

AD-A133 956

CRYSTAL OSCILLATOR DESIGN EMPLOYING DIGITAL INTEGRATED  
CIRCUITS AS THE ACTIVE ELEMENT(U) TELECOM AUSTRALIA  
RESEARCH LABS MELBOURNE M F LANE JAN 75 6949

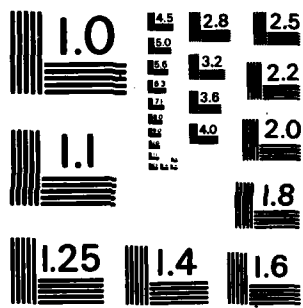
1/1

UNCLASSIFIED

F/G 9/5

NL

END
1 8 5



MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A

AD-A133956

①

# Research Laboratories

Report Number 6949

**Crystal Oscillator Design  
Employing Digital  
Integrated Circuits as  
the Active Element**

By M. F. Lane

APPROVED  
FOR PUBLIC RELEASE

DTIC  
76103 010915 E

DIC FILE COPY



**Telecom Australia**

83 09 30 058



**Telecom Australia Research Laboratories**

59 Little Collins Street, Melbourne, Victoria, Australia 3000

**Report Number 6949**

**Crystal Oscillator Design  
Employing Digital  
Integrated Circuits as  
the Active Element**

**By M. F. Lane**

ABSTRACT

This report presents the design criteria and experimental results of crystal oscillators whose active element is a digital integrated circuit.

Also a method for extending the tuning range of the crystal oscillator is provided.

ZE 4/11  
Case: 26005  
Distribution: B, C, D, E, J, K, L.  
January 1975

Index Headings

1. Crystal Oscillators
2. Digital Circuits
3. Integrated Circuits

(1)

CONTENTS

	<u>Page</u>
1. Introduction	1
2. Basic Oscillator Circuits	1
3. Practical Crystal Oscillator Circuits	2
4. The Frequency Tuning Range of a Quartz Crystal Unit	3
5. Extending the Tuning Range of a Crystal Oscillator	4
6. Crystal Oscillator Circuits with Extended Tuning	5
7. Spurious Resonances in Crystal Units	6
8. Frequency Stability	6
9. Conclusion	6
References	

(Sgd.) R.L. TRAINOR  
for Director, Research



Accession For	
ERIC	X
ERIC	
Univ.	
Journal	
By	
Dist	
Acq. /or	
Dist	
A	

RESEARCH LABORATORIES - REPORT 6949CRYSTAL OSCILLATOR DESIGN EMPLOYING DIGITAL INTEGRATED  
CIRCUITS AS THE ACTIVE ELEMENT1. INTRODUCTION

Due to the widespread use of digital integrated circuits nowadays, it has become convenient to employ a logic element as the amplifier in a crystal oscillator circuit. Many such crystal oscillators are being introduced into service although the results are not always satisfactory, due to the non-linearity of the active element used. Careful design can produce a reliable general purpose crystal oscillator for the frequency range 1 MHz to 100 MHz, whose active element is not necessarily linear over its full dynamic range. Such designs can also cover crystal oscillators requiring an extended tuning range.

The basic requirements for crystal oscillator circuit design are the same no matter what circuit is used for the active element. In order that the oscillator may start when power is supplied to the circuit, and that it may deliver the required power to the load, the correct impedance, phase and gain relationships around the oscillator feedback path must be satisfied. That is, the crystal unit must be matched to the amplifier; the algebraic sum of the phase around the regenerative loop must be zero (criterion for positive feedback); and the amplifier's gain must be greater than unity at noise input levels. ✓

The problems associated with using digital elements as the amplifier in an oscillator circuit are primarily due to two device characteristics; they are, the spread of triggering levels and the propagation delay through the device. Due to the triggering characteristics of digital elements within an integrated circuit device, each individual circuit requires its own bias in the oscillator circuit to ensure that the oscillator will start reliably. Also when the digital element is biased for operation over its linear region, the oscillator will oscillate readily at frequencies determined by the propagation delay of the element and time constants external to the element.

For correct oscillator design it is imperative that unwanted modes of operation be suppressed.

BASIC OSCILLATOR CIRCUITS

Either an inverting or a non inverting logic gate may be used as the amplifier in an oscillator. One of the conditions for a circuit to oscillate is that the sum of the phases around the regenerative loop be equal to 360 or zero degrees. Figures 1A and 1B show the two amplifier variations, and figures 1C and 1D show the basic circuits that will satisfy the phase requirements for the circuit to be regenerative when a quartz crystal unit is employed as the phase maintaining element. In each oscillator the crystal network is designed to provide a phase change equal to that appearing across the amplifier, however as the network completes the feedback loop the amplifier output becomes the network input and the algebraic sum of the phase change around the loop is zero. In operation the phase of the current through the crystal relative to the voltage appearing at the network input will automatically adjust to compensate for phase errors occurring within the loop.

As the propagation delay through the gate will be seen as a negative phase shift to the phase across the crystal network will be less than nominal, i.e. less than zero degrees for the non-inverting or series oscillator and more than  $180^\circ$  for the inverting or parallel oscillator case. In each case, the precise frequency of operation is determined by the phase across the crystal network. For the case where the phase across the crystal network is less than nominal, the operating frequency of the series oscillator will be high in comparison with the same series or non-inverting oscillator which has zero phase across its crystal network. For the case of the inverting or parallel oscillator the capacitance across the crystal network input will appear to be greater than its actual value so the oscillator frequency will be lowered. Figure 2 tabulates the relative operating frequencies of the various networks for ideal phase conditions. This table may also be used to estimate the circuit capacity to be included in the specification when ordering a crystal for a particular oscillator circuit.

Apart from the above-mentioned frequency offset due to non ideal phase conditions which may occur around the oscillator loop, the factor  $d\phi/df$  for a crystal network will also deteriorate, because, under these conditions the crystal network will operate away from the steepest part of its frequency versus phase curve and consequently produce a reduction in the frequency stability of the oscillator. Therefore when selecting a logic gate to be used as the amplifier in a crystal oscillator it is necessary to choose one whose propagation delay is far smaller than the period of oscillation.

