz oscillator

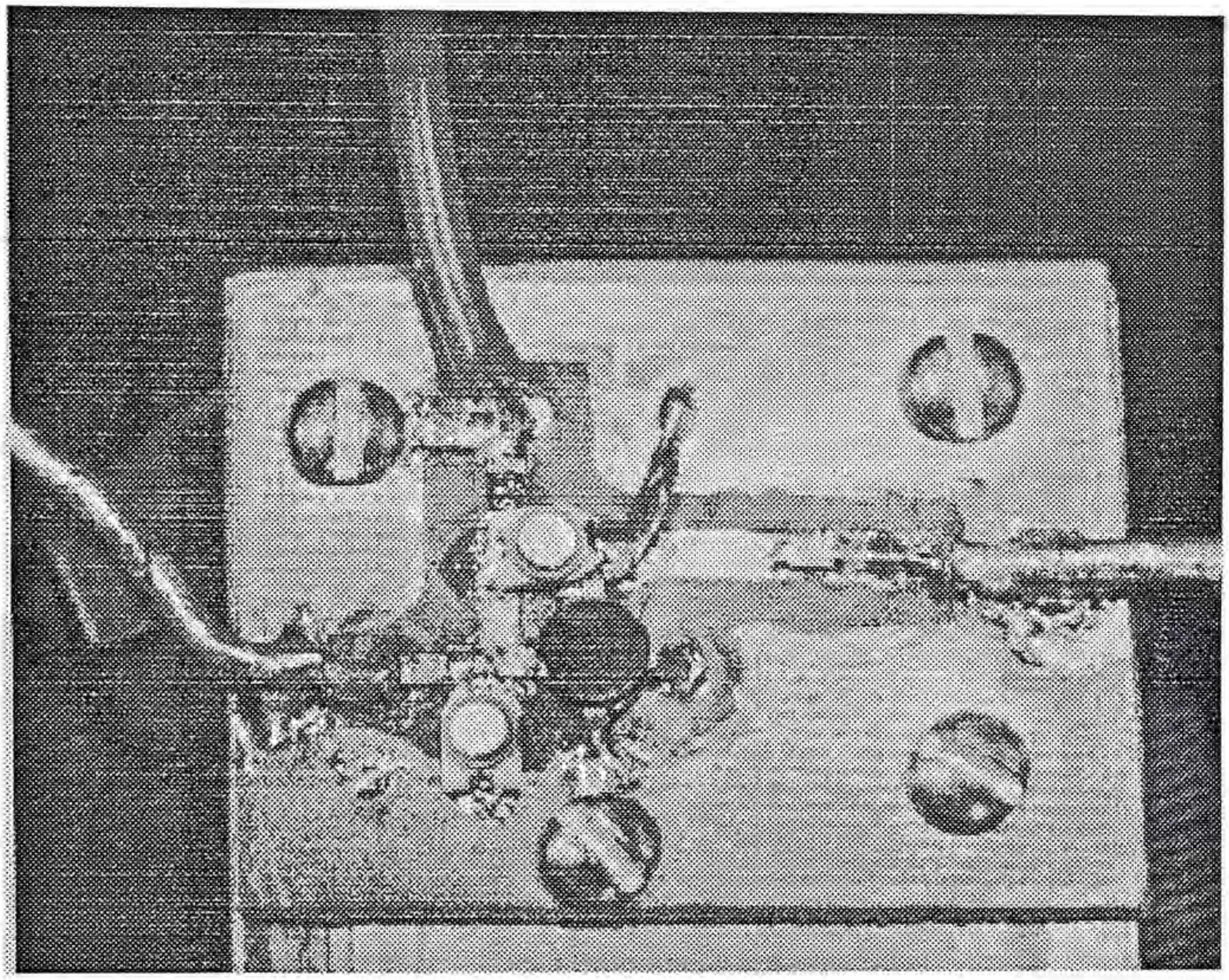


Fig. 5-4 Another view of the prototype oscillator

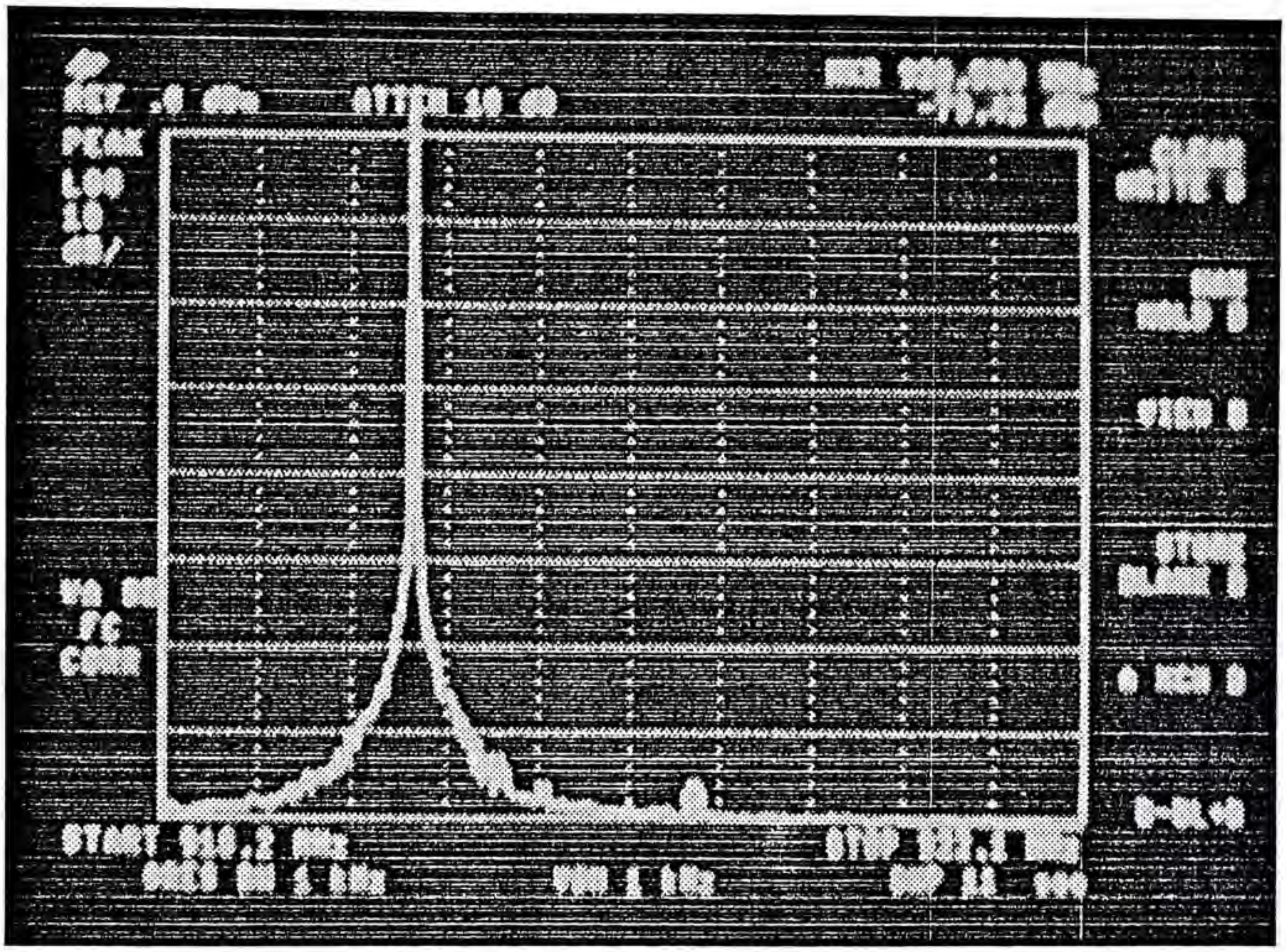


Fig. 5-5 Free running frequency component of the oscillator viewing from a spectrum analyzer

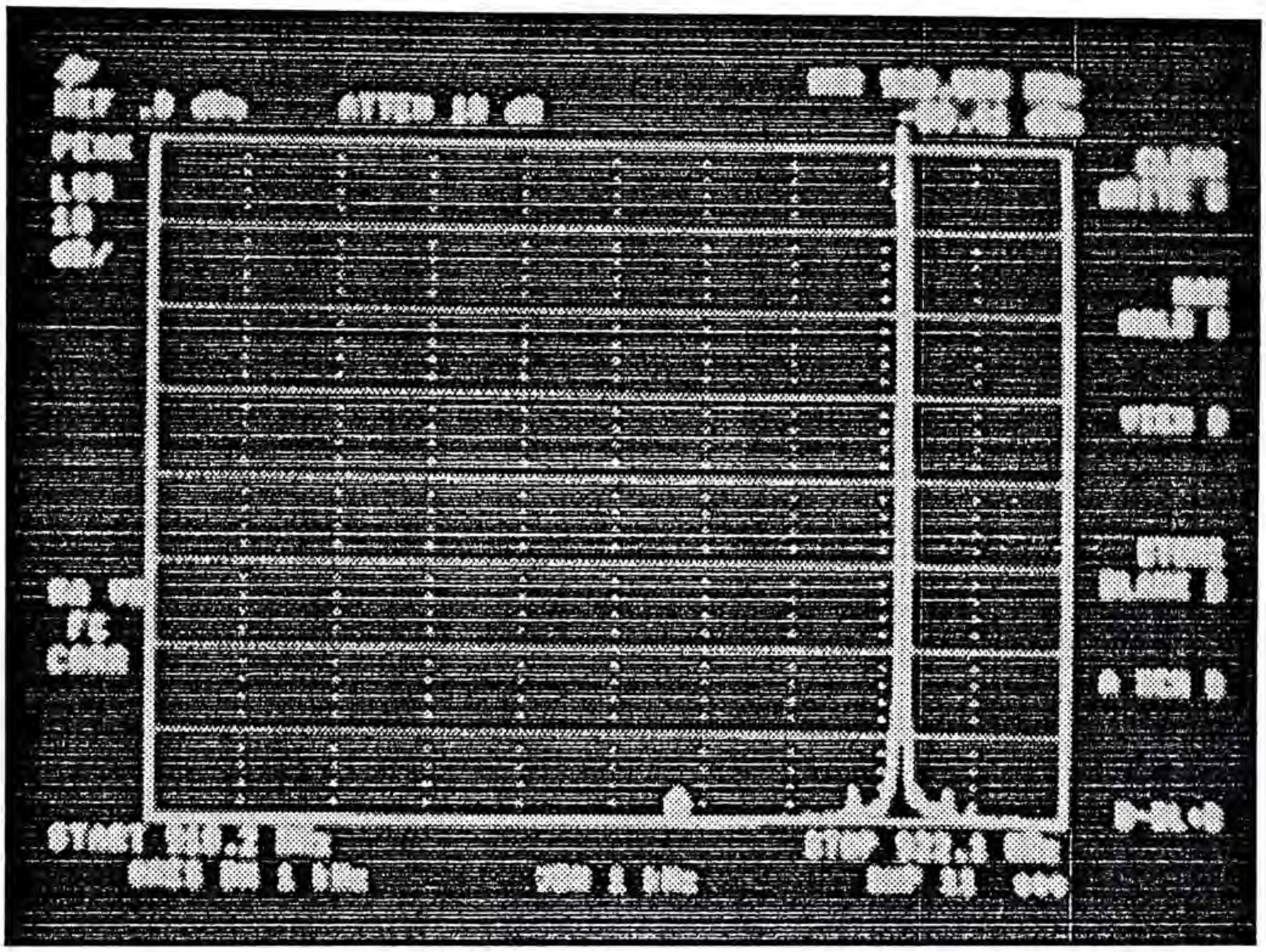


Fig. 5-6 The frequency spectrum of the oscillator under injection locked.
Notice that phase noise is improved under the injection locking.

