A SIMPLE CIRCUIT OF A CRYSTAL OSCILLATOR AND ITS APPLICATION TO A HIGH-RESOLUTION NMR SPECTROMETER

J. T. Lue

A Simple Circuit of a Crystal Oscillator and Its Application to a High-Resolution NMR Spectrometer

JUH TZENG LUE

Abstract—**A simple circuit of a crystal oscillator operating at frequencies from several megahertz to a hundred megahertz with a frequency stability of one part to 10^8 can be constructed by use of a dual insulated-gate metal–oxide–semiconductor field-effect transistor (MOSFET). This RF transmitter accompanied by an RF-tuned receiver can be used as a high-resolution NMR spectrometer and as a precise gaussmeter.**

I. Introduction

A SIMPLE CRYSTAL oscillator with a frequency stability of one part to 10^8 can be constructed by using a dual-insulated-gate metal–oxide–semiconductor field-effect transistor (MOSFET) in a simple circuit. The circuit operates effectively for crystal frequencies from several megahertz to a hundred megahertz without changing the component values. Because of its exceptional frequency stability, this simple transmitter accompanied by an RF-tuned receiver can be used in a high-resolution NMR spectrometer. Also, a series of such transmitters with slightly different frequencies can be arranged, with the proton resonance or other suitable resonances, to provide a convenient marker lattice for magnetic field measurements in magnetic resonance experiments. Each crystal in the series has its proton resonance frequency so that when the magnetic field is linearly swept to the position for the proton resonance to occur an NMR mark will be placed on the same recording chart of another magnetic resonance spectrum.

II. Circuit Descriptions

The crystal oscillator using an RCA dual insulated-gate FET is of the form shown in Fig. 1. This self-biasing circuit corresponds to an input resistance

$$R_i' = R_i \| R'$$

where

$$R' = R_1 \| R_2 = \frac{R_1 R_2}{R_1 + R_2}$$

and a bias supply

$$V_{GG} = \frac{R_2 V_{DD}}{R_1 + R_2}.$$

Manuscript received June 11, 1974. This work was supported by the U.S. Army Research Office-Durham under Grant DAHCO-4-74-G0034 and by the Chinese Science Council.

The author is with the Department of Physics, National Tsing Hua University, Hsinchu, Taiwan, Republic of China, on leave from Department of Physics, Duke University, Durham, NC 27706.

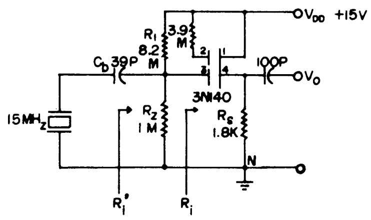

Fig. 1. A crystal oscillator using an RCA 3N140.

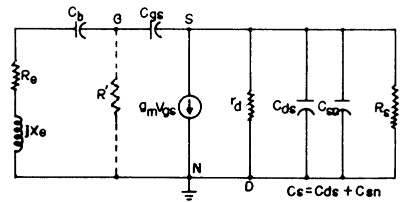

Fig. 2. The equivalent circuit of Fig. 1.

Since

$$R_i \approx \frac{1}{j\omega C_{gd}} \gg R'$$

it is seen that $R_i' \approx R'$, in our case R_i' is about 900 hΩ. The topological equivalent circuit of this voltage series feedback at high frequencies is shown in Fig. 2. The resistance R' has been omitted in this drawing for its very high value comparing with other component values.

By application of the Kirchhoff current-loop theorem to node S we find

$$0 = \frac{V_0}{R_e + jX_e + 1/j\omega C_b + 1/j\omega C_{gs}} + g_m V_{gs} + V_0 \left(\frac{1}{R_s'} + j\omega C_s\right) \quad (1)$$

where R_e and X_e are the equivalent resistance and reactance of the crystal, respectively, and $C_s = C_{ds} + C_{sn}$, $R_s' = R_s \| r_d$.

The input to output voltage ratio R is

$$R = \frac{V_{gs}}{V_0} = \frac{gm\left[1 + \left(\frac{1}{R_s'} + j\omega C_s\right)\left(R_e + jX_e + \frac{1}{j\omega C_b} + \frac{1}{j\omega C_{gs}}\right)\right]}{R_e + jX_e + \frac{1}{j\omega C_b} + \frac{1}{j\omega C_{gs}}}. \quad (2)$$

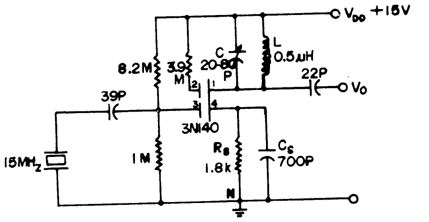

Fig. 3. A variety of crystal oscillator of Fig. 1.

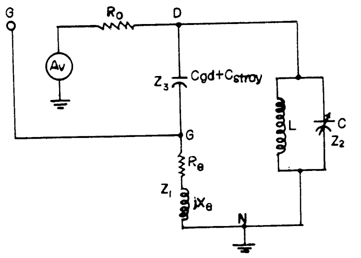

Fig. 4. The linear equivalent circuit of Fig. 3.