The second factor to be considered when choosing a logic gate is the rise and fall time of the gate, as this will determine the upper frequency limit of the amplifier and hence the oscillator (Reference 3). Finally, the saturating type logic elements when used in oscillators, favour a narrow band of frequencies that are directly related to the propagation delay of the gate. This characteristic is a problem with oscillator circuits which are aperiodic. Figure 1C is an example of an oscillator circuit which exhibits this limitation. The capacitive pi network of Figure 1D is a more selective circuit which if properly proportioned will suppress frequencies higher than the nominal crystal frequency. Also the inverting amplifier will not oscillate by direct feedback through the stray capacitance or the static capacitance of the crystal.

### 3. PRACTICAL CRYSTAL OSCILLATOR CIRCUITS

Oscillators covering the frequency range 1 MHz to 100 MHz are shown in Figures 3, 4, 6 and 7. The power dissipated in the crystal is in all cases moderate (less than 2 mW) and the stability of each of the circuits is comparable with that of well designed self limiting crystal oscillators using discrete transistors as the active element (Ref 1).

The circuit shown in figure 3 is suitable for the frequency range 1 MHz to 20 MHz. The table below the circuit gives the required components for different frequencies which cover the stated range. The amplifier is of the inverting type, (the reason for this choice has previously been discussed in Section 2) and is a T.T.L. SN7404 digital integrated circuit hex inverter. The circuit will perform equally as well using a two input nand gate or a two input nor gate (see figure 3B). The bias for this integrated circuit is provided by R1. It has been found that the value of R1 will differ for individual integrated circuit packages and must be experimentally adjusted to provide reliable starting upon application of power and reliable restarting when oscillation has been interrupted without the loss of power.

The same frequency range (1 MHz to 20 MHz) is covered by the circuit shown in Figure 4, using an LM 375 National Semiconductor integrated circuit. This integrated circuit is designed as an oscillator and provides either a sine wave output or a T.T.L. compatible square wave (Reference 4).

For the frequency range 20 MHz to 100 MHz one basic circuit is employed. As most crystals produced for this frequency range will resonate at nominal frequency by vibrating at an overtone, an LC circuit tuned to nominal crystal frequency is included to ensure that regeneration at that frequency is favoured. Two proven circuits are shown in figures 6 and 7. Oscillators designed for adjacent frequencies will require the substitution of component values in the tuned circuit to suit the crystal frequency. Once again an inverter is used as the active element. In the circuit used for this frequency range, the L-C circuit provides most of the complementary phase change required to match the phase across the inverter, and the crystal operates about zero phase, (i.e. nonreactive low resistance).

#### 4. THE FREQUENCY TUNING RANGE OF A QUARTZ CRYSTAL UNIT

A quartz crystal unit is, in most cases, employed to determine the frequency generated by an oscillator that is required to produce a precise frequency. The only tuning required is the initial calibrate and periodical compensation for changes in frequency resulting from aging of the crystal and circuit components. The crystal is manufactured to produce nominal frequency when combined with a specific value of capacitance in series with the crystal. A crystal unit is readily applied in this application and the circuit designer is generally more concerned with the quality of manufacture than with the specific value of its electrical parameters. However, when designing for an extended tuning range of frequency, some loss of stability must be anticipated and it is necessary to know the values of the components comprising the equivalent circuit of the crystal in order to design a network that will provide the tuning required.

The equivalent circuit of a two terminal crystal unit, at frequencies around the mechanical resonance of the quartz is shown in figure 9. The curve of reactance versus frequency is shown in figure 8. By substituting the equivalent circuit of the crystal for the crystal in a network, standard circuit theory can be used to determine the behaviour of a crystal in circuit. (References 1 and 2).

Applying the above-mentioned equivalent circuit procedure will indicate the following:

- (i) (a) The crystal arm of network D (Figure 2) is series resonant at the same frequency as network B is parallel resonant i.e., when  $C_1$ ,  $C_2$ , and  $C_3$  in series are equal to  $CL$ .
- (b)  $C_0$  is part of the effective capacitance in both cases, i.e. the effective capacitances are  $C_L + C_0$ , and  $C_1$ ,  $C_2$ ,  $C_3$  in series plus  $C_0$ .
- (ii) When the reactance seen by the crystal is capacitive, the resonant frequency of a network will be greater than the



- (iii) For resonance to occur at a frequency less than  $f_r$ , the reactance seen by the crystal must be inductive.

Apart from the configuration of the equivalent circuit, the most significant feature the equivalent circuit brings out is the high L/C ratio of the motional arm,  $L_m$ ,  $C_m$ ,  $R_m$ . In the low frequency range crystals, this may be as high as 10 to the 18th power, whereas in the high frequency range the 12th power is typical. These figures give an indication of the high

reactances involved; at resonance  $X_L = X_C = \sqrt{\frac{L}{C}}$ . Because of the high L/C ratio and comparatively low resistance, the quartz crystal unit has a high Q and a limited change in resonant frequency when coupled with a reactive component of practical magnitude. The greater frequency change will, of course, be realized with a crystal having a lower L/C ratio; that is a comparatively high value for  $C_m$ . Manufacturers of crystal units have some control over the value of  $C_m$  but standard processing is designed to retain a low value. A crystal resonating at an overtone will have a lower value for  $C_m$  compared with one producing the same frequency when resonating at its fundamental mode of motion, consequently a fundamental unit is better suited for an oscillator requiring a wide tuning range. The upper limit of readily available fundamental mode crystals is less than 30 MHz.