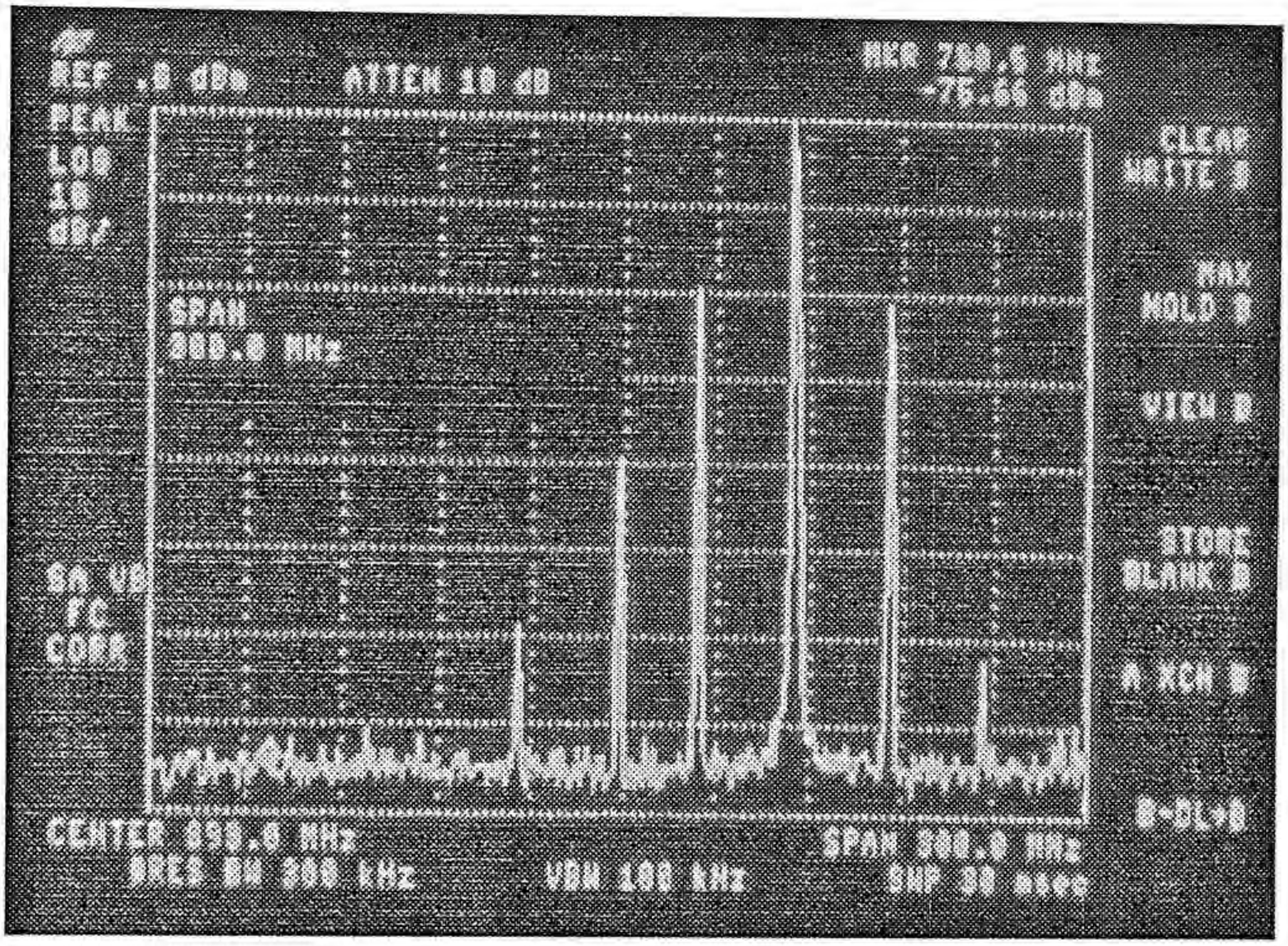


Fig. 5-7 Driven but unlocked state of the injection locked oscillator

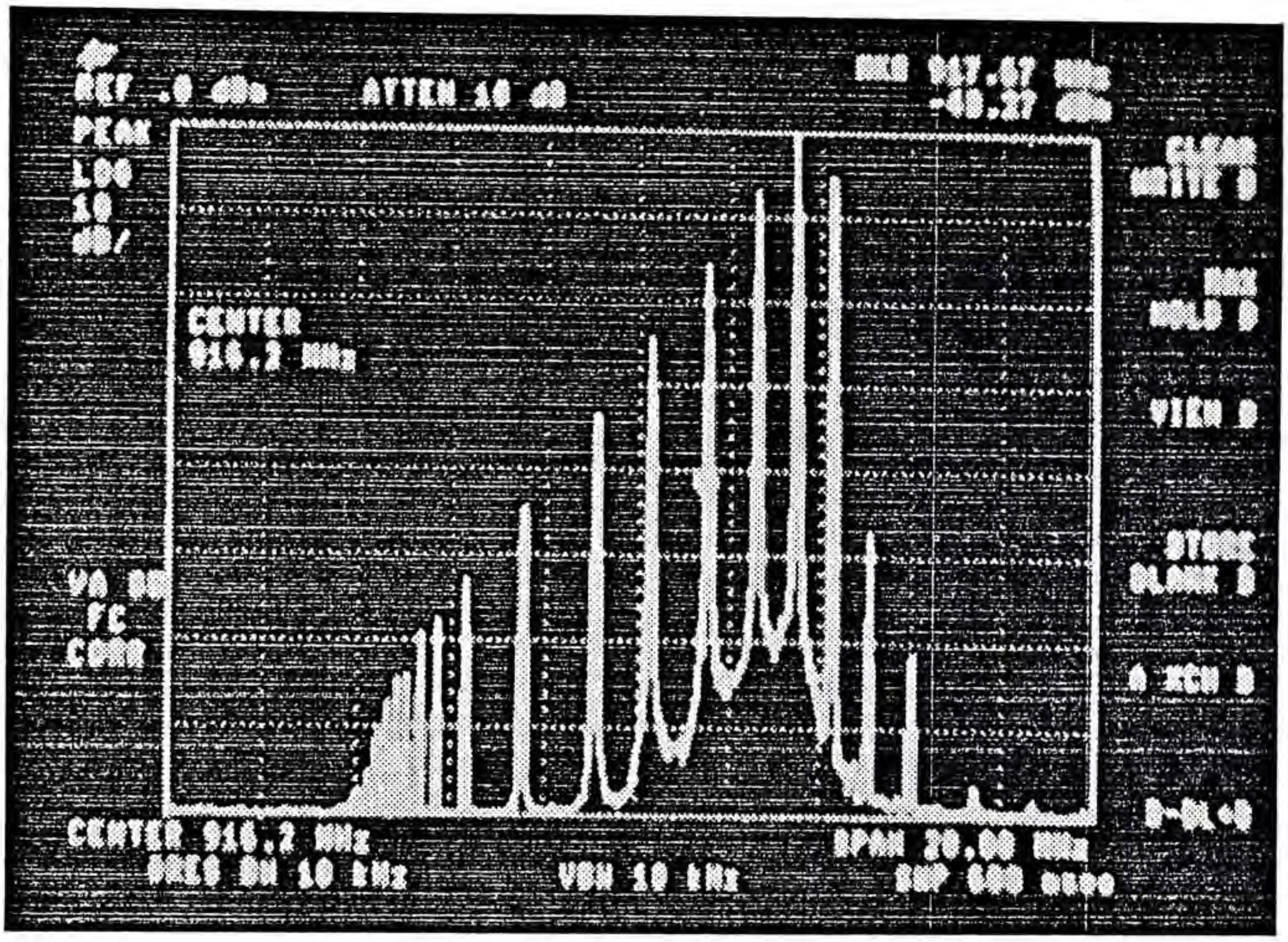


Fig. 5-8 Driven but unlocked state of the oscillator. Notice that the frequency component is more closed together which means the oscillator is almost locked.

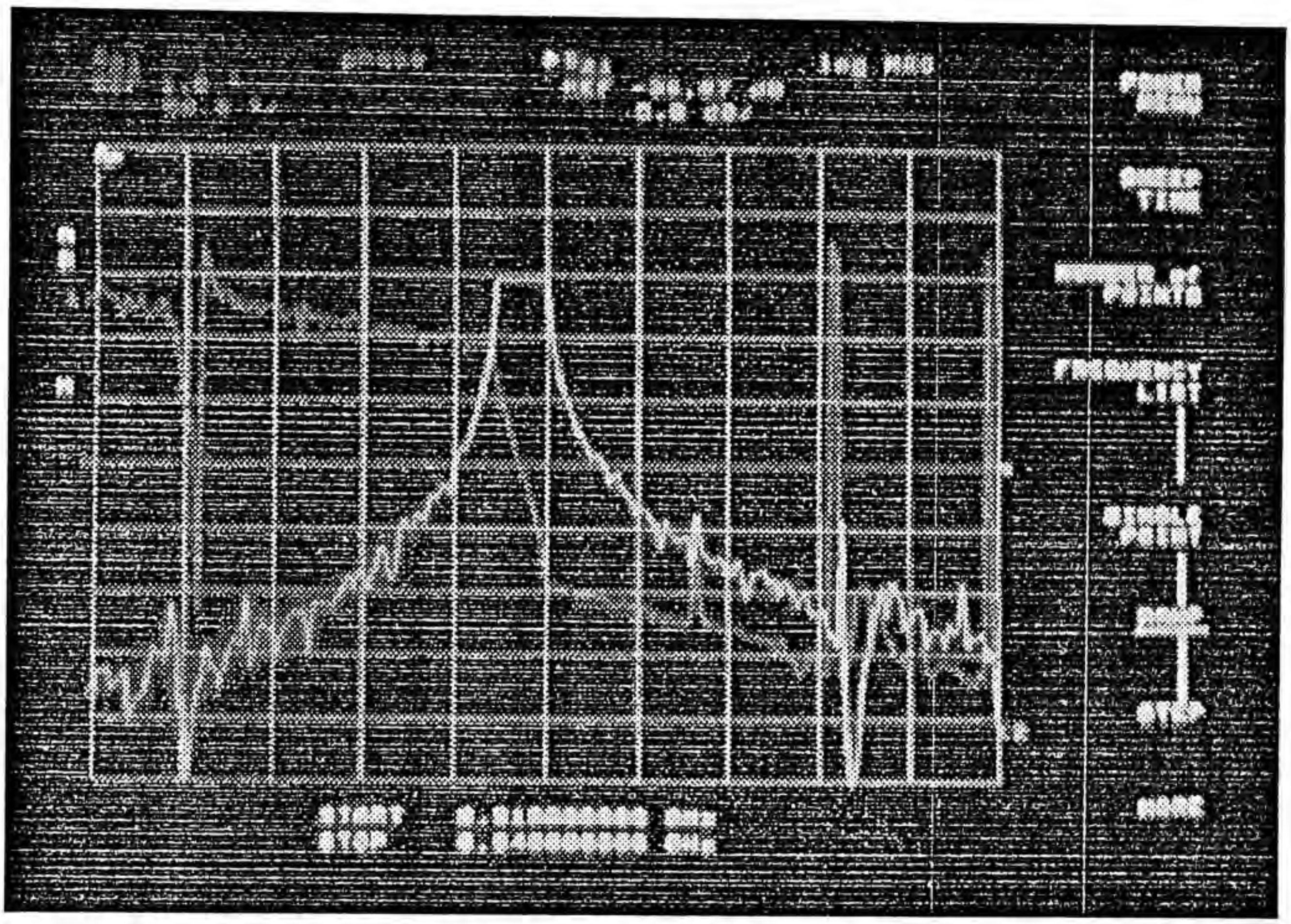


Fig. 5-9 Transfer characteristics of the oscillator measured using a network analyzer.

5.3 NON-INTEGRAL SUBHARMONIC LOCKING[35]-[36]

Non-integral subharmonic injection locking means the injection signal is a non-integral submultiple, say for example, 3/4, 2/3, 2/5 etc. of the output signal.

5.3.1 Nonlinear feedback model

Zhang *et al.*'s feedback model can be used to explain the non-integral subharmonic signal injection locking behavior. The model consists of a nonlinear network f(er), and a linear feedback network H(D). The output of the oscillator, u, feeds back to the input via H(D).

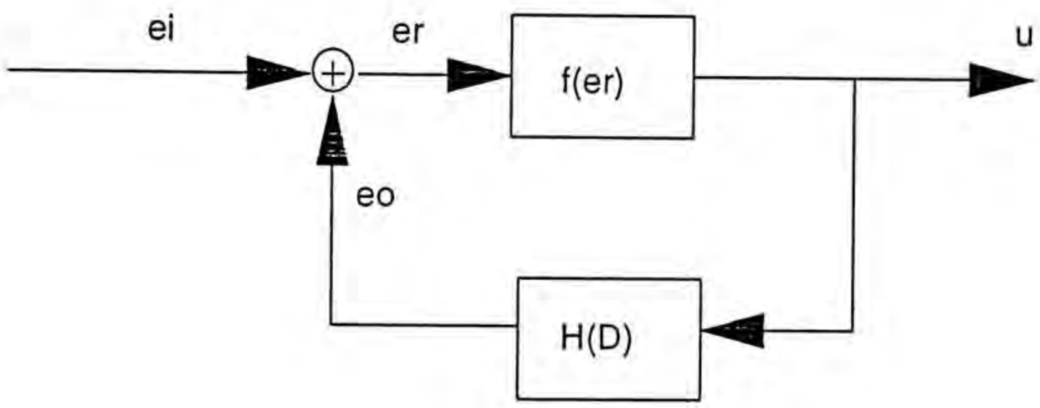


Fig. 5-10 Nonlinear feedback model for non-integral subharmonic injection

When a non-integral subharmonic signal is injected into the nonlinear network, it beats out an integral subharmonic signal which is then fed back to the input of the nonlinear network. The signal then acts as a normal integral subharmonic injection. The locking range for 2/3 non-integral subharmonic injection is derived. For simplicity, the nonlinear network is described mathematically as follows :

$$u = f(e_r) = \alpha_1 e_r + \alpha_2 e_r^2 + \alpha_3 e_r^3 \qquad (5.1)$$

$$e_r = e_i + e_o \tag{5.2}$$

where $$e_o = \frac{E}{2}(e^{jwt} + e^{-jwt}) \; ; \; e_i = \frac{E_i}{2} e^{j\frac{2}{3}wt} \tag{5.3}$$

When equation (5.3) is substituted into (5.2) then (5.1), the ω/3 integral frequency is generated as follows.

$$\left[\frac{\alpha_2}{2} E \cdot E_i + \frac{\alpha_3}{3} \cdot \left(\frac{E}{2}\right) \cdot \left(\frac{E_i}{2}\right)^3\right] \cdot e^{\frac{j\omega t}{3}} \tag{5.4}$$

This integral signal feeds back and injects to the nonlinear network as a normal integral subharmonic injection. From the Zhang *et al.* model, the locking range of the 2/3 non-integral subharmonic injection is given as :

$$\Delta\omega_{2/3} = \frac{\omega_o}{2Q} \frac{U_{2/3}}{U_{out}} \tag{5.5}$$

where $$U_{2/3} = \alpha_3 \cdot a^3 \cdot \left[\frac{\alpha_2}{2} \cdot E \cdot E_i + \frac{\alpha_3}{3} \cdot \frac{E}{2} \cdot \left(\frac{E_i}{2}\right)^2\right]^3 \tag{5.6}$$

where a is the attenuation due to the feedback network, and is the output oscillation magnitude.

5.3.2 Circuit description

Two BJT injection-locked oscillators were implemented for measurement. One oscillator was implemented using MRF941 BJT operating at 880MHz with -6dBm power output and the other using MMBTH10 BJT operating at 200MHz with 7dBm power output. The circuit diagrams are shown in Fig. 5-11 to Fig 5-14 respectively. The circuits were implemented using lump elements.