The phase angle of R is then given as

$$\phi = 180° - \tan^{-1} \frac{R_s' \{R_e^2 \omega C_s + (X_{ct} - X_e)[1 + \omega C_s (X_{ct} - X_e)]\}}{R_s' R_e + R_e^2 + (X_e - X_{cx})^2}$$

$$= 180° - \tan^{-1} \frac{R_s' \{a + X_e' + \omega C_s X_e'^2\}}{b + X_e'^2} \quad (3)$$

where $X_{ct} = 1/\omega C_b + 1/\omega C_{gs}$, $a = R_e^2 \omega C_s$, $b = R_s' R_e + R_e^2$ and $X_e' = X_{ct} - X_e$.

The phase angle will equal 180° when

$$a + X_e' + \omega C_s X_e'^2 = 0. \quad (4)$$

This is the one criterion for oscillation, i.e., that the total phase shift around the loop be an integral multiple of 360°. Equation (4) gives the value of the loading capacitor C_b in series with the crystal. The frequency of minimum impedance will occur when the total reactance is zero. The equivalent crystal resistance R_e is small when the antiresonance frequency f_a is close to the resonance frequency f_s [1]. However, the loading capacitance becomes infinite as f_s is approached. It is impractical to use a large value of C_b which may violate the gain and phase requirements for stable oscillation. A choice of values for C_b from 8 to 47 pF is found to serve equally well.

The other important requirement for stable oscillation is a large variation of phase with frequency. We wish to find the maximum of $d\phi/d\omega$. Since $dX_e/d\omega$ can be regarded as constant in the small frequency range around f_a,

$$\frac{d\phi}{d\omega} = \frac{dX_e}{d\omega} \frac{d\phi}{dX_e} = K \frac{d\phi}{dX_e}. \quad (5)$$

The maximum of $d\phi/d\omega$ implies that $d^2\phi/d\omega^2 = 0$. We then have

$$X_e'^3 + 3(a - b\omega C_s) X_e'^2 - 3bX_e' + b^2 \omega C_s - ab = 0. \quad (6)$$

If all the electrical characteristics of the FET are known, the value of R_s can be determined from (6). The choice of R_s is not very critical; the oscillator can adjust its frequency automatically so that a large value of $d\phi/d\omega$ is obtained.

A variation of the crystal oscillator of Fig. 1 is shown in Fig. 3. Here we have added a LC-tuned combination for the load. The linear equivalent circuit is shown in Fig. 4 [2]. The loop gain is found to be

$$-A\beta = \frac{-A_v z_1 z_2}{R_0(z_1 + z_2 + z_3) + z_2(Z_1 + z_3)} \quad (7)$$

where $-A_v$ is the negative gain of the FET without feedback and R_0 is the output resistance and is equal to $r_d + R_s \| C_s$. Since Z_2 and Z_3 are pure reactances, we set $Z_2 = jX_2$, $Z_3 = jX_3$ and obtain

$$-A\beta = \frac{A_v X_2 (X_e - jR_e)}{R_0 R_e - X_2(X_e + X_3) + j[R_0(X_e + X_2 + X_3) + R_e X_2]}. \quad (8)$$

For zero phase shift of the total loop, we have

$$X_e R_0 (X_e + X_2 + X_3) + R_e(R_e R_0 - X_2 X_3) = 0. \quad (9)$$

For an ideal crystal with zero series resistance, R_e will also be zero. By use of the zero-phase-shift equation, (8) can be reduced to

$$-A\beta = \frac{A_v X_e}{X_2}. \quad (10)$$

The circuit will oscillate at the resonant frequency determined by (9). Since $-A\beta$ must be positive and at least unity in magnitude, then X_e and X_2 must have the same sign (A_v is positive). Thus, the LC network as well as the crystal reactance must be both inductive or capacitive at the same time. If the loop gain is to be greater than unity, from (10), we see the X_e cannot be too small. A large value of X_e will occur for oscillating frequencies between f_s and f_a. Since the crystal has a high Q value which corresponds to a large value of $d\phi/d\omega$, the frequency of the oscillator depends essentially on the crystal itself. A change of the capacitance of Z_2 will, at most, change the frequency to 3 part per million. However, the inductance in Z_2 will trigger different overtone frequencies of the crystal.

III. Applications

The oscillator shown in Fig. 3 can be employed as an RF transmitter without any requirement of amplification in the NMR studies if a receiving coil is wound around a sample with its axis perpendicular to both the axis of the transmitter coil and the direction of the mag-

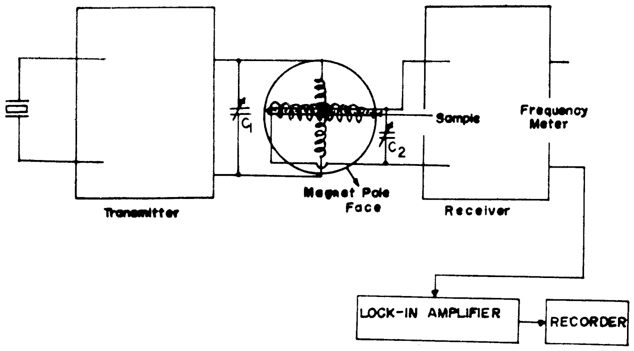

Fig. 5. The schematic diagram of a simple NMR spectrometer. The lockin amplifier is used in conjunction with the magnetic-field modulation to recover the line.