#### 5. EXTENDING THE TUNING RANGE OF A CRYSTAL OSCILLATOR

In a capacitive pi network such as shown in figure 3, tuning  $C_s$  will change the total capacitance in series with the crystal and resonance will occur at a new point along the inductive curve between  $f_r$  and  $f_a$ ; i.e. the series and parallel resonant frequencies respectively. (See figure 8). In this circuit the tuning range is limited by the fixed capacitance of the network. A wider tuning range is possible with a series circuit having network terminations which are non-reactive and low in resistance. In such a circuit the crystal is resonant at  $f_r$ . When a capacitance is placed in series with the crystal,  $f_r$  is moved to a higher frequency and tuning the capacitance will vary the resonance of the crystal - capacitance circuit about this new frequency. The expression for the new frequency is given as

$$f_r' = \frac{1}{2\pi} \sqrt{\frac{1}{L_m C_m} + \frac{1}{L_m (C_o + C_L)}} \quad (5.1)$$

where  $C_L$  is the added capacitance in series with the crystal. From expression (5.1) it can be seen that varying the series capacitance,  $C_L$ , will not lower the frequency below  $f_r$ , the value for infinite  $C_L$ . When the series component is inductive, resonance occurs at a frequency below  $f_r$ ; that is, referring to figure 8,  $f_r$  is shifted to the left on the frequency axis and variation of the inductance causes the resonant frequency to move about its new position. Therefore a tuning range covering frequencies above and below  $f_r$  of the crystal is achieved when the total reactance seen by the crystal is variable about zero, i.e. covering both positive and negative reactance changes. Figure 5 shows this type of network, the series combination of inductance  $L_s$  and variable capacitance  $C_s$  is proportioned to resonate at  $f_r$  when  $C_s$  is tuned about the centre of its frequency range. Tuning  $C_s$  will vary the reactance from a high capacitive value,  $X_Ls - XCs$ , through zero to an inductive value approaching  $XLs$ . The inductance  $L_p$  is adjusted to resonate with  $C_o$  at the frequency  $f_r$ , making the reactance of  $C_o$  over the frequency range

negligible. This is necessary as  $C_0$  places a limit on the highest frequency attainable, for

$$\Delta f = \frac{C_m f_r}{2(C_0 + C_s)} \quad (5.2)$$

Also with  $C_0$  neutralized, the stability at frequencies below  $f_r$  is improved. With  $C_0$  and  $L_p$  parallel resonant, the only reactive components in the circuit are  $L_s$ ,  $C_s$ ,  $L_m$  and  $C_m$ , so there will be zero phase across the network at series resonance of the  $L_s$ ,  $C_s$ ,  $L_m$  and  $C_m$  combination.

In an oscillator there will be some phase discrepancy due to the amplifier, therefore the operating frequency will not be exactly at the resonance of the network, and as this phase error will appear as a reactance looking into the network, the frequency tuning range obtained will be less than the theoretical range. Disregarding the small frequency error due to the imperfections of the amplifier, the frequency of operation may be calculated by the familiar resonant frequency formula:

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (5.3)$$

where  $L$  and  $C$  are the effective values of series inductance and capacitance of the crystal. For an assessment of the tuning range above and below  $f_r$  that may be obtained with a particular crystal in a network, the following formulae may be used.

$$\text{Frequency above } f_r = f_r \sqrt{1 + \frac{C_m}{C_s}} \quad (5.4)$$

$$\text{Frequency below } f_r = f_r \sqrt{\frac{L_m}{L_m + L_s}} \quad (5.5)$$

Equations 5.4 and 5.5 illustrate how the tuning of the crystal is limited by the high  $L/C$  ratio of the crystal; above 5 MHz, crystals can be obtained that will provide a tuning range of  $\pm 0.2\%$  of  $f_r$  in the type of network shown in figure 5.

If a varactor diode is used in place of  $C_s$ , linear frequency variation with varactor voltage can be achieved by the use of a non-linear amplifier which matches the non-linear voltage to frequency characteristic of the crystal. (Reference 6). Because of the wide range of reactance required, the maximum tuning range is not obtainable with the simple LC series circuit at fig. 5. A more complicated network using a transformation to increase the range of the network reactance is given in reference 5. A computer program is supplied for the determination of the network components.

## 6. CRYSTAL OSCILLATOR CIRCUITS WITH EXTENDED TUNING

The circuit and tuning curve of a 20 MHz crystal oscillator with a tuning range of 0.02% above and below  $f_r$  is shown in figure 10. The crystal used in the circuit is a fundamental unit with a  $C_m$  of 0.026 pF.

The terminations of the crystal arm in this circuit are for practical purposes resistive over the frequency range. The LC pi network is tuned to resonate at  $f_r$ . This type of circuit, which uses an inverter with a  $180^\circ$  pi network, was chosen to ensure operation at the nominal crystal frequency over the tuning range. While this pi network does not suppress spurious crystal resonances, it does suppress spurious oscillations favoured by the T.T.L. inverter. Curve B shown in figure 10 is the reactance curve of  $L_s$  and  $C_s$  as  $C_s$  is varied. Naturally a different tuning curve will be obtained for each different value of  $L_s$ .

The tuning curve for a 24.4 MHz third overtone crystal with a  $C_m$  of 0.002 pF, operating in a circuit similar to that used in figure 10 is shown in figure 11. The comparatively low value of  $C_m$  accounts for the lower percentage frequency change for a similar series reactance. It should also be noted that the stability of these oscillators will depend to a large extent on the quality of the inductances used.

#### 7. SPURIOUS RESONANCES IN CRYSTAL UNITS

A crystal unit used in an oscillator required to provide a wide tuning range, must be free of spurious resonances within and close to the proposed frequency range. For this reason a unit that performs satisfactorily when operated at nominal frequency may be unsuitable when the tuning range is extended. This is often the case when frequency modulation of a crystal oscillator is attempted. Overtone crystal units are more prone to spurious resonances than those produced for fundamental operation.

#### 8. FREQUENCY STABILITY

The overall frequency stability of a crystal oscillator using a logic gate as the active element is similar to that of a general purpose self-limiting crystal oscillator employing discrete transistors. Typical recordings of the short term stability of both the integrated circuit and discrete transistor oscillators are shown in Figures 12A and 12B. These recordings were obtained by monitoring a Frequency Difference Meter (FDM) with a chart recorder, the FDM compared each of the abovementioned oscillator outputs against the output from a high quality reference oscillator. Figure 12C shows the recording of the comparison between two oscillators of the type used as the reference when recording figures 12A and 12B.