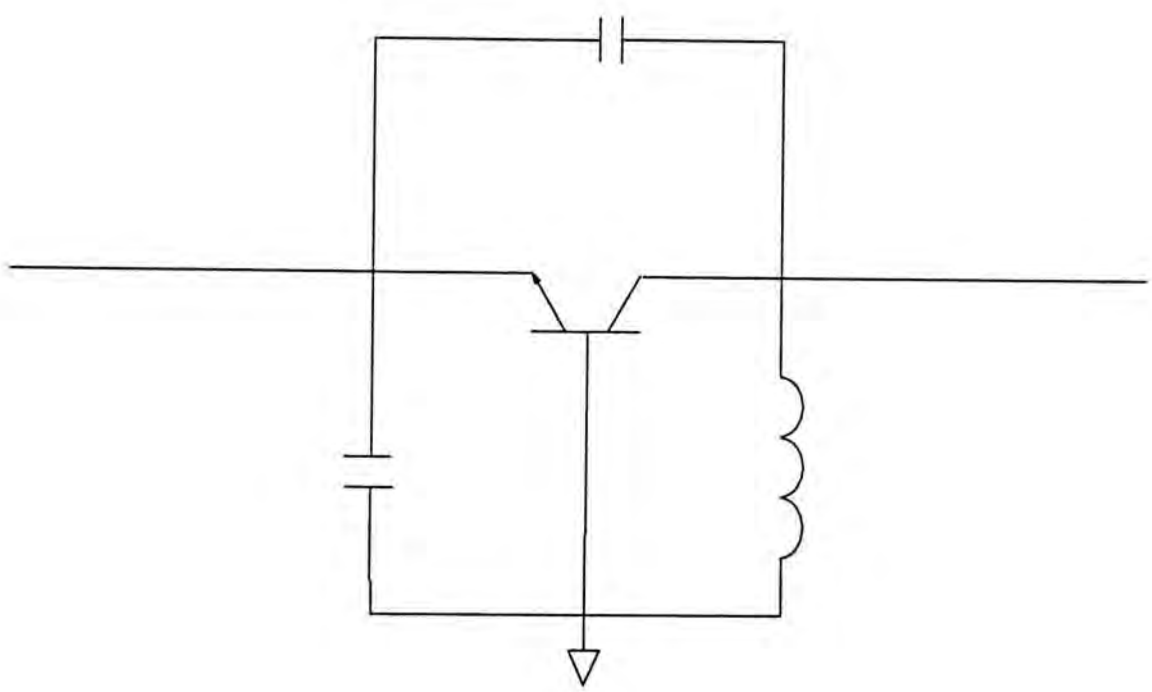


Fig. 5-11 AC diagram of the 880MHz oscillator

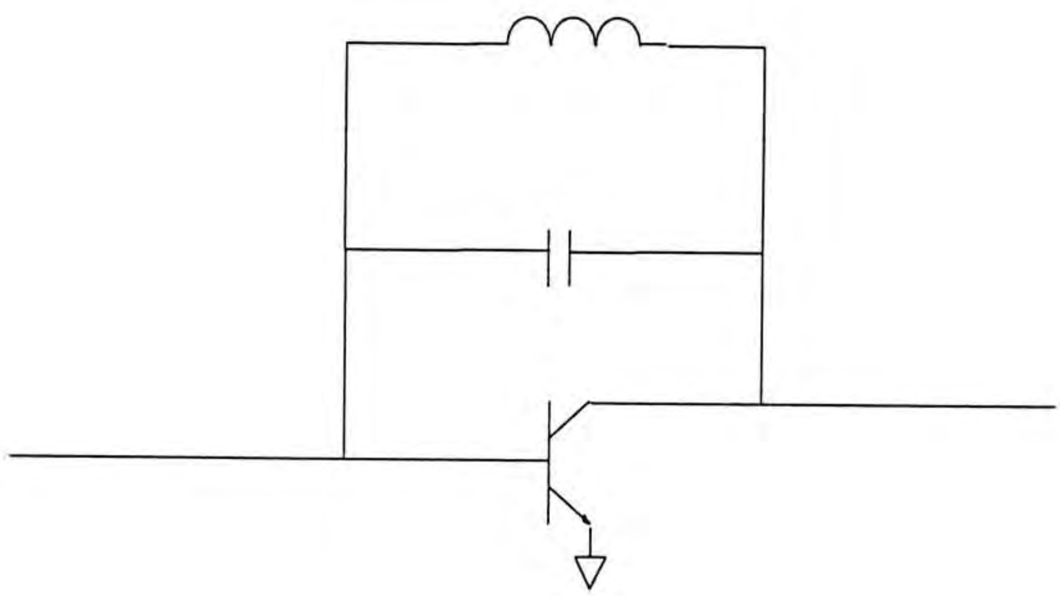


Fig. 5-12 AC diagram of the 200MHz oscillator

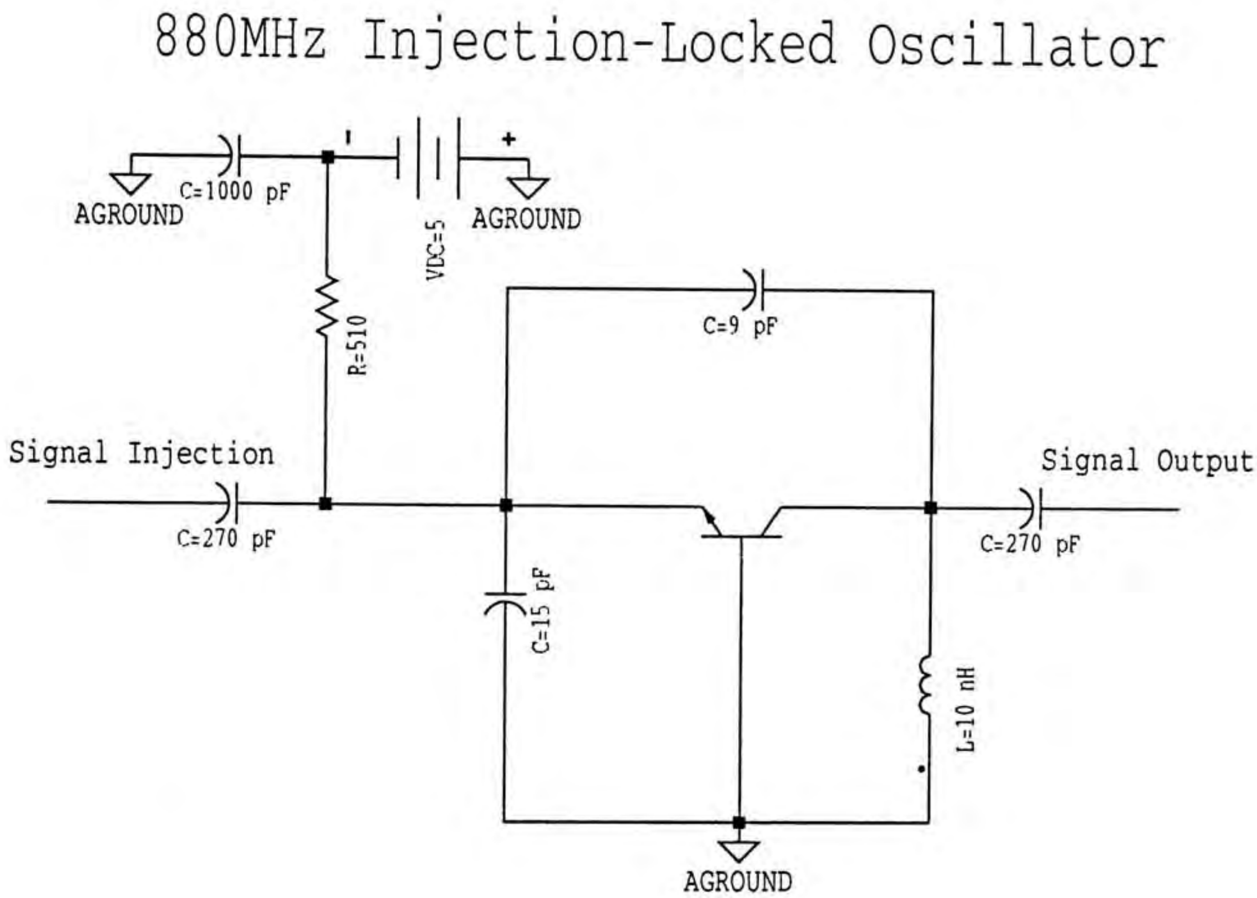


Fig. 5-13 Full circuit diagram of the 880MHz Oscillator

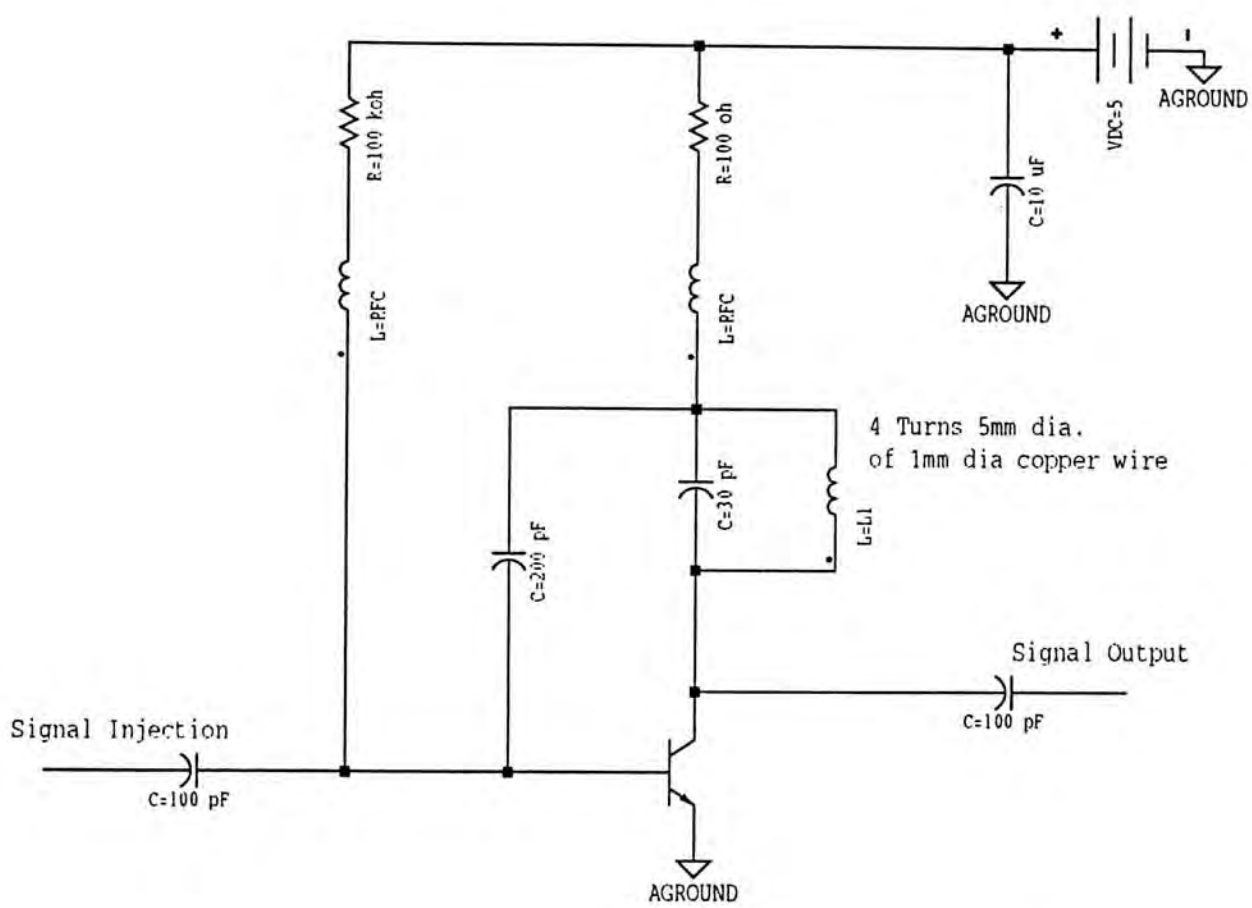


Fig. 5-14 Full circuit diagram of the 200MHz oscillator

5.3.3 Experimental results

The oscillators were measured using a spectrum analyzer and a signal source. The experimental setup is shown in Fig. 5-15. In each measurement, the injection power was fixed and the injection frequency was varied. An asymmetric sideband was observed just above locking and just below locking as in [23]-[24]. This indicates the oscillator is in the driven but unlocked state[33]-[34]. The oscillators were regarded as locked when the asymmetric sideband suddenly disappeared and gave a single frequency component.

The measurements show that the 880MHz oscillator can lock to its 1/2, 1/3, 1/4, 1/5, 2/3, 3/4 and 2/5 subharmonics. The 200 MHz oscillator can lock to its 3/4, 2/3, 2/5, 2/7, 2/15, and 2/19 non-integral subharmonics in addition to the even and odd subharmonics. The fundamental locking range is 3MHz under -40dBm power injection for the 880MHz oscillator, and is 4MHz under 0dBm power injection for the 200MHz oscillator. Fig. 5-16 and Fig. 5-17(a)-(c) show the measured locking ranges under different locking gains for different subharmonics.

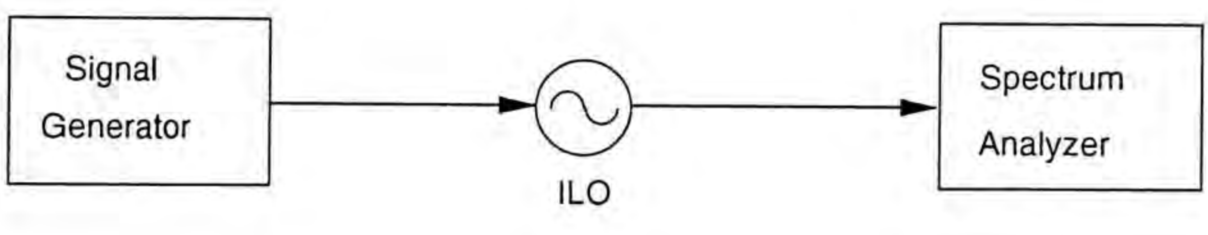


Fig. 5-15 Experimental setup for non-integral subharmonics locking range measurement

