New Design Approach for Wide-Band FET Voltage-Controlled Oscillators

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Abstract —**A new, computer-assisted method, based on small-signal "S" parameters, is described for the systematic design of wide-band VCO's. The method has been applied to design 6–12-GHz and 12–18-GHz GaAs FET VCO's, and it has shown an excellent capability to predict the maximum obtainable tuning bandwidth. The tuning linearity of the VCO's has also been optimized: $\Delta f/f \leqslant \pm 0.4$ percent over a 3-GHz bandwidth.**

I. Introduction

AMONG WIDE-BAND tunable microwave sources, such as YIG-tuned oscillators and voltage-controlled oscillators, the VCO's have the advantages of small size, low weight, and high settling speed. The development of GaAs monolithic integrated circuits (MMIC's) adds the advantage of integrability of VCO's. However, adjustment of integrated circuits is impossible, and this imposes the need for precise computer-aided design methods for each different type of circuit. In particular, designing VCO's is more difficult than YIG-tuned oscillators or dielectric resonator-stabilized oscillators (DRO's) due to the lack of a high-Q resonant circuit.

Up to now, proposed VCO design methods have been essentially based on graphical or empirical approaches [1]–[3]. To our knowledge, a method based on quasi-automatic computer search techniques for optimization of the overall circuit has not yet been proposed.

Our method is based on a suitable choice of the cross section within the circuit with the highest sensitivity to circuit element values where there is no important phase (or frequency) deviation during the transition from small-signal to steady-state large-signal operation.

Our procedure allows maximum bandwidth to be obtained for a given varactor and a given GaAs FET. This method, applied to the design of 6–12- and 12–18-GHz VCO's, has yielded excellent agreement between measured and calculated frequency tuning bandwidths.

II. Generalized VCO Design Approach

The oscillation condition of an oscillator can be expressed by

$$\Gamma_L \cdot \Gamma_R = 1 \tag{1a}$$

or

$$Z_L + Z_R = 0 \tag{1b}$$

where Γ_L and Γ_R are the reflection coefficients of the left and right parts of the circuit cut at an arbitrary plane, and Z_L and Z_R are the corresponding impedances (Fig. 1). Since usually only small-signal parameters are known, the design will be based on the "oscillator starting condition"

$$|\Gamma_L \cdot \Gamma_R| > 1 \quad \text{and} \quad \phi_L + \phi_R = 0 \tag{2a}$$

or

$$\mathrm{Re}(Z_L + Z_R) < 0 \quad \text{and} \quad \mathrm{Im}(Z_L + Z_R) = 0. \tag{2b}$$

It is important to recognize that (1a) and (1b) are not equivalent to (2a) and (2b) since they depend on the point in the circuit at which they are expressed. The ideal analysis point is the one where ϕ_L and ϕ_R (or $\mathrm{Im}(Z_L)$ and $\mathrm{Im}(Z_R)$) are independent of signal amplitude. The methods usually proposed use a plane between the resonator and the active device (transistor).

In our automatic design method, we analyze the circuit at a point where a component is grounded. So the left part of the circuit is simply a short circuit with $\Gamma_L = -1 + j0$ and $Z_L = 0 + j0$. Equation (2) can be simplified to

$$|\Gamma_R| < 1 \quad \text{and} \quad \phi_R = -180^\circ \tag{3a}$$

or

$$\mathrm{Re}(Z_R) < 0 \quad \text{and} \quad \mathrm{Im}(Z_R) = 0. \tag{3b}$$

It is interesting to notice that (3a) and (3b) are strictly equivalent. An analysis using a large-signal model of the active device (FET and varactors) has shown that the phase deviation during the transition from small signal to steady state of the circuit opened at the junction between gate varactor and ground is sufficiently low compared with the tolerance of the different parts of the circuit. This method allows us to analyze the complete circuit, including the resonator and the transistor at the same time, and to optimize it.

As it is evident that the smallest capacitance value determines the highest frequency of oscillation, which is given in the specifications, we establish a computer program including microwave circuit analysis and optimization.

Manuscript received September 5, 1985; revised June 11, 1986.
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IEEE Log Number 8610135.

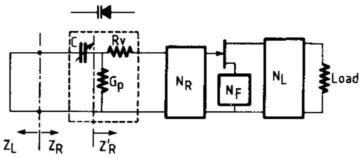


Fig. 1. Schematic of the VCO.

A. Initial Values

For a given minimum varactor capacitance $C = C_{\min}$, and a maximum frequency of oscillation $f = f_{\max}$, the element values of the networks N_R, N_F, and N_L are chosen interactively or by means of a small preoptimization in order to obtain

$$\mathrm{Re}(Z_R) < 0(\approx -5\Omega)^1$$
$$\mathrm{Im}(Z_R) = 0. \tag{4}$$

In order to avoid parasitic oscillations, the varactor connected at the source terminal (if existing) is biased for the lowest capacitance value.

B. Bandwidth Optimization

1) For $f_1 = f_{\max}$, we calculate C_1 from the following equation:

$$C_1 = 1/2\pi \,\mathrm{Im}(Z'_R(f_1)) \cdot f_1 \tag{5}$$

where Z'_R is the impedance of the circuit without the varactor capacitance (Fig. 1). This avoids the time-consuming iterations which would be necessary if we attempted to determine the relationship between the varactor capacitance and the oscillation frequency.

2) If for this value of C_1 the following conditions at