#### 9. CONCLUSION

Integrated circuit inverting and non-inverting logic gates designed for logic applications may be used as the active element in a general purpose crystal oscillator.

A number of medium stability oscillator circuits suitable for operation in the frequency range 1 MHz to 100 MHz have been developed, and the circuits and performance figures are presented.

#### REFERENCES

1. M.F. Lane, Transistor Crystal Oscillators to cover the Frequency Range 1 kHz - 100 MHz R.L. Report 6513.
2. Quartz Crystal Oscillator Circuits Design Handbook - Magnavox Serial No TP64-1072 the Magnavox Company.

3. MECL System Design Handbook Motorola Semiconductor Products Inc.
4. Linear Integrated Circuits National Semiconductor Corporation.
5. M.M. Driscoll and D.J. Healey - Voltage Controlled Crystal Oscillators, I.E.E.E. Transactions on Electron Devices Vol. ED18, No. 18, August 1971:
6. A.A.R. Townsend - A Non Linear Amplifier for Linearizing the Voltage to Frequency Characteristic of a Voltage Controlled Oscillator. R.L. Report 6761.
7. M.M. Driscoll - Two Stage Self-Limiting Series Mode Quartz - Crystal Oscillators Exhibiting Improved Short-Term Frequency Stability. I.E.E.E. Transactions on Instrumentation and Measurement - Vol. IM22, No. 2, June 1973.
8. L.H. Murfett - Oscillators and Buffer Amplifiers for the Radio Australia Transmitters at Shepparton (Vic.) Appendix II R.L. Report 5447.

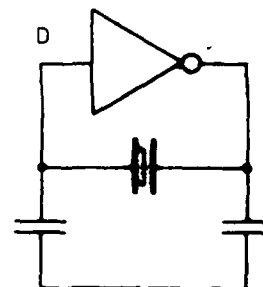
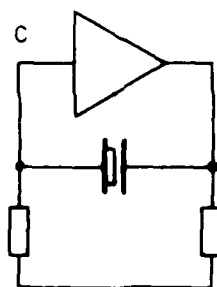
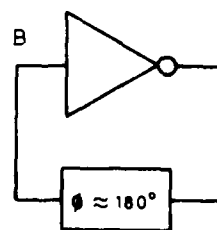
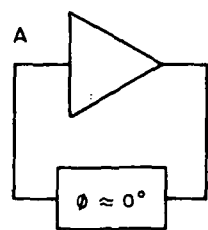


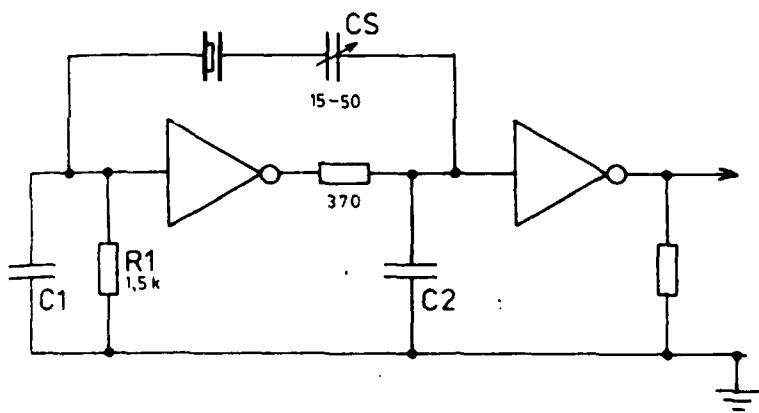
FIG. 1. DEVELOPMENT OF CRYSTAL OSCILLATORS USING LOGIC GATES

CRYSTAL NETWORK	EQUIVALENT AT RESONANCE	CIRCUIT CAPACITY (CL)	RESONANT FREQUENCY
<p>A</p>		$\frac{C_1 \times C_2}{C_1 + C_2}$	$f_r + \Delta f$
<p>B</p>		$\frac{C_1 \times C_2 \times C_3}{C_2 C_3 + C_1 C_3 + C_1 C_2}$	$f_r + \Delta f$
<p>C</p>		$\infty$ (SERIES RESONANCE)	$f_r$
<p>D</p>		$CL$	$f_r + \Delta f$

$f_r$  = SERIES RESONANCE OF CRYSTAL, SEE FIG. 8

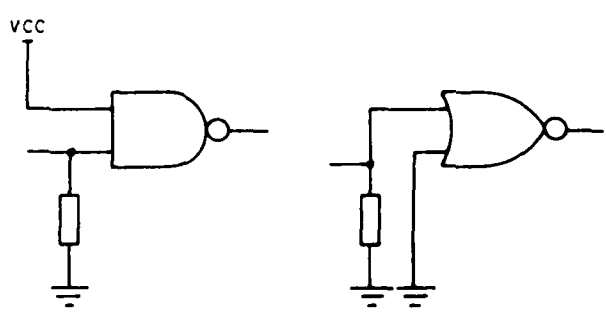
$$\Delta f \approx \frac{C_m}{2(C_0 + CL)} \times f_r \quad \text{SEE FIG. 9 \& REF. 8.}$$