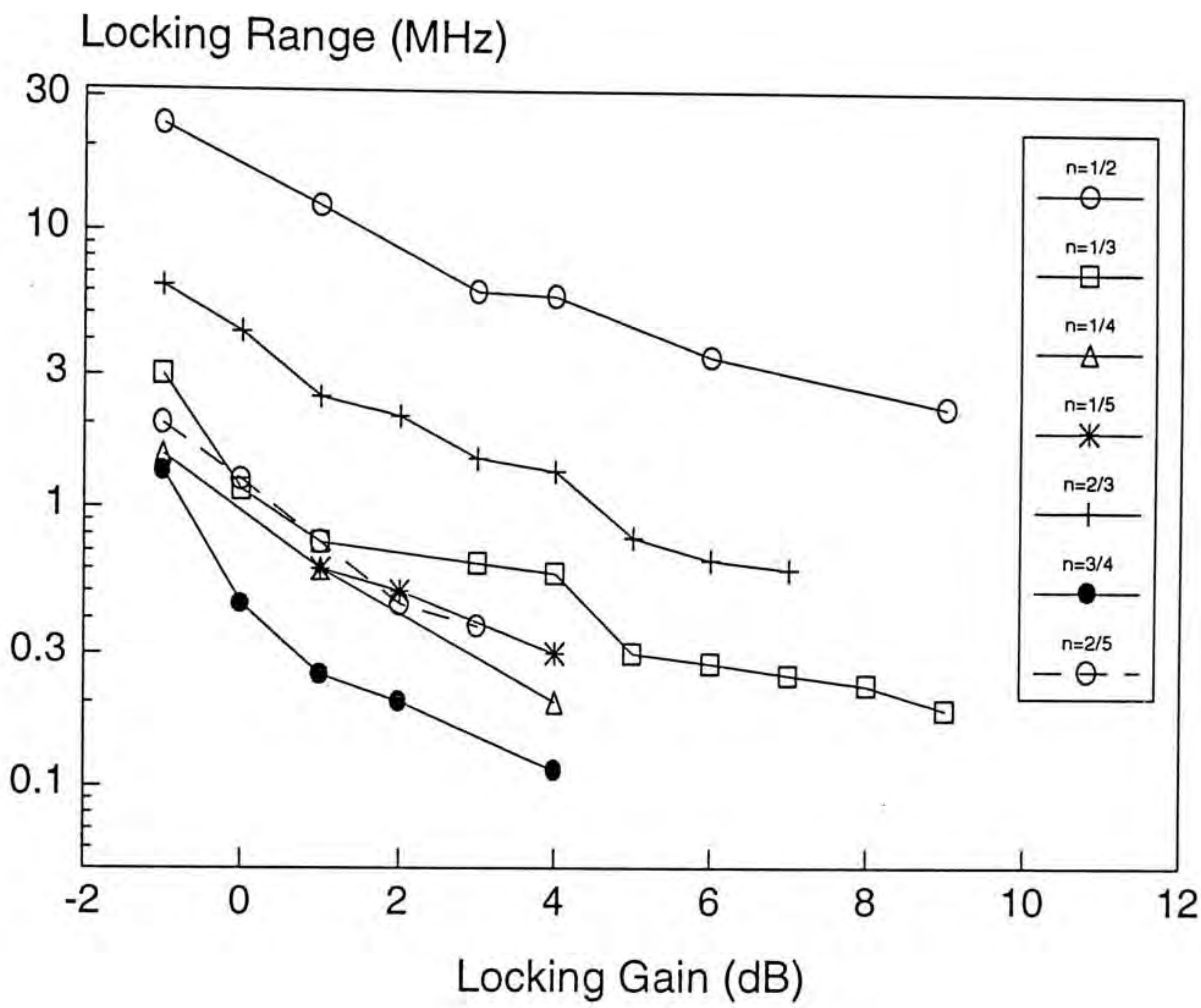


Fig. 5-16 Subharmonic locking ranges for the 880MHz oscillator at -6 dBm output

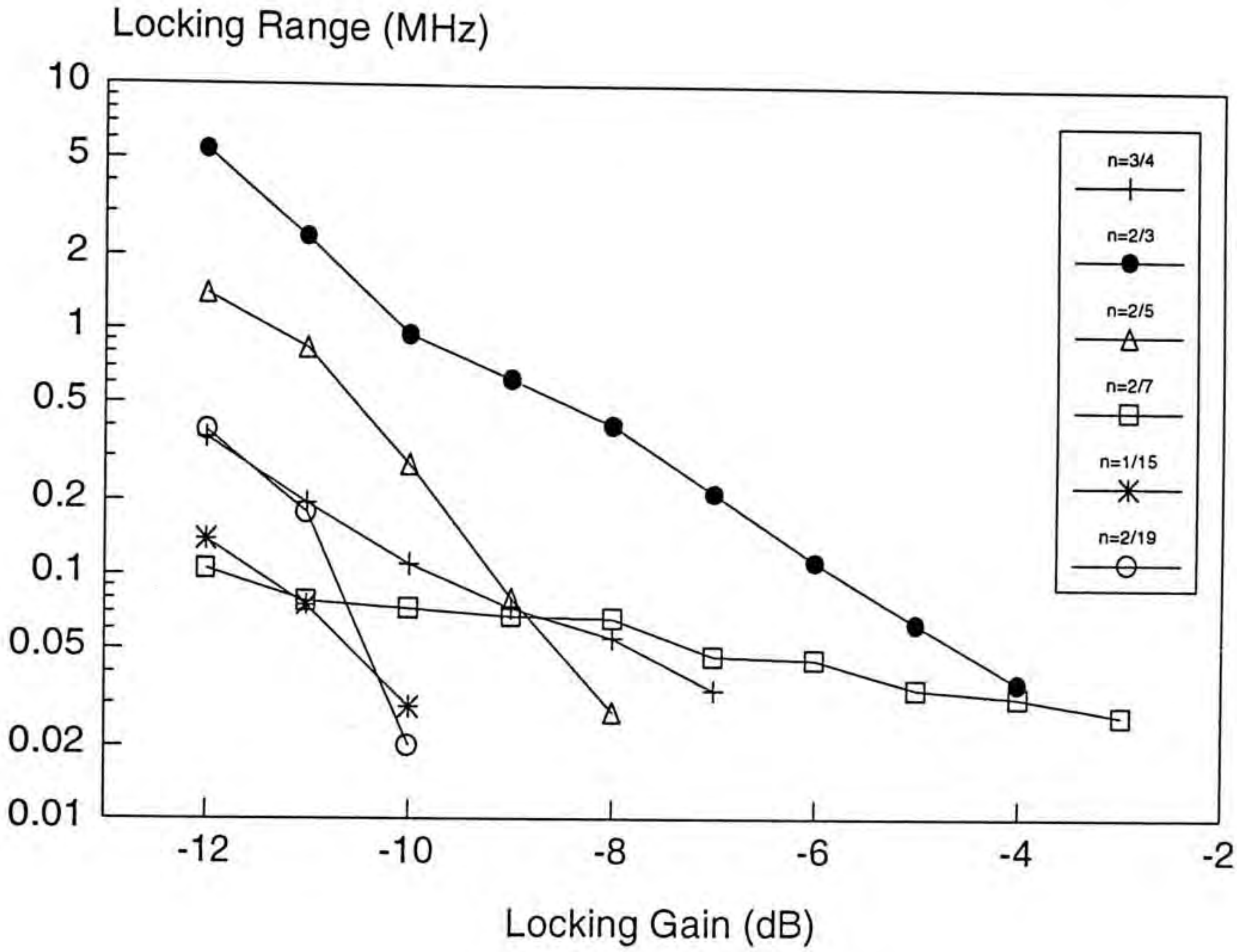


Fig. 5-17 (a) Non-integral subharmonic locking ranges for the 200MHZ oscillator, 7dBm output power

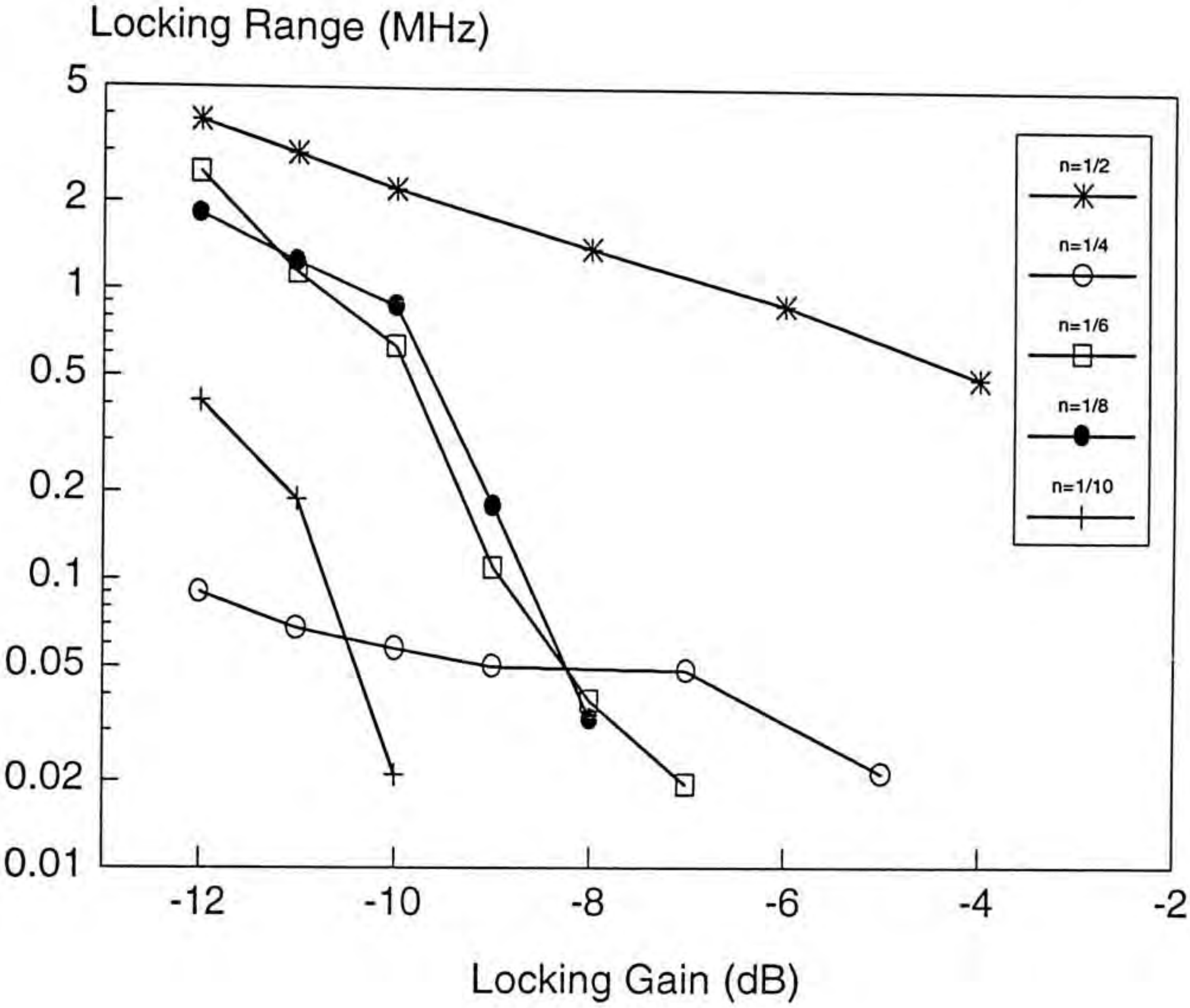


Fig. 5-17 (b) Even integral subharmonic locking ranges for the 200MHz oscillator, 7dBm output power

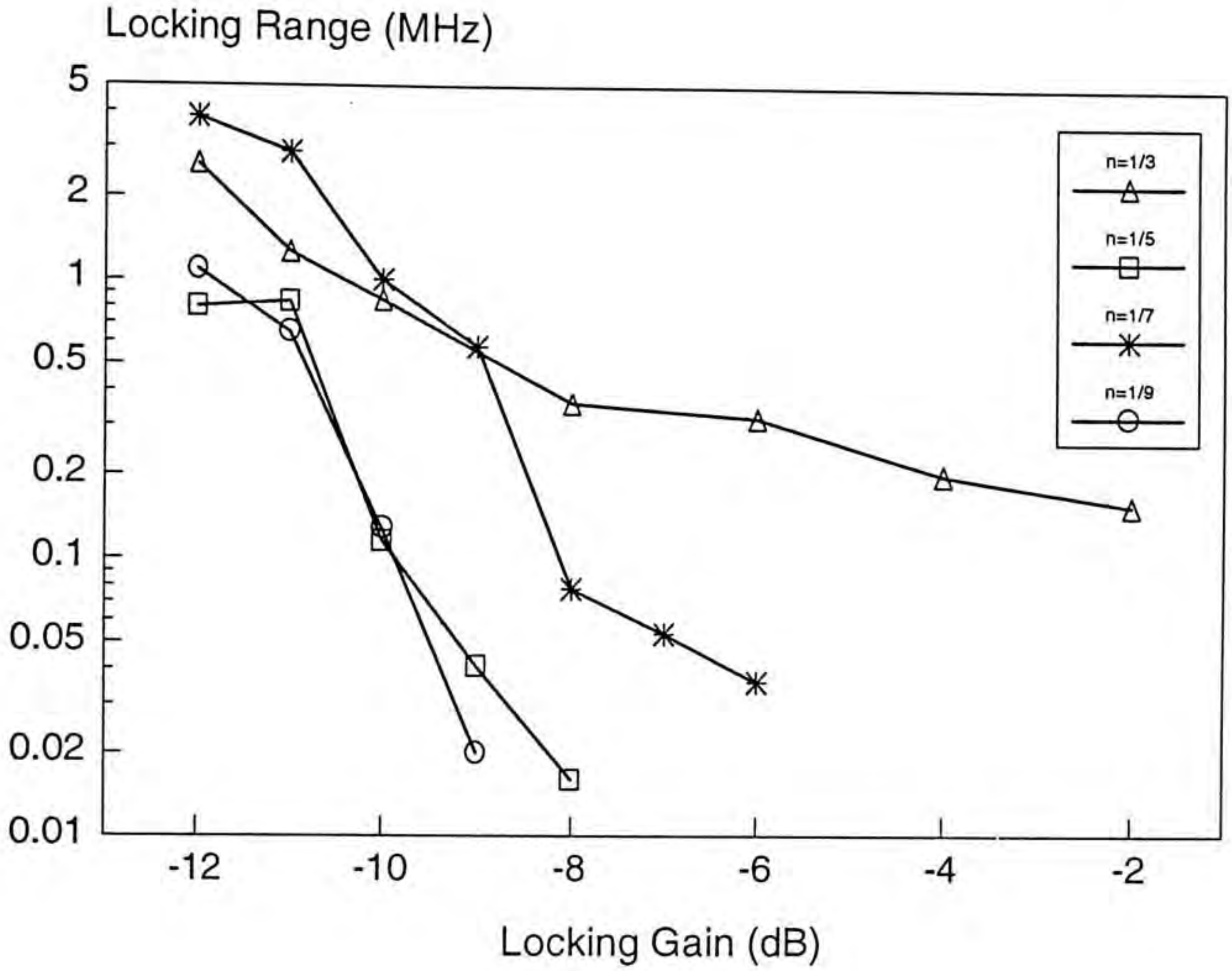


Fig. 5-17(c) Odd integral subharmonic locking ranges for the 200MHz oscillator, 7dBm output power

5.3.4 Summary

It is found that in addition to integral subharmonic locking, both BJT oscillators can also lock to its non-integral subharmonic signal. The non-integral subharmonic injection locking behavior is experimentally demonstrated, and explained using a feedback model.

The results show that the locking range is not directly proportional to the locking gain. This is due to the nonlinear characteristics in the oscillator. On the other hand, it can be found that the locking ranges for some non-integral subharmonic locking range is comparable to some integral subharmonic locking range for the same power level of injection. Therefore, in addition to using integral subharmonic signal for high frequency oscillator stabilization, non-integral subharmonic signal can also be used. It thus increases the design flexibility when a low frequency source is needed to stabilize a high frequency oscillator using injection locking technique.

On the other hand, non-integral subharmonic injection locked oscillator can act as a non-integral frequency multiplier. Traditionally, to build a non-integral frequency multiplier, one needs an integral frequency multiplier and an integral frequency divider. If non-integral subharmonic injection locking is used, the circuit can be highly simplified.

5.4 SELECTIVE SUBHARMONIC LOCKING RANGE ENHANCEMENT[37]-[38]

Subharmonic injection locking has a smaller locking range in comparison with fundamental injection for the same power level of injection. This section presents a simple but practical method to enhance the subharmonic locking range for a desired subharmonic frequency.

5.4.1 Multi-feedback nonlinear model

Based on the feedback model proposed by Zhang *et al.*[30], it is found that the subharmonic locking range depends on the fundamental signal generated from the nonlinear network, which is dependent on the subharmonic signal strength input to the nonlinear network. Thus, in order to increase the subharmonic signal strength, an additional feedback path resonating at the desired subharmonic frequency is introduced to the oscillator. The multi-feedback nonlinear model is shown in Fig. 5-18. When the subharmonic signal is injected to the oscillator, it is amplified by the nonlinear network and fed back to the input of the nonlinear network through the additional feedback path.

5.4.2 Circuit description

An injection-locked oscillator operating at 950MHz is implemented using a motorola MRF941 BJT transistor biased at Vee of -5V and Iee of 10mA. The oscillator schematic diagram is shown in Fig. 5-19 and Fig. 5-20. It is a colpitts oscillator with an additional series R-L-C tank circuit as the additional feedback path. The tank circuit resonates at 1/3 of the free-running oscillator frequency. The 1/3 subharmonic locking range of the oscillator is examined when the feedback resistance in the R-L-C tank circuit is left open. The process is repeated for R=20 ohm, 10 ohm, and 0 ohm.