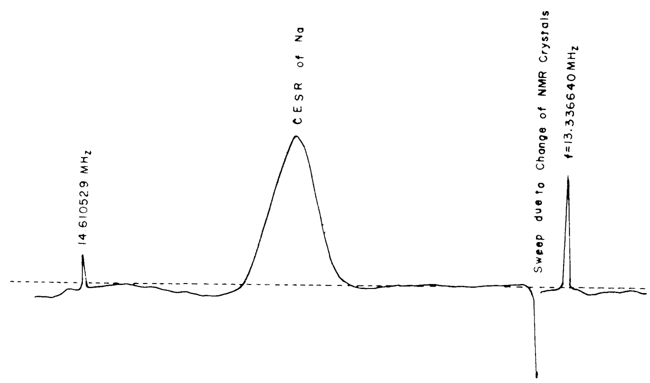

Fig. 6. The conduction electron spin resonance spectrum of sodium accompanying with two NMR marks which have been added to the CESR signal.

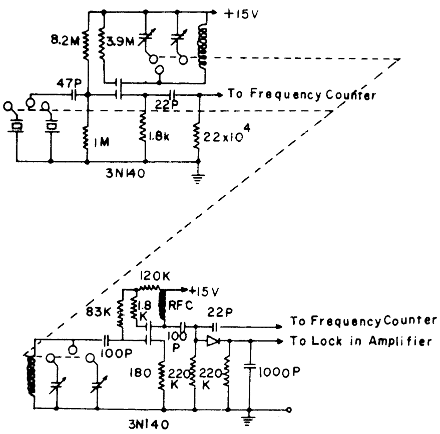

Fig. 7. The detailed circuit of a precise Gaussmeter. The upper section of the figure is the transmitter, and the lower section is the receiver. The NMR sample is associated with the receiver coil.

netic field. When the receiving coil, shunted with a capacitor, if further connected to an RF-tuned amplifier, a high-resolution NMR spectrometer is made possible since the frequency has a stability of one part to 10^8 and does not shift even at an NMR resonance. A regulated temperature-control oven may further increase the frequency stability above the value mentioned above. In this induction method [3] since the driving electromagnetic field is very much larger than the weak NMR absorption signal, the coupling between transmitter receiver coils must be small. This is the reason why we place the two coils at right angles to each other. The schematic diagram of the spectrometer is shown in Fig. 5.

The only variables subject to change during change of crystal frequencies are the capacitances of C_1 and C_2. At each oscillating frequency, these capacitors must be adjusted to give maximum coupling of the RF field. To provide a lattice of markers for ESR spectroscopy, a series of quartz crystals and a series of coupling capacitors C_1 and C_2 are arranged on a multiswitch to control, in turn, the frequency and the coupling of transmitter and receiver. As the magnetic field sweeps past the value at which the first crystal allows the proton resonance to occur, a point is marked on the ESR spectrum, and then the next crystal and capacitors are switched in. This process continues so that a series of field marks are recorded on the spectrum. The field can be accurately calibrated by use of the NMR marks. The magnetic field measured in Gauss is equal to 234.84 × NMR frequency (in megahertz) [4]. One of the conduction electron spin resonance lines of sodium accompanied by two NMR marks is shown in Fig. 6. The NMR marks in this figure are somewhat like an absorption curve. Decreasing the NMR modulating field would give the first derivative of the absorption curve, but this will decrease the intensity of the NMR lines. The linewidth of this proton resonance is 0.6 G. An improvement of the magnet field homogeneity would certainly diminish this value. With these two NMR marks and the linear sweep of the magnetic field, we can accurately determine the g value of the EPR line. The detailed circuit of this precise gaussmeter is shown in Fig. 7.

Acknowledgment

The author is very grateful to Prof. Y. T. Yang for innumerable valuable discussions on this experiment. He is also indebted to Prof. W. Gordy, who read the manuscript and offered many constructive criticisms.

References

[1] S. S. Eaton, *Micropower Crystal-Controlled Oscillator Design Using RCA Cos/MOS Inverters*, RCA data books, ICAN-6539, 1972, pp. 221–228.

[2] J. Millman and C. C. Halkias, *Integrated Electronics: Analog and Digital Circuits and Systems*. New York: McGraw-Hill, 1972, p. 491.

[3] F. Bloch, W. W. Hansen, and M. Packard, *Phys. Rev.*, vol. 70, p. 474, 1946.

[4] J. A. Pople, W. G. Schneider and H. J. Bernstein, *High-Resolution Nuclear Magnetic Resonance*. New York: McGraw-Hill 1959, p. 480.