FIG. 2. CIRCUIT CAPACITY AND RESONANT FREQUENCY OF CRYSTAL NETWORKS



A

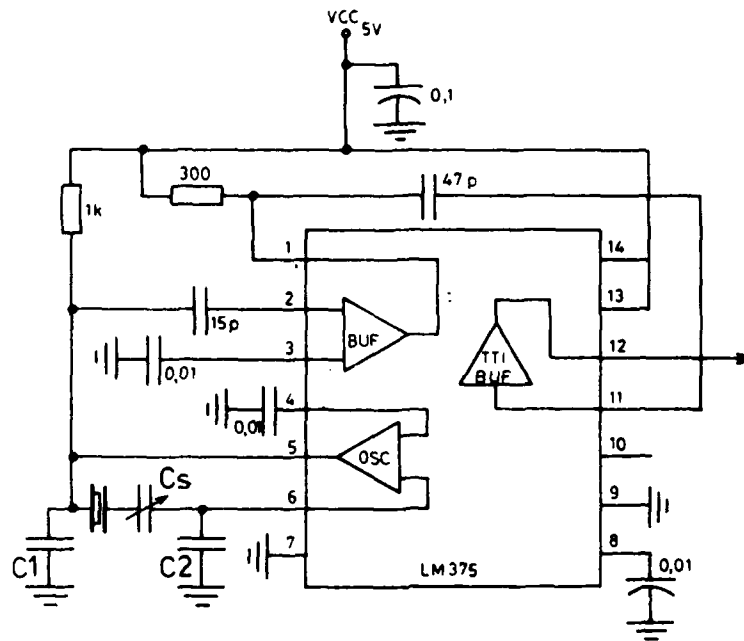
FREQUENCY	C <sub>1</sub> pF	C <sub>2</sub> pF	CRYSTAL CURRENT
1 MHz	1000	1000	1,5 mA
2 "	1000	1000	1,5 mA
4 "	470	470	1,5 mA
5 "	330	330	2,5 mA
8 "	100	330	2,5 mA
10 "	100	220	2,5 mA
12 "	100	100	3 mA
15 "	100	100	2 mA
20 "	50	50	2 mA



B

BIASING OF NOR AND NAND GATES FOR USE IN 'A'