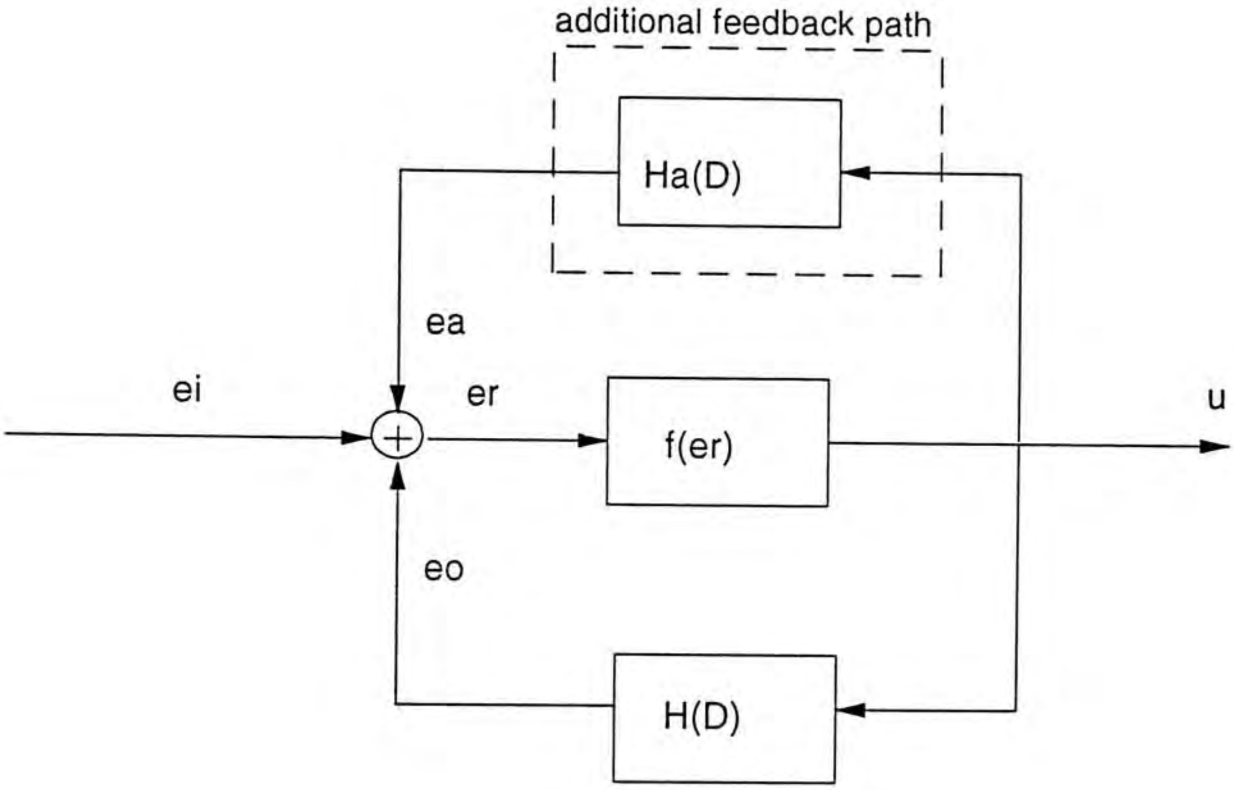


Fig. 5-18 Multi-feedback model for subharmonic injection locking

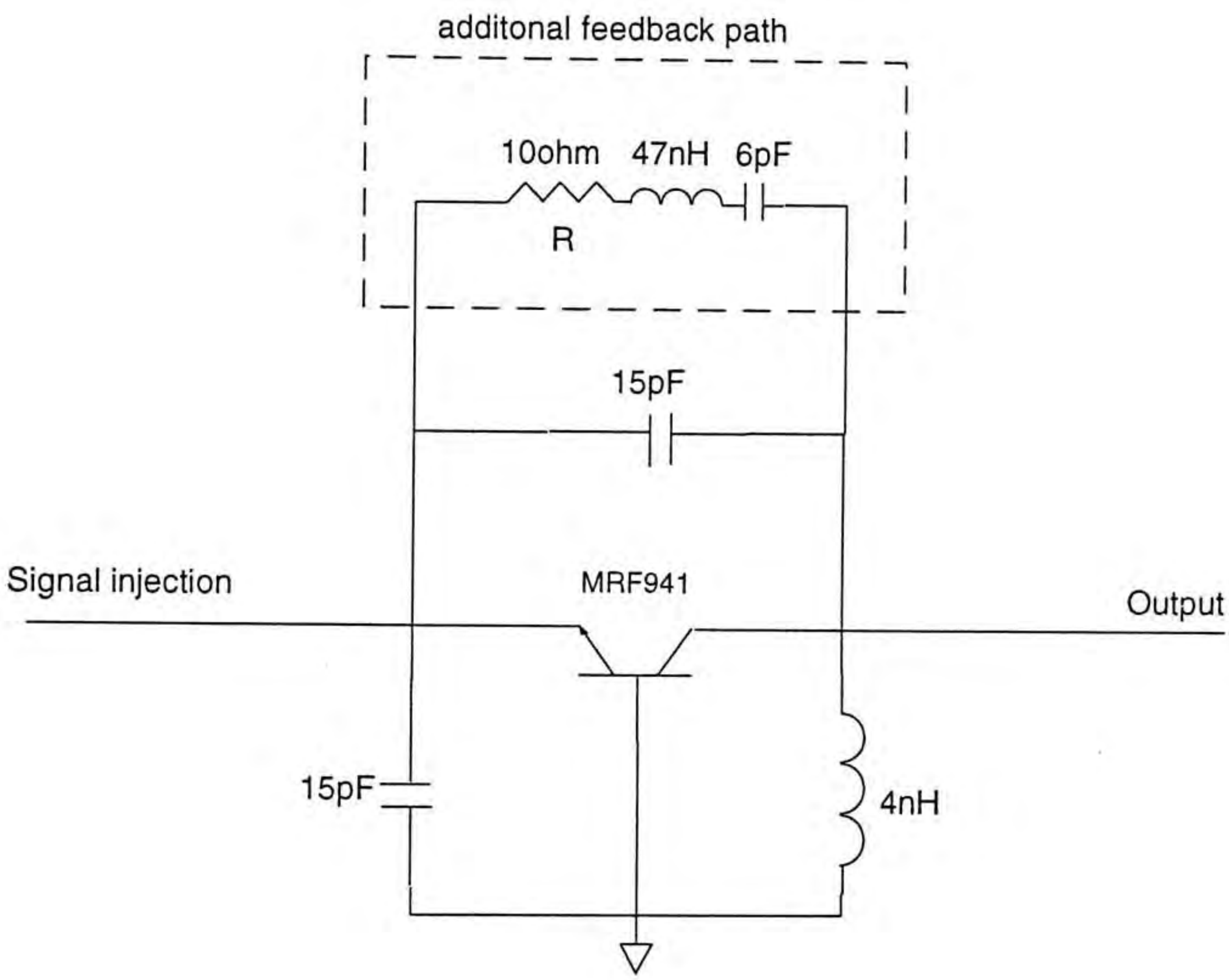


Fig. 5-19 AC Circuit diagram of the oscillator

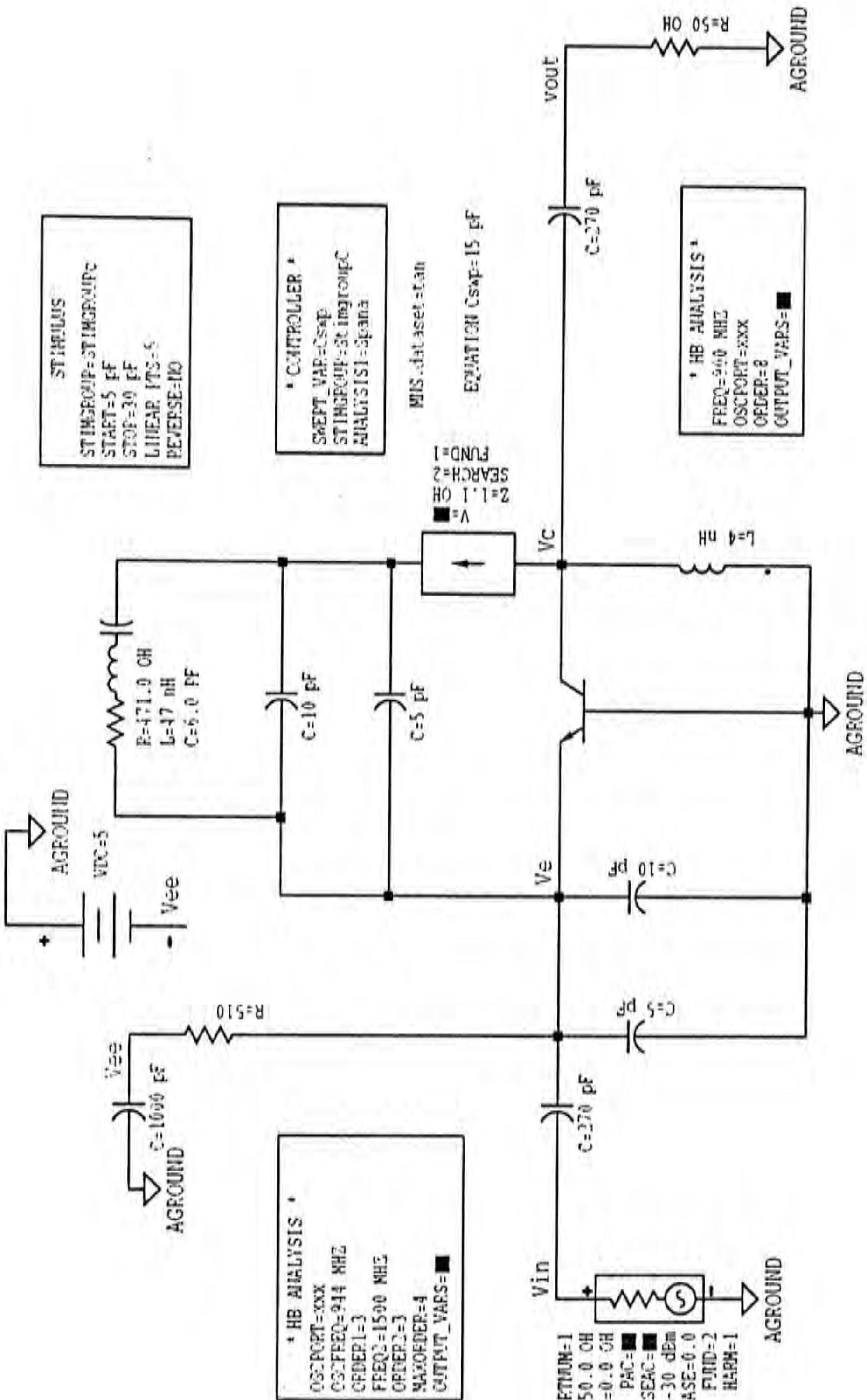


Fig. 5-20 Full circuit diagram of the 2 feedback injection locked oscillator

5.4.3 Experimental results :

The injection-locked oscillator was built. The output power and frequency were examined using an HP 8592A spectrum analyzer and a signal generator as shown in Fig. 5-21. Results showed that the oscillator oscillates at 950MHz with +2.2dBm power output. The fundamental locking range is 120MHz under -15dBm power injection when the addition feedback path is open. The 1/3 subharmonic locking range are measured under different power levels of injection. The resistor in the feedback path is changed to 0 ohm, 10 ohm, 20 ohm and open respectively. The corresponding 1/3 subharmonic locking ranges were measured. The results are shown in Fig. 5-22.

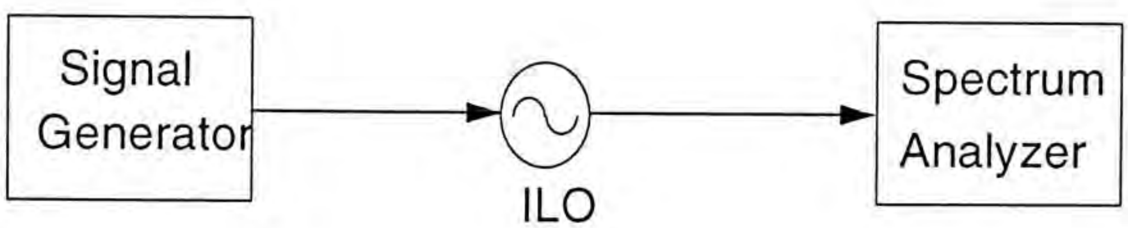


Fig. 5-21 Experimental setup for subharmonics locking range enhancement

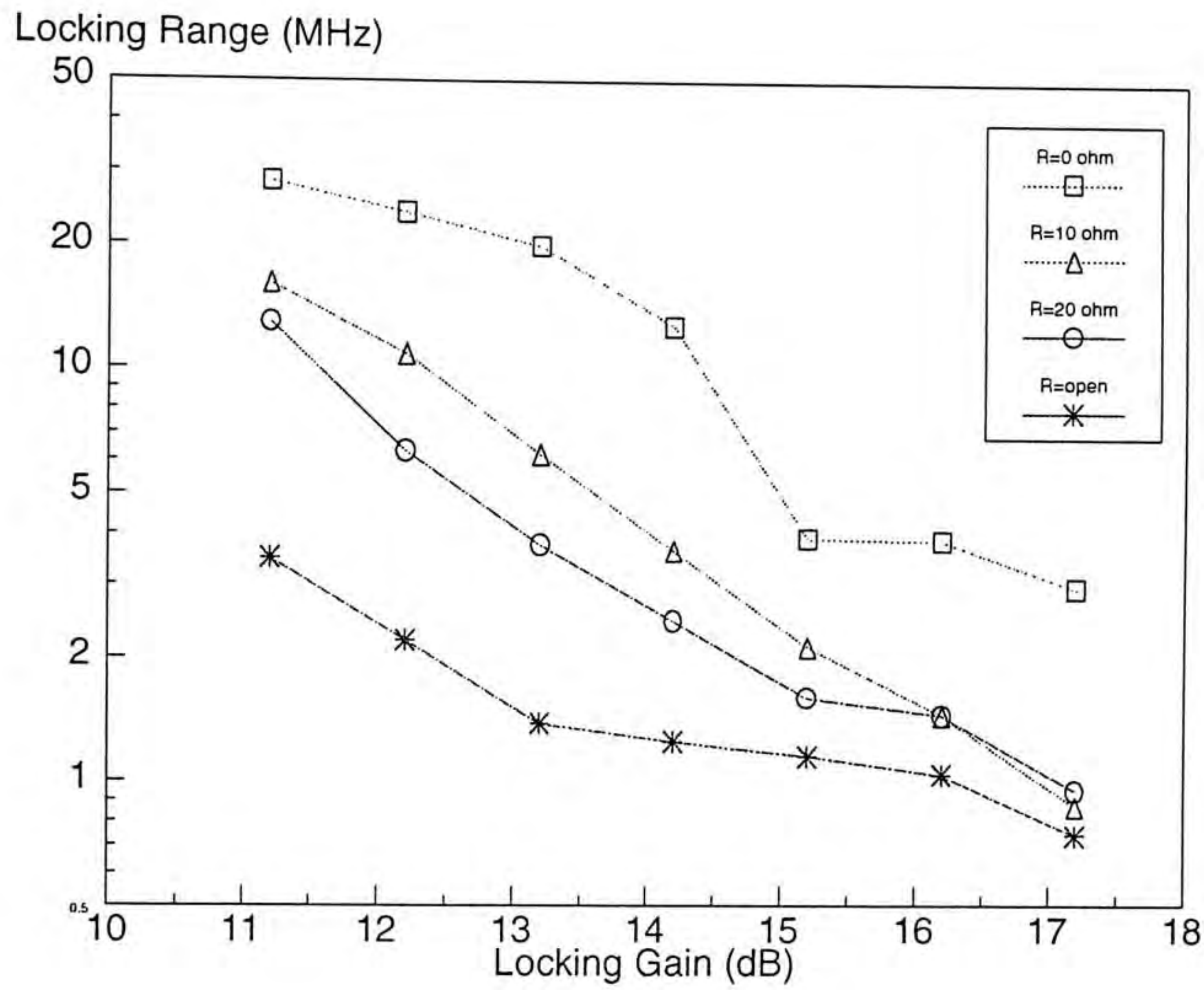


Fig. 5-22 1/3 Subharmonic locking ranges at different feedback resistances

5.4.4 Summary

From the 1/3 subharmonic locking characteristics, it is found that the locking range increases as the feedback resistance decreases, and is improved up to 8 times at about 11dB locking gain as the feedback resistor is varied from R=open (no feedback) to R=0 ohm. Therefore, when subharmonic injection locking is used for high frequency oscillator stabilization, the subharmonic locking range can be enhanced or controlled by this method.

5.5 FEEDBACK TYPE INJECTION LOCKED OSCILLATOR[39]

Tajima and Mishima[31] pointed out that there are two types of injection locked oscillator. They are the reflection type and the transmission type injection-locked oscillator, depending on the point of signal injection. They found that transmission type injection locked oscillator gives a larger locking range compared to that of reflection type.

Recently, Birkeland and Itoh[40]-[41] proposed a 2-port injection locked oscillator consisting of a single FET amplifier with a microstrip coupler providing feedback. The injection signal and the load are connected to the microstrip coupler. This type of oscillator exhibits an increase in locking bandwidth over alternative approaches. From these, it is believed that the point of injection for an injection locked oscillator is important for its locking range. In this part, a comparative study on the locking range with two different points of injection in a BJT oscillator is presented. In addition to fundamental locking range, 1/2th subharmonic locking was also measured and compared.

5.5.1 Feedback type injection locked oscillator model with different injection points

A block diagram of a typical feedback oscillator is shown in Fig. 5-23. It consists of a transistor acting as an amplifier and a feedback network. Injection signal is either injected from point 1 or from point 2. For point 1 injection, injection signal is injected to the feedback network. For point 2 injection, injection signal is directly injected to the transistor. It is the transmission type injection locking[31], a most commonly used configuration. For reflection type injection locking, signal is injected at the output port via a circulator. This type of injection locking will not be discussed here.