FIG. 3. CRYSTAL OSCILLATOR - 1 MHz TO 20 MHz. USING HEX INVERTOR, 7404



FREQUENCY MHz	C1 pF	C2 pF
1 - 2	330	330
2 - 5	220	220
5 - 10	150	150
10 - 15	100	100
15 - 20	68	68

FIG. 4 CRYSTAL OSCILLATOR-1MHz TO 20 MHz

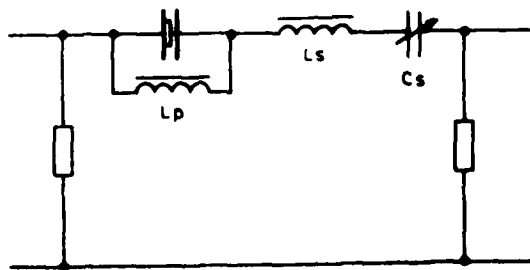


FIG. 5. CRYSTAL NETWORK WITH WIDE TUNING RANGE



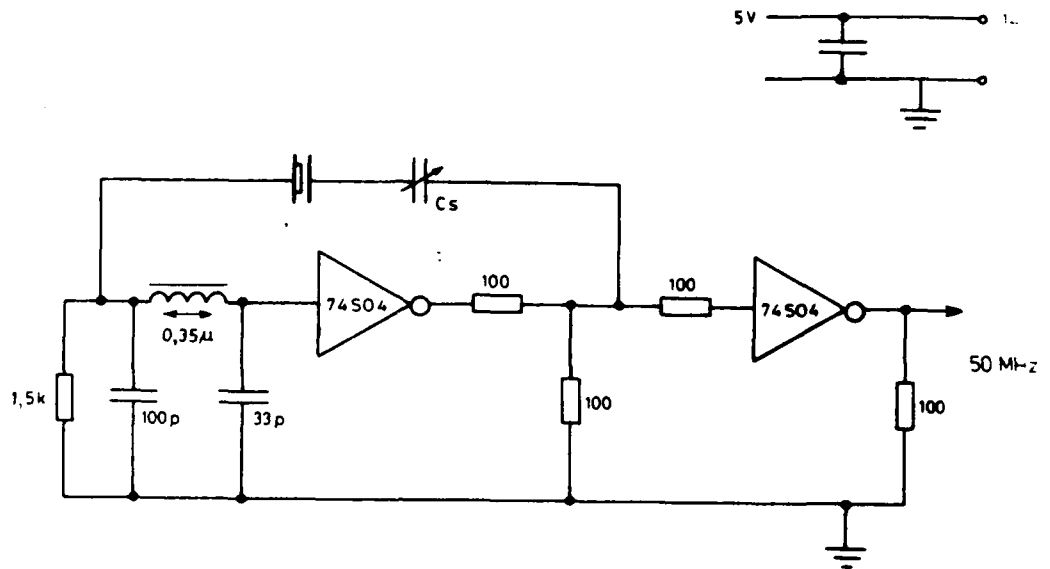


FIG. 6 50 MHz CRYSTAL OSCILLATOR

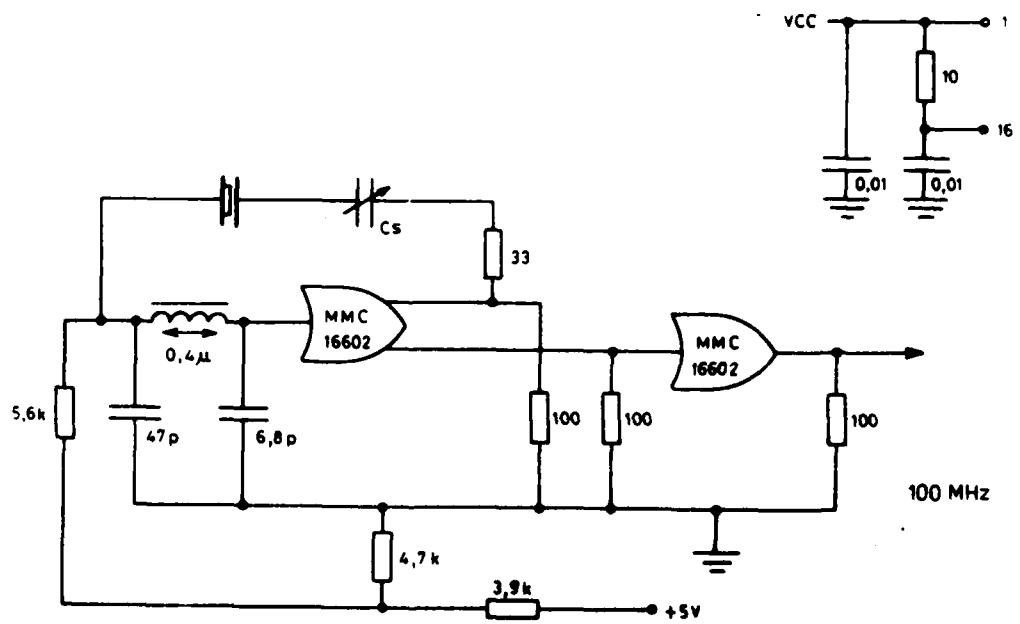


FIG. 7 100 MHz CRYSTAL OSCILLATOR

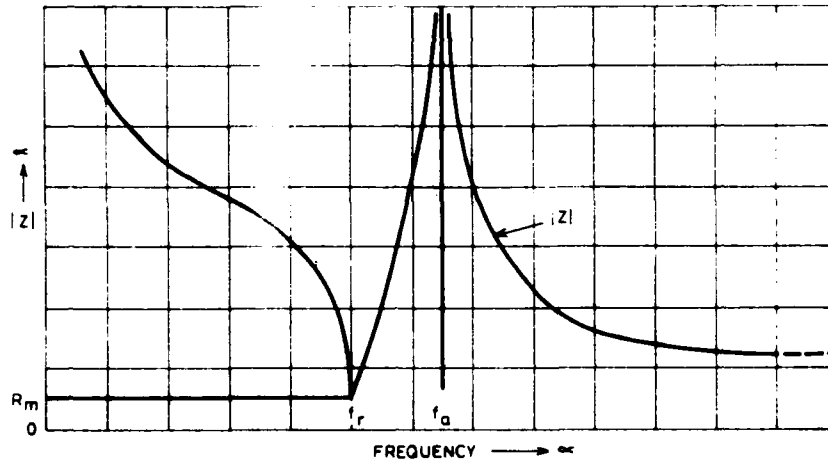
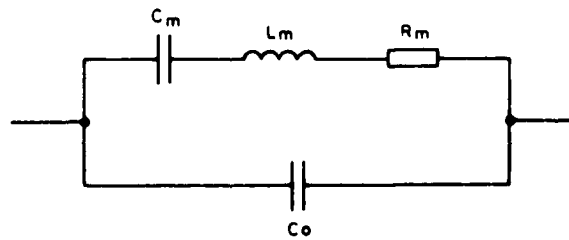