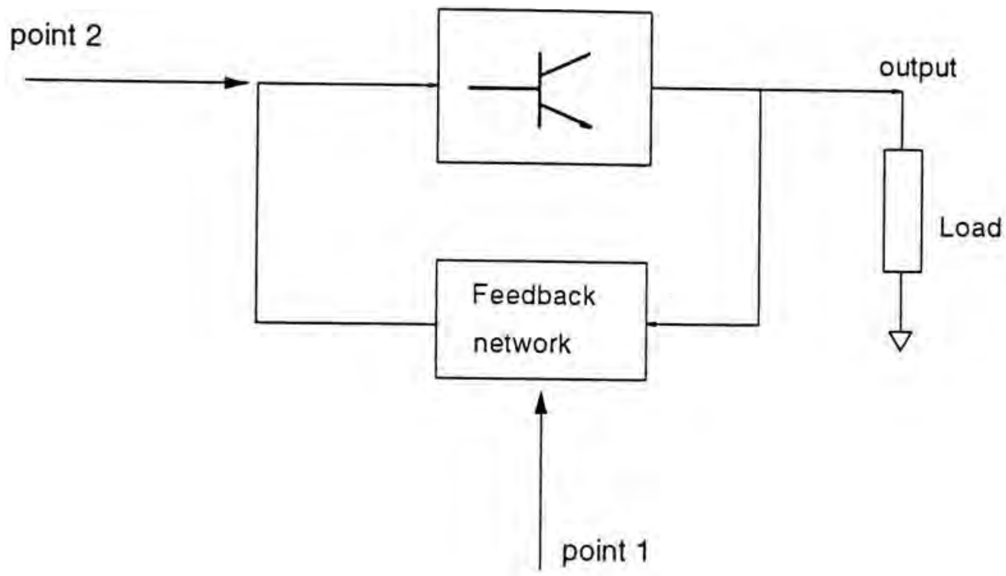


Fig. 5-23 Feedback type injection locked oscillator model with 2 different injection points

5.5.2 Circuit description

A BJT oscillator was implemented for the comparative study. The oscillator was designed and analyzed by a commercial software HP MDS (Microwave Design System) before implementation. The circuit diagram of the oscillator is shown in Fig. 5-24 and 5-25. A MRF941 BJT in common base configuration is used for the amplifier. The feedback circuit is constructed with L and C elements. The load is connected to the output of the oscillator. Injection signal is injected at point 1 or point 2.

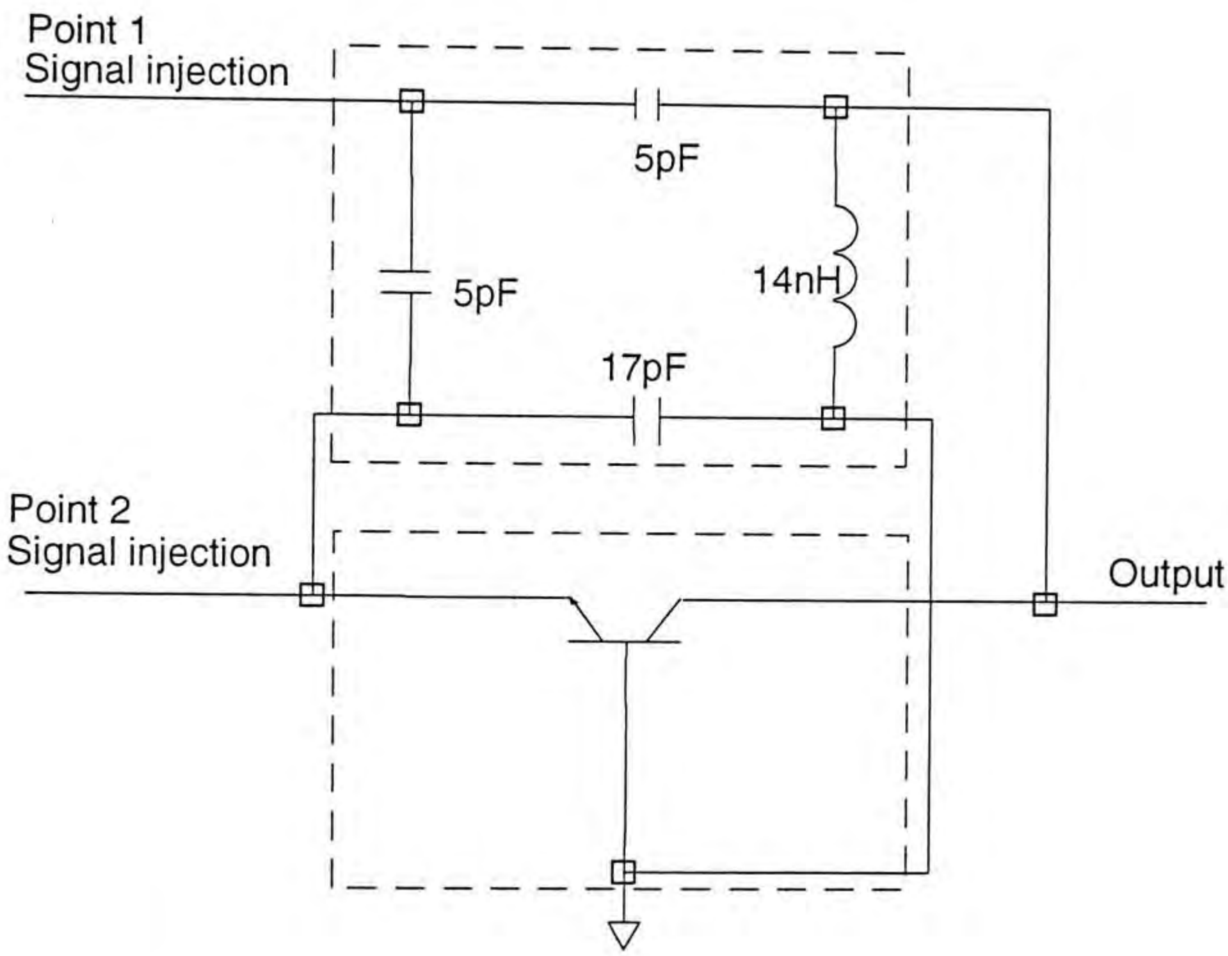


Fig. 5-24 AC circuit of the feedback type oscillator with 2 different points of injection.

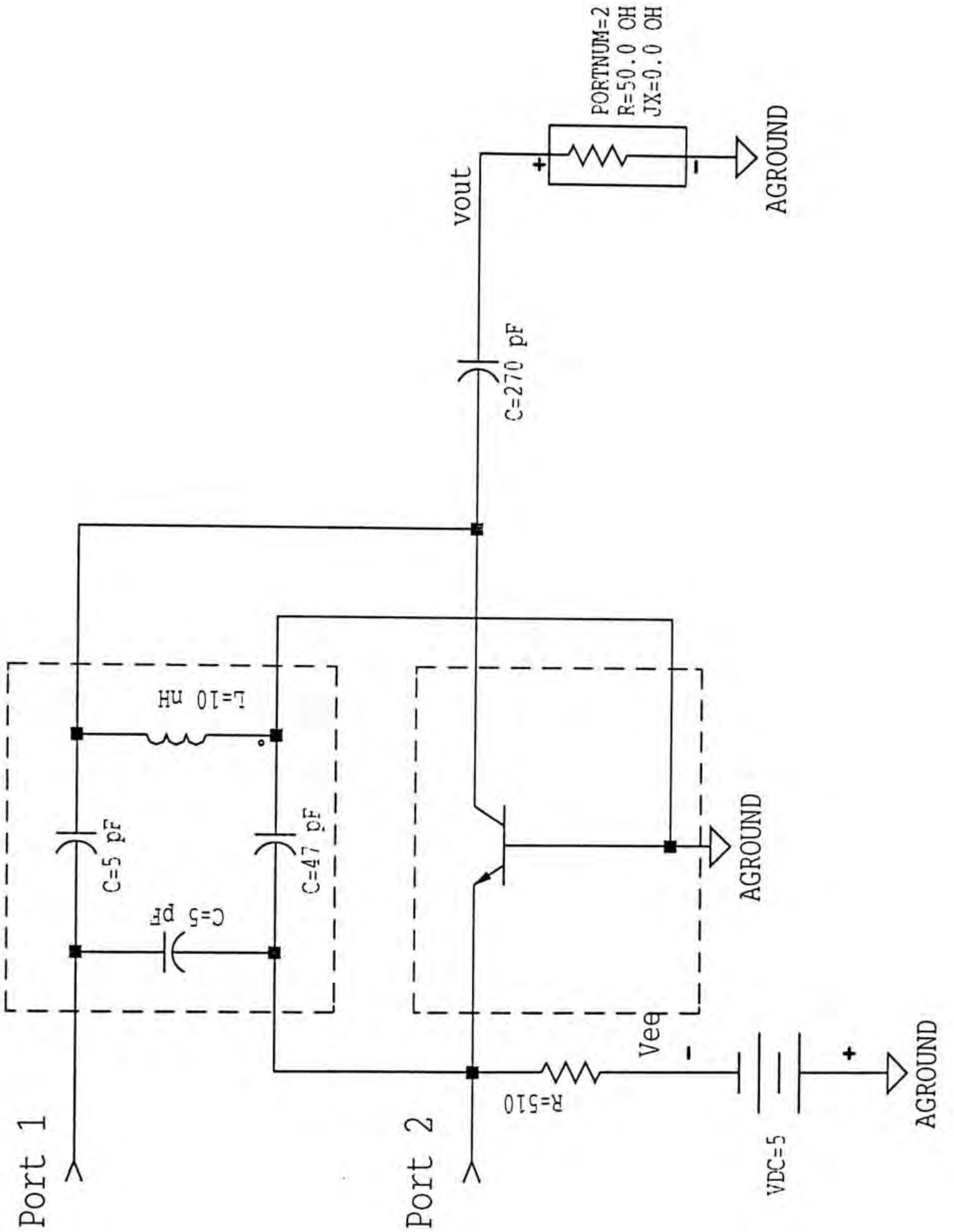


Fig. 5-25 Full circuit diagram the feedback type oscillator with 2 different points of injection.

5.5.3 Experimental results

The oscillator was measured using a spectrum analyzer and a signal source. The free-running frequency is 0.95GHz and the output power is +1.2dBm. For injection locking, injection signal was injected from point 1 and point 2 respectively. When one point was connected to the injection signal, the other point was terminated by a 50ohm load. The fundamental locking ranges at different locking gains for point 1 and point 2 injections are shown in Fig. 5-26. For 1/2 subharmonic injection, the results are shown in Fig. 5-27.

5.5.4 Summary

The locking ranges in fundamental and 1/2 subharmonic locking are compared for two different points of injection. Injection signal is injected either directly at the transistor or at the feedback network. Experimental results show that both fundamental and 1/2 subharmonic locking ranges are significantly increased for signal injected at the feedback network.

From the results, it is found that the locking ranges for point 1 injection (injected to the feedback) are much higher than in point 2 injection both in fundamental locking and 1/2 subharmonic locking. The locking ranges for fundamental injection increased by about 4 to 15 times. The locking ranges for 1/2 subharmonic injection increased by about 4 to 10 times.

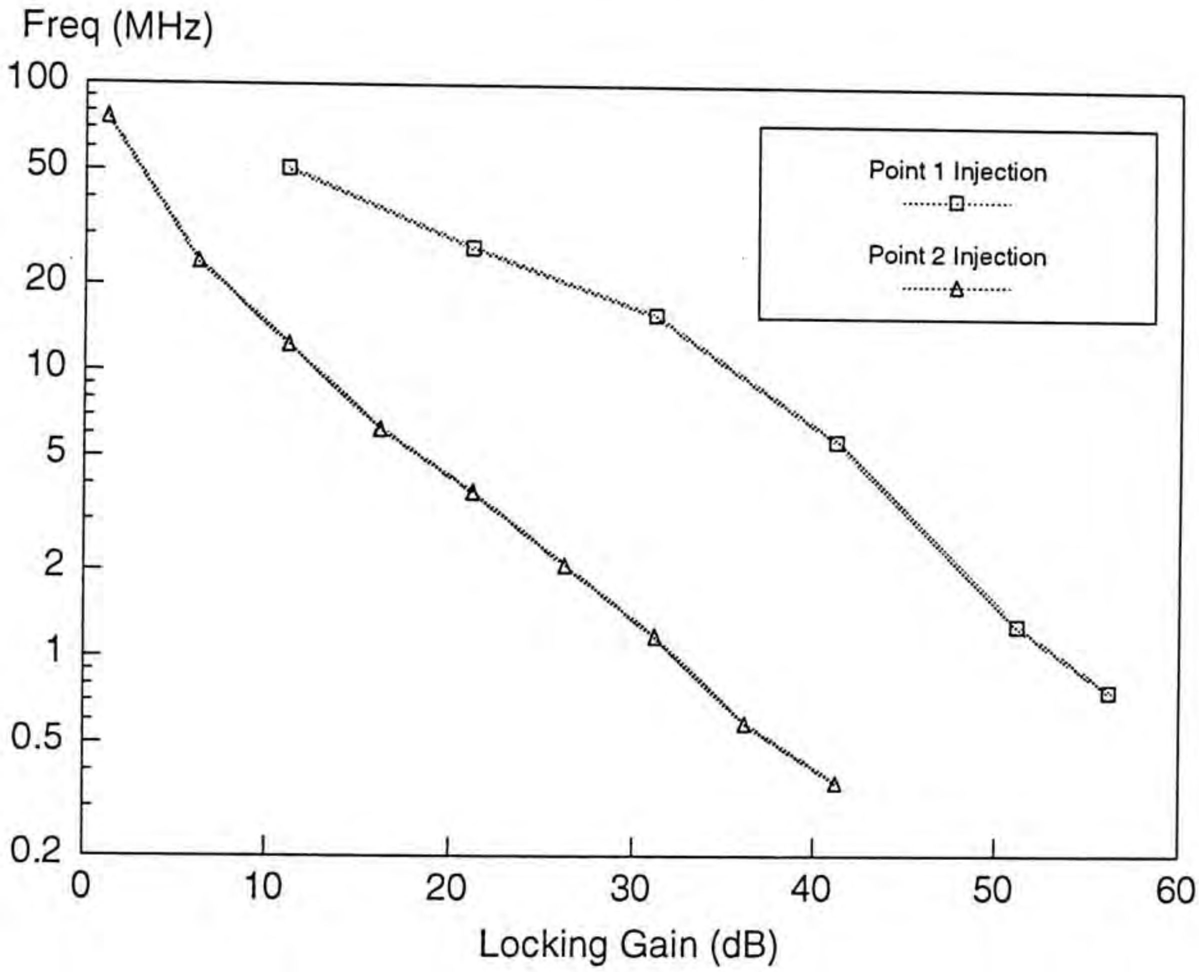


Fig. 5-26 Comparison of fundamental locking range for the 2 different points of injection.

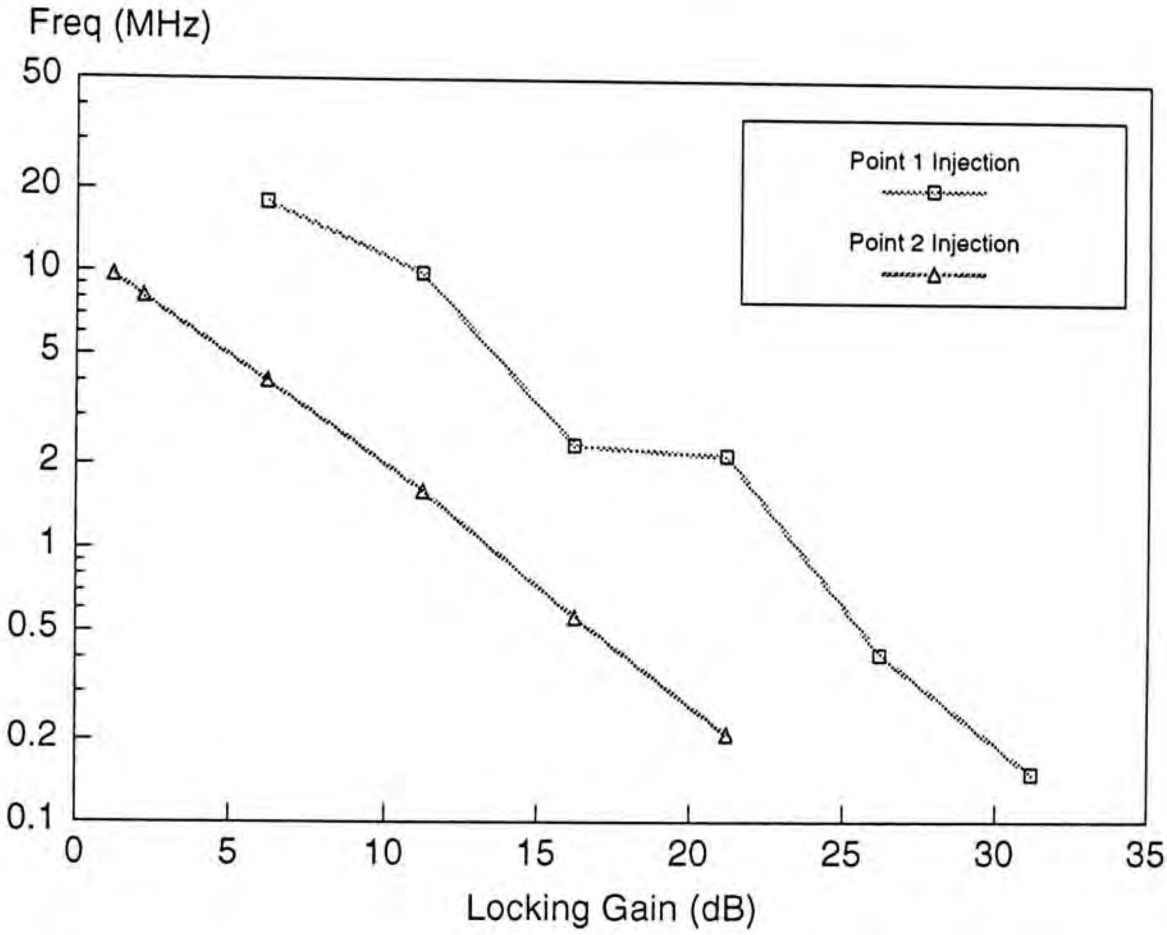


Fig. 5-27 Comparison of 1/2 subharmonic locking range for the 2 different points of injection

5.6 PHASE TUNING BEYOND 180 DEGREES BY INJECTION LOCKING[42]-[44]

Kurokawa[8] showed that injection locked oscillator can provide phase control of 180° over the locking bandwidth, and when nonlinear reactance is taken into account, the phase change can be greater than 180°, say 192°. Esman *et al.*[29], however, demonstrated a phase range of 187° for an optically injection-locked FET microwave oscillator when nonlinear device reactance is taken into account and used transfer characteristics to determine the locking range and the phase change.

Phase control beyond 180° can be achieved when two or more injection locked oscillators are cascaded together and simultaneously locked to the input frequency. It is due to the phase delay accumulation in each injection locked oscillator Theoretically, cascading two injection locked oscillators can provide 360° phase tuning range. Here, a one stage injection locked oscillator is compared with a 2 stage injection locked oscillator.

5.6.1 Phase change by single injection locked oscillator

With small signal analysis, the locking range $\Delta f_{\max}$ of an oscillator, with natural frequency f_o, relative to the injection power P_{inj} , the oscillator output power P_o, and the oscillator external Q_{ext} is given by[29]

$$\Delta f_{\max} = \frac{f_o}{Q_{ext}} \sqrt{\frac{P_{inj}}{P_o}}$$

Under the locking region, with ø being the phase angle between the oscillator signal and the injection signal, df/dt=0 and[8]-[9]

$$\phi = \arcsin\left(\frac{2\Delta f}{\Delta f_{max}}\right)$$

where Δf is the frequency difference between the injection signal frequency and the natural frequency. When the oscillator is locked, the output of the frequency is synchronized to the injection frequency. The phase can then be controlled by changing the natural frequency of the oscillator. It can be done either by varying the transistor biasing or by tuning the resonating element in the oscillator.

5.6.2 Phase change by cascaded injected locked oscillators

When two oscillators are cascaded together as shown in Fig. 5-28, the total phase difference can be increased to 360° with each oscillator providing a maximum of 180° phase delay.

This is true only when the locking ranges of the two oscillators are exactly the same. When two ILOs are cascaded together with different locking ranges, the resultant locking range will be limited by the oscillator with smaller locking range and the phase difference will be less than 360°. For two oscillators having different locking regions, the resultant locking region will be the overlapping region of the two locking regions, and the resultant phase change will be the sum of each phase delay provided within the resultant locking region. With the same methodology, more than two oscillators can be cascaded together to provide further phase tuning range. A clearer picture can be obtained by using the transfer characteristics of the ILOs to explain the phase accumulation. The case in which both ILOs have the same locking bandwidth will be discussed first. For simplicity, the transfer characteristics are drawn as a rectangle shape. It has a flat top region and a sharp cutoff at two locking boundaries. The phases are assumed to be linear within the locking ranges.

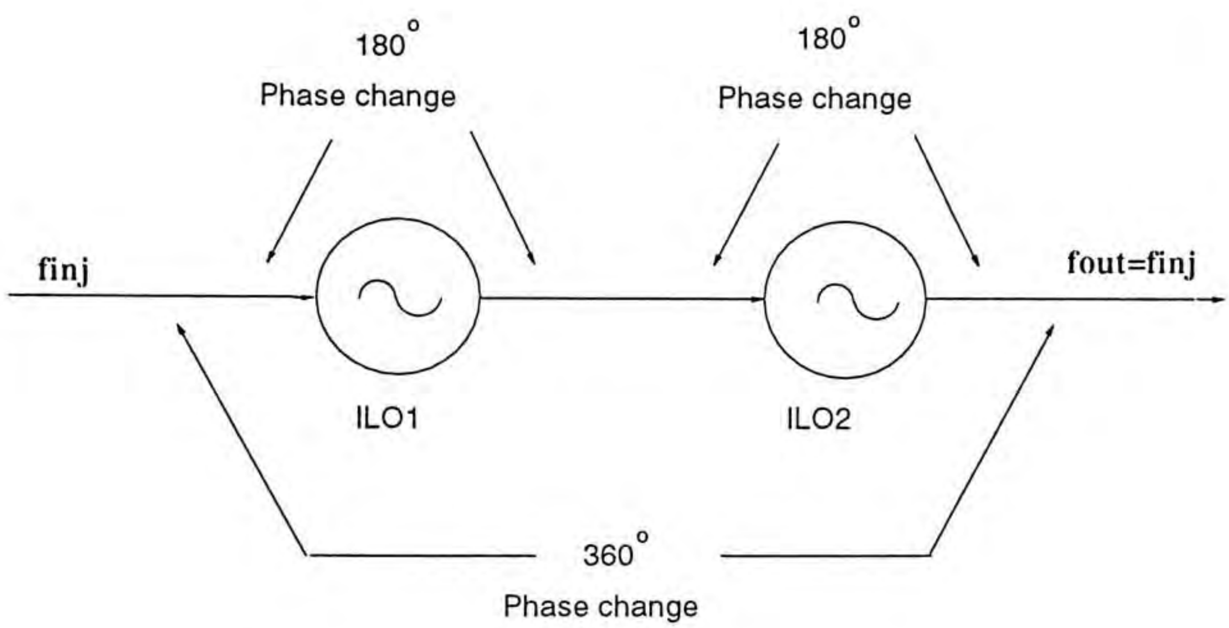


Fig. 5-28 Two ILOs cascaded together to provide 360 degrees phase shift

1) Two oscillators with the same transfer characteristics :

Fig 5-29 shows the case when the two ILOs have the same transfer characteristics, i.e., same locking bandwidth. It consists of three transfer characteristics. Fig. 5-29 (a) and Fig. 5-29 (b) are transfer characteristics of the first ILO (ILO1) and the second ILO (ILO2) respectively. Fig. 5-29 (c) is the resultant transfer characteristics. When the two oscillators have the same locking bandwidth, the resultant locking bandwidth does not change. However, due to phase shift accumulation, 180° from each stage, the total phase shift is 360° maximum.

2) Two oscillators with different transfer characteristics :

Fig. 5-30 shows the case when the two ILOs have different locking bandwidths. Suppose that the second ILO (ILO2) has a wider locking range than the first one as shown in Fig. 5-30 (a) and in Fig. 5-30 (b), the resultant locking bandwidth is the overlapping region of two locking bandwidth as shown in the Fig. 5-30 (c). However, the resultant phase is 180° + $\Delta\phi$, where $\Delta\phi$ is the phase shift due to the second ILO (ILO2) in the resultant locking bandwidth.

Similar argument can be applied for the case when the first ILO has a wider locking range than the second one. The resultant locking bandwidth is limited by the second ILO which has a smaller locking bandwidth, and the total phase shift is 180° plus the phase shift due to the second state ILO within the resultant locking bandwidth. It can also be applied for the case when the locking bandwidths of two ILOs are misaligned with each other. The resultant locking bandwidth is the overlapping region of the two ILOs, and the total phase shift is the sum of phase shifts in the resultant locking bandwidth due to the first suboscillator and the second ILO. The total phase shift may be greater or smaller than 180° depending on the overlapping extent of the two locking bandwidths.

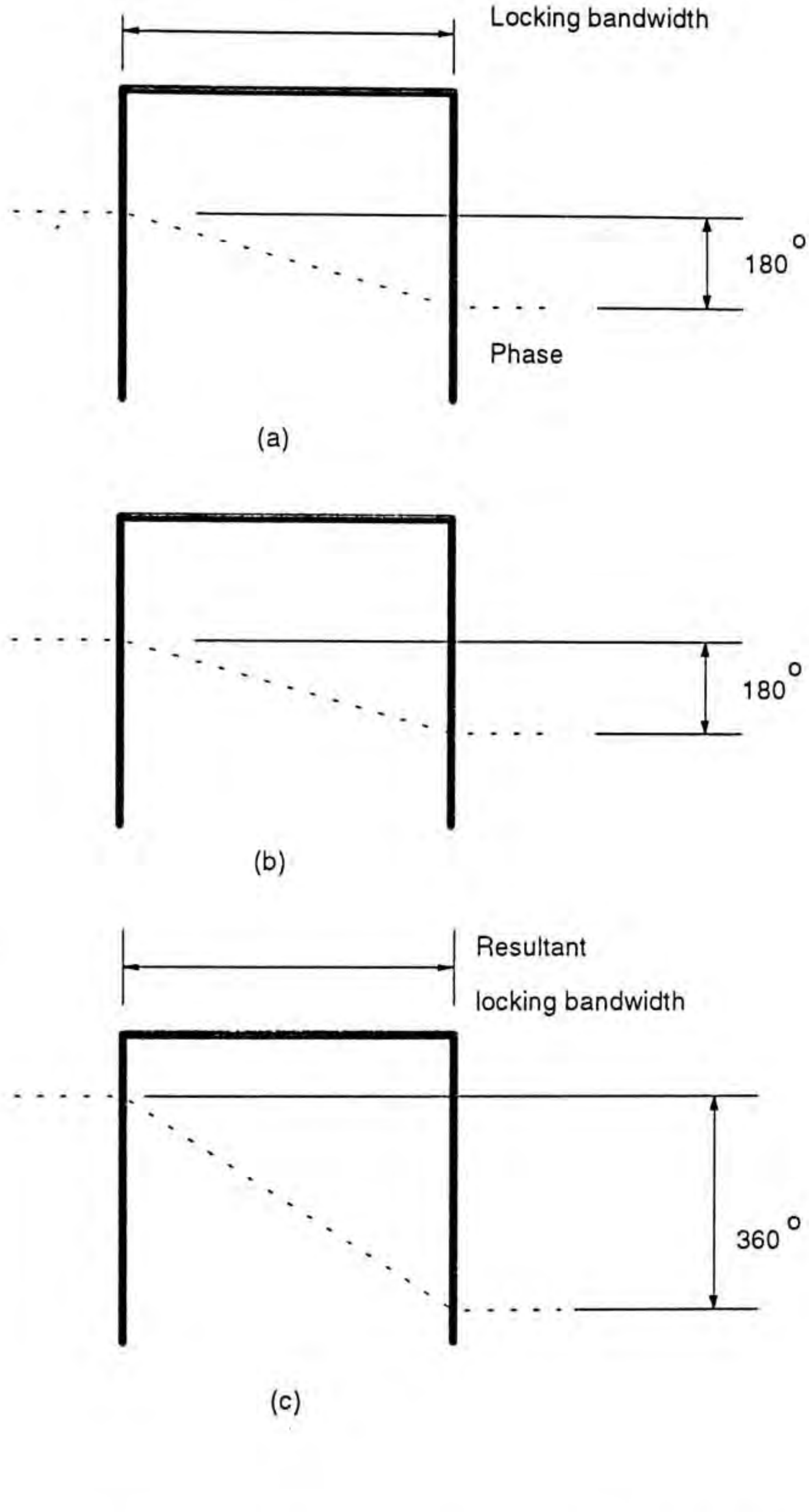


Fig. 5-29 Resultant of a 2-stage injection-locked oscillator when the two oscillators have same transfer characteristics. Transfer characteristics of (a) first-stage oscillator, (b)second-stage oscillator, and (c) resultant characteristics.

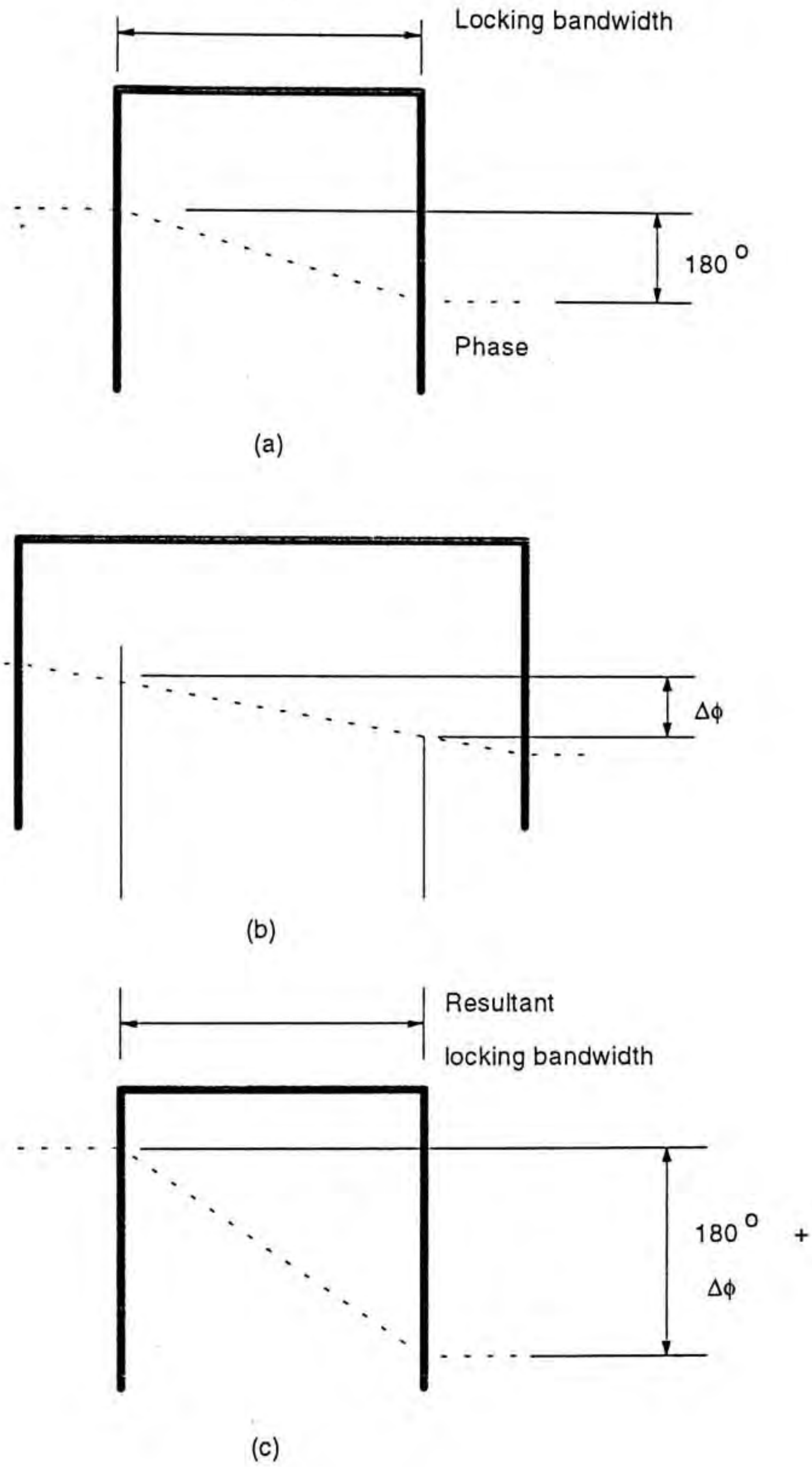


Fig. 5-30 Resultant of a two-stage injection locked oscillator when the second oscillator has a wider locking bandwidth. Transfer characteristic of (a) first-stage oscillator, (b) second-stage oscillator, and (c) resultant characteristics.