FIG. 8 REACTANCE CURVE OF A QUARTZ CRYSTAL UNIT



$$Q = \frac{\omega L_m}{R_m}$$

FIG. 9. ELECTRICAL EQUIVALENT OF A QUARTZ CRYSTAL UNIT AT FREQUENCIES CLOSE TO MECHANICAL RESONANCE

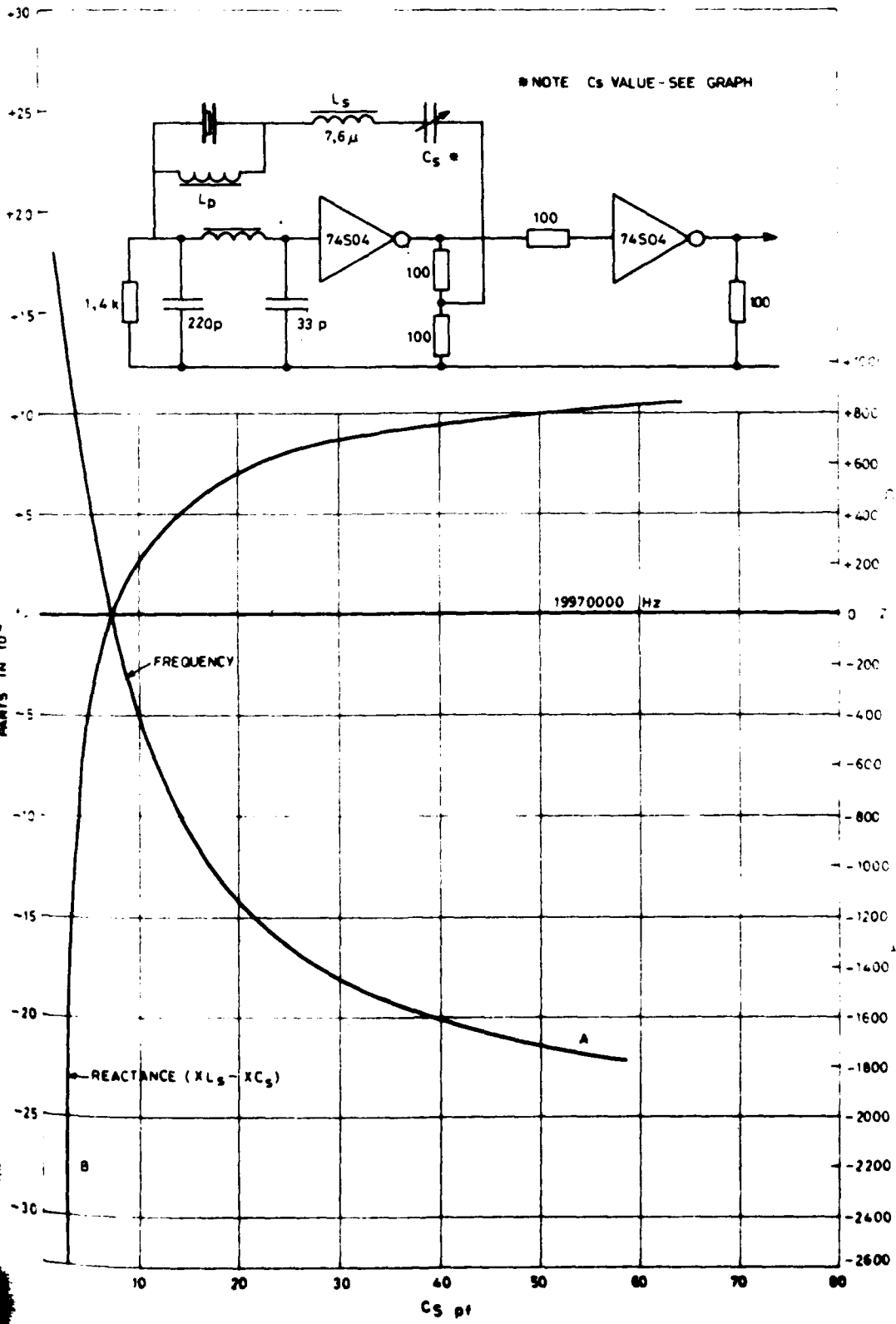


FIG 10. -20 MHz CRYSTAL OSCILLATOR WITH EXTENDED TUNING RANGE

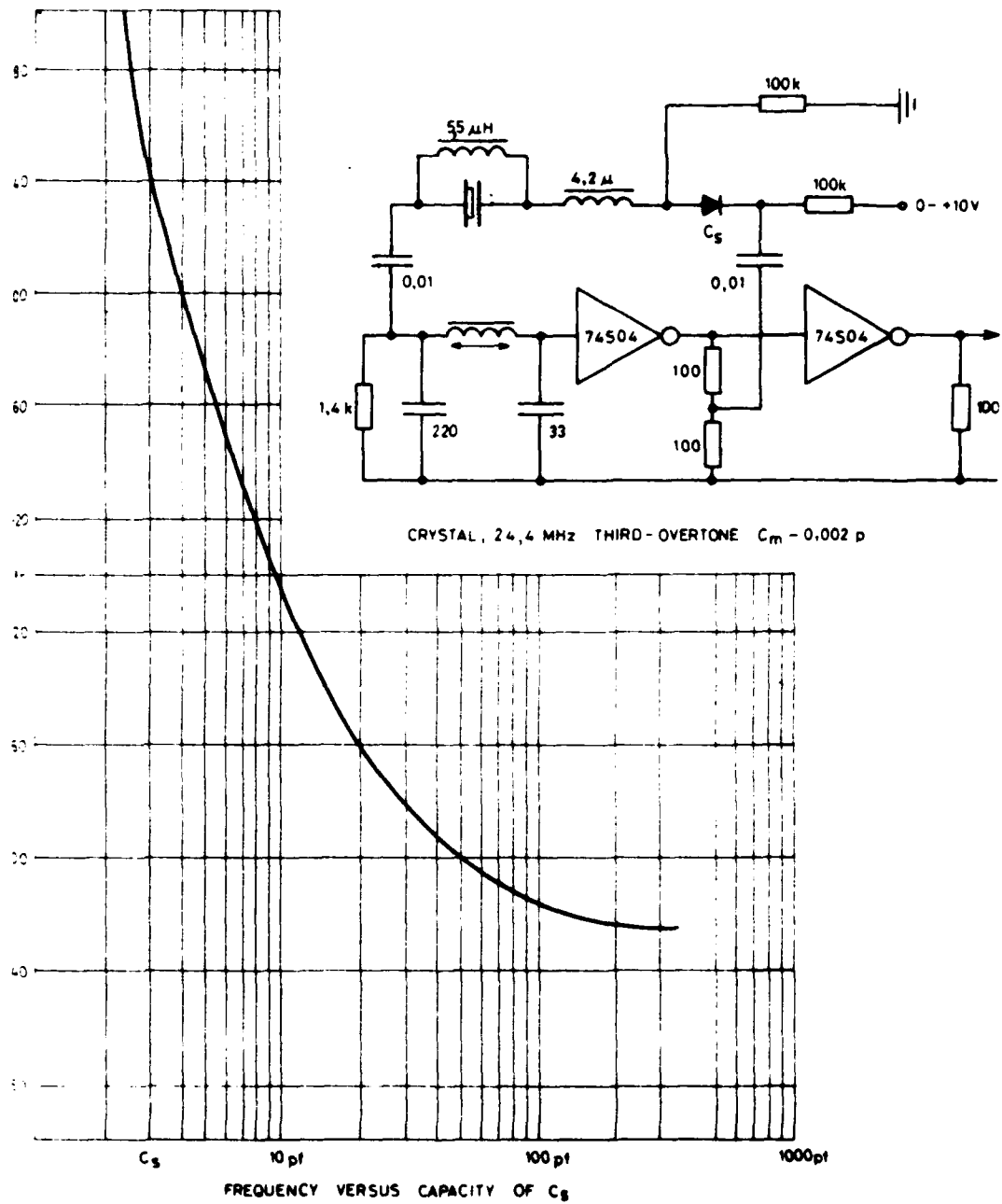


FIG. 11. 24.4 MHz CRYSTAL OSCILLATOR WITH EXTENDED TUNING RANGE

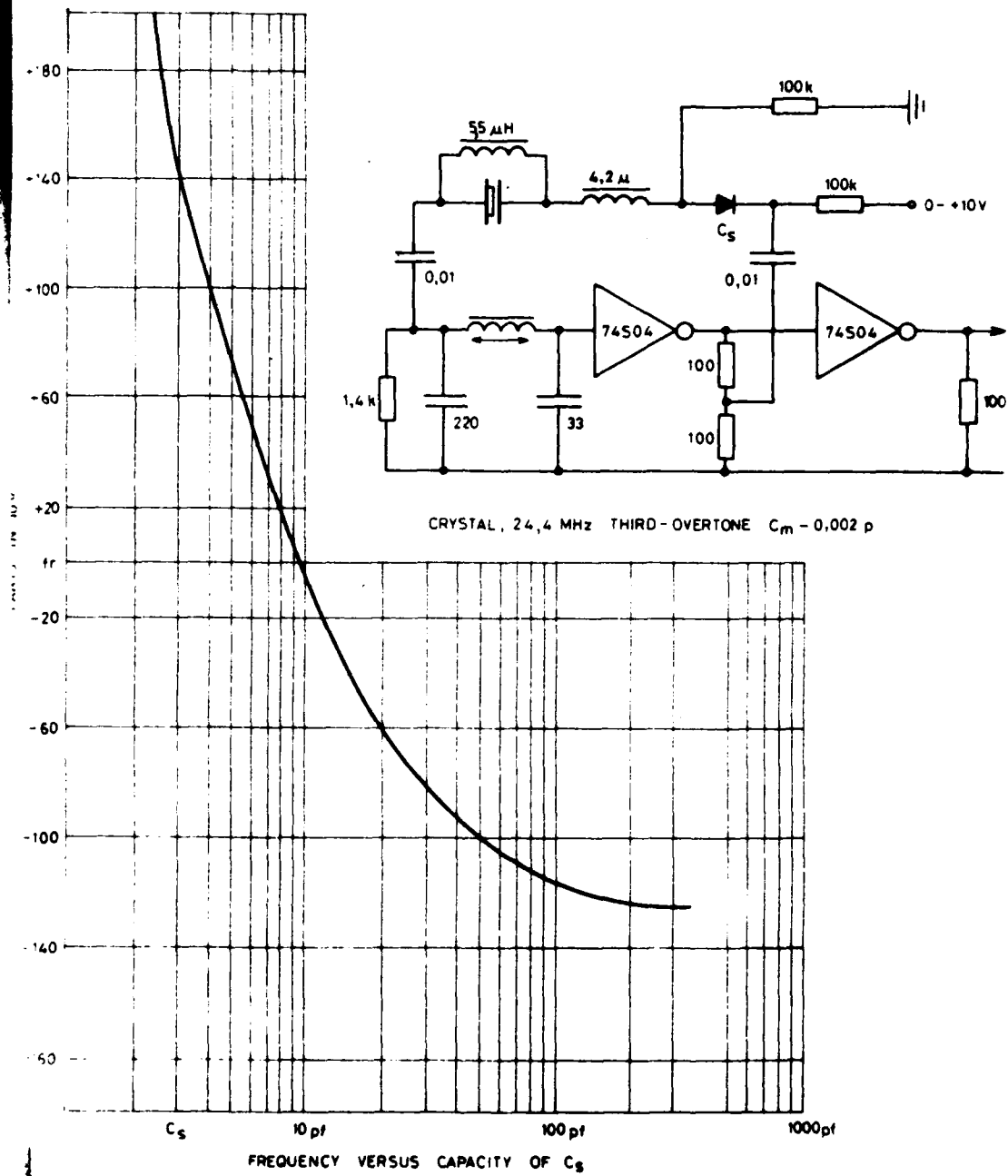
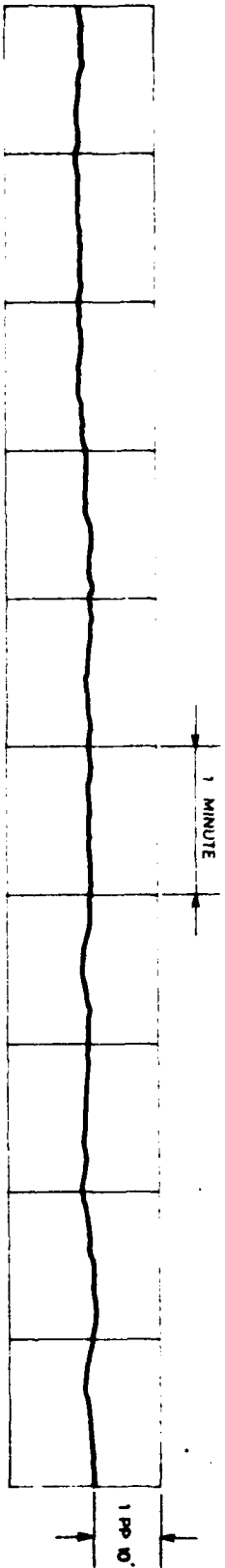