5.6.3 Experimental results

Two injection locked BJT oscillators operating at 850MHz frequency band were used to verify the theoretical prediction. Transfer characteristics of the oscillators were first measured individually using HP8510C network analyzer. The oscillators were then cascaded with a variable attenuator connected in between. The attenuator was used to control the level of power injected to the second oscillator (ILO2), and hence the locking range. It was set to 30 dB in the measurement. The experimental setup is shown in Fig. 5-31 the measurement result is shown in Fig. 5-32 and Fig. 5-33. Fig. 5-33 shows that the cascaded oscillators provide 9.5MHz resultant locking range and a 285° phase change.

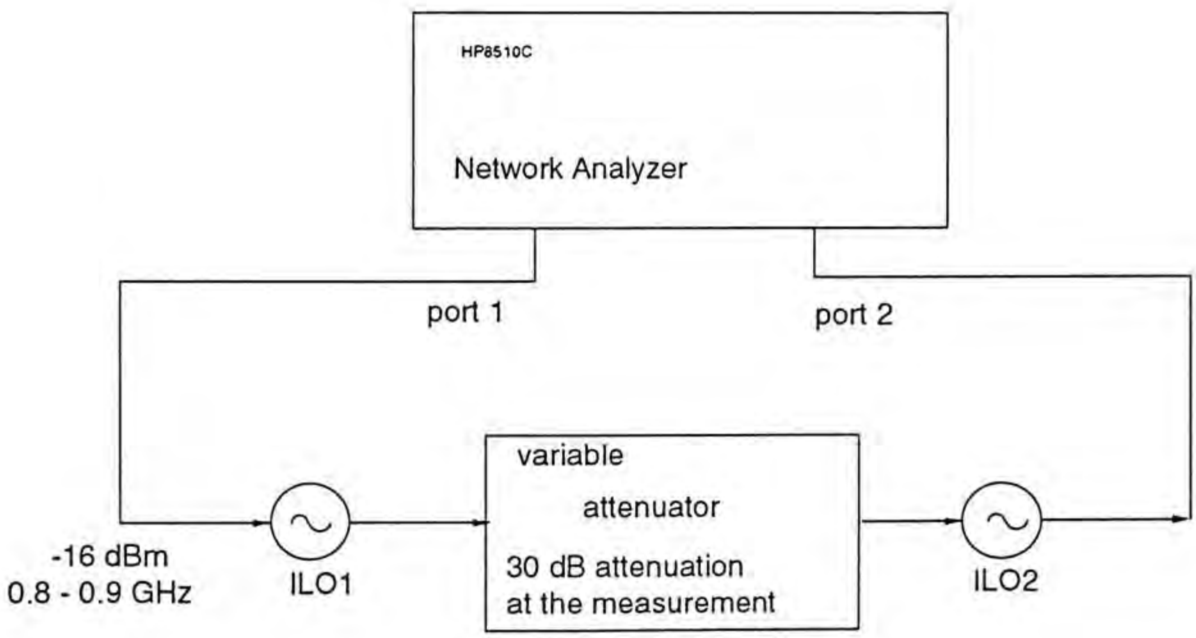


Fig. 5-31 Measurement set up of the cascaded ILOs

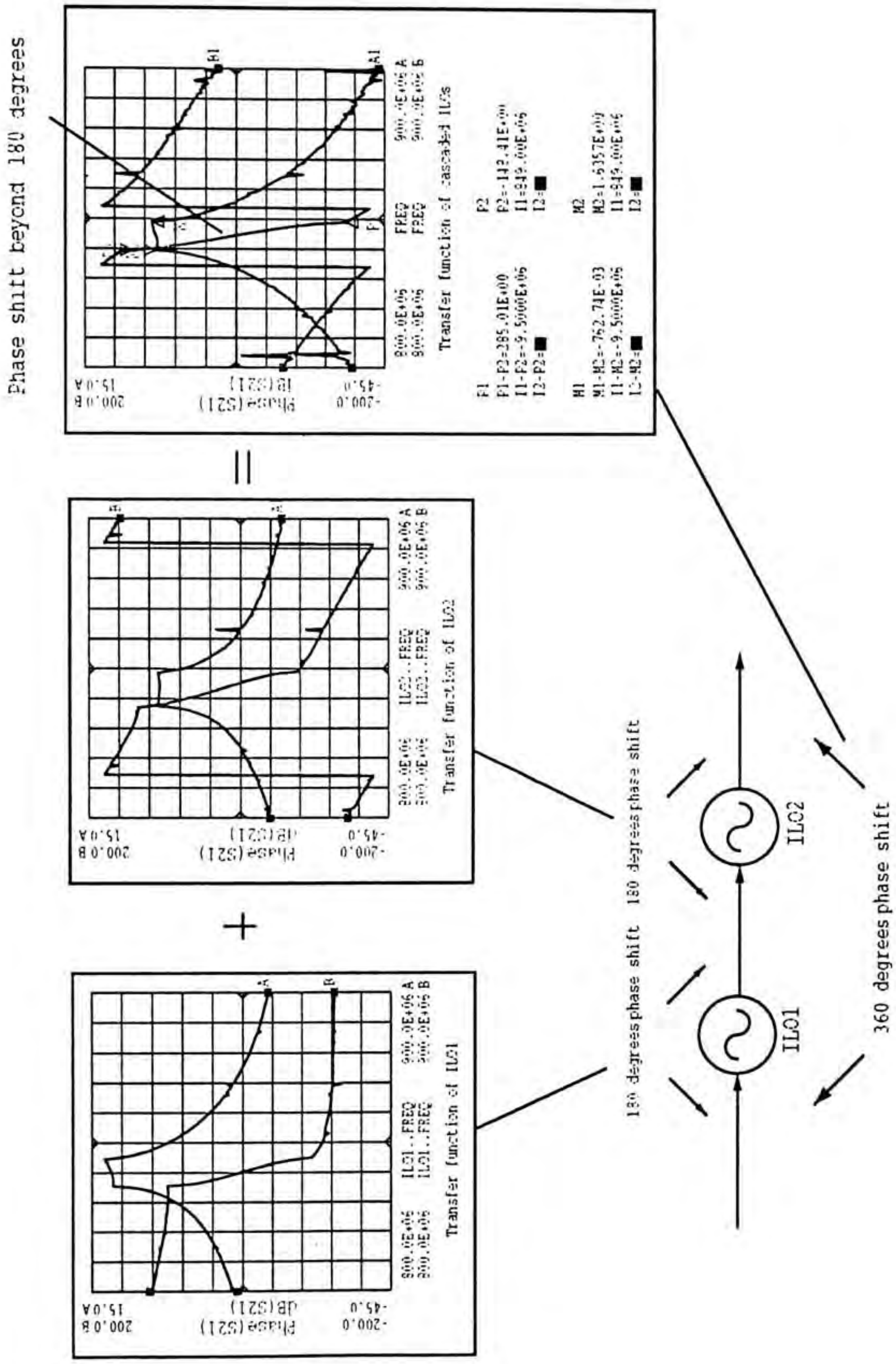


Fig. 5-32 Measured transfer characteristics of the ILO1, ILO2 and after cascading

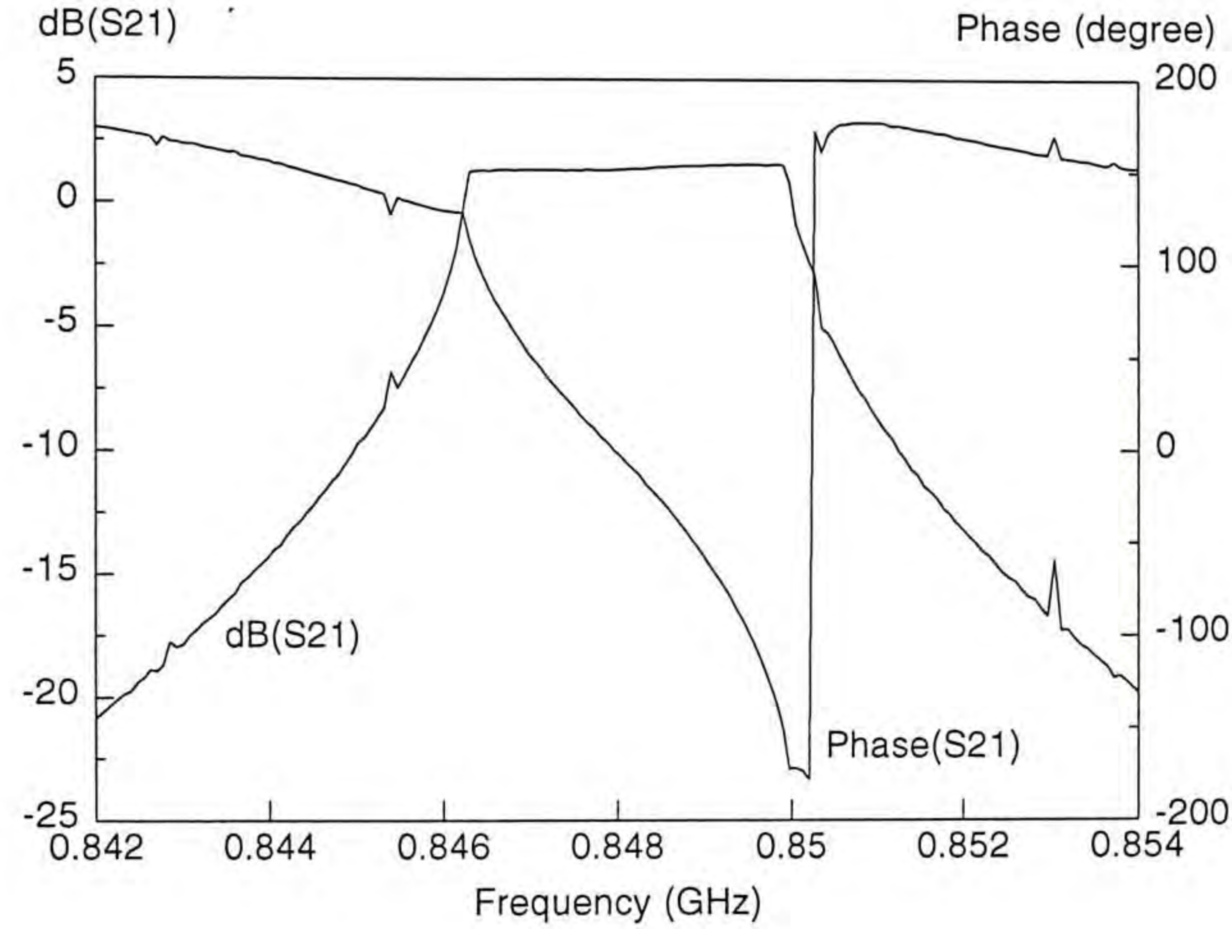


Fig. 5-33 Measured transfer characteristic of the cascaded ILOs

5.6.4 Summary

The flat top region corresponds to the locking region. It is 9.5MHz. The experiment shows that a continuous phase change of 285° can be obtained, which is well beyond the 180° limit of a single injection locked oscillator. With this cascading topology, each oscillator can be tuned individually to provide the desired phase control.

Full 360° operation can be achieved by optimizing the two cascaded oscillators. However, due to temperature drift, which in turn causes drift in the center frequency and the locking range, operation at the boundaries of the locking range will not be stable. If 360° operation is really necessary, the problem can be overcome by cascading more than two injection locked oscillators to provide a sufficient cumulative phase change within the locking range.

5.7 CONCLUSION

In this chapter, four experimental studies are presented. They are non-integral subharmonic locking, multi-feedback for subharmonic locking range enhancement, comparison of injection points, and phase tuning beyond 180 degrees. These injection locking techniques can be used in modern communication systems such as frequency synthesis for local oscillator, and on phase tuning beyond 180 degrees for phased array antenna.

CHAPTER 6

CONCLUSION

This thesis reports four new techniques concerning injection locked oscillator utilization. The new techniques are non-integral subharmonic injection, selective subharmonic locking range enhancement using mutli-feedback, locking range enhancement using feedback type injection locked oscillator, and technique of phase tuning range beyound 180 degrees. Experimental results demonstrate that these techniques are superior to the current usage of injection locking. Applications can be found in frequency synthesis, and in phased array antenna for phase tuning.

The goal of enhancing the locking range is successfully achieved by the second and the third techniques. The first technique, non-integral subharmonic locking, provides an extra flexibility on circuit design in which the limitation of using integral subharmonic locking is removed. The goal of phase tuning beyond 180 degrees by injection locking is achieved and demonstrated in the fourth technique. Besides, a graphical model is proposed to explain the locking range effects on the phase tuning range.

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[1] K.W.Wong, and A.K.Y.Lai, "Microwave injection-locked oscillator subharmonic locking bandwidth enhacement using multi-feedback technique", *Elect. Lett.* vol. 29 no.12, pp.1086-1087, June 1993.

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[3] K.W.Wong, and A.K.Y.Lai, "A novel feedback configuration for selective subharmonic injection locking range enhancement", *1993 Asia-Pacific Microwave Conference*, **APMC'93**, October, Hsinchu, Taiwan China (accepted for presentation)

[4] K.W.Wong, and A.K.Y.Lai, "Optimization of injection point for injection locked oscillator" , *1993 Asia-Pacific Microwave Conference*, **APMC'93**, October, Hsinchu, Taiwan China (accepted for presentation)

[5] K.W.Wong, and A.K.Y.Lai, "Phase tuning beyound 180 degrees by injection-locked oscillators", *1993 IEEE Region Ten Conference*, **TENCON'93**, October, Bejing, China (accepted for presentation)

[6] K.W.Wong, and A.K.Y.Lai, "Frequency synthesis using non-integral subharmonic injection locking", *1993 IEEE Region Ten Conference*, **TENCON'93**, October, Bejing, China (accepted for presentation)

[7] K.W.Wong, and A.K.Y.Lai, "Non-integral subharmonic locking in injection locked oscllator" *1993 International Symposium of Personal Communications,* **ISPC'93**, October, Nanjing, China (accepted for presentation)

[8] K.W.Wong, A.K.Y.Lai, and X.Zeng, "A novel phase control technique for injection locked oscillators", *Journal of Electronics* (submitted)

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