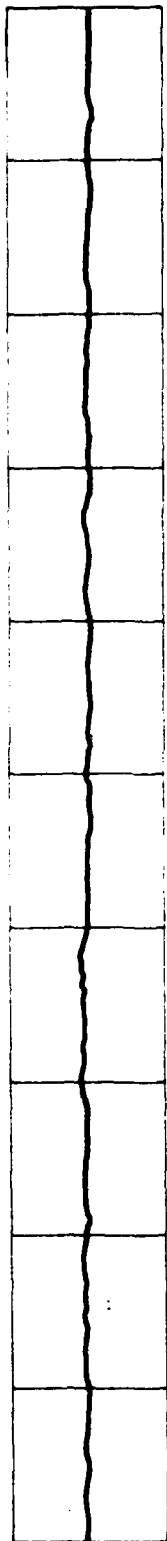


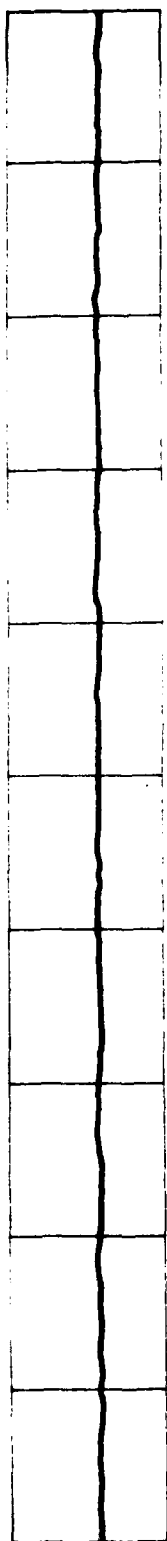
FIG. 11. 24,4 MHz CRYSTAL OSCILLATOR WITH EXTENDED TUNING RANGE



A SHORT-TERM STABILITY — 5 MHz OSCILLATOR USING CIRCUIT SHOWN IN FIG. 3



B SHORT-TERM STABILITY — 5 MHz SELF-LIMITING TRANSISTOR CRYSTAL OSCILLATOR



C SHORT-TERM STABILITY — COMPARISON OF TWO 5 MHz REFERENCE OSCILLATORS

FIG. 12 SHORT TERM STABILITY OF 5 MHz CRYSTAL OSCILLATORS

END

DATE  
FILMED

11 83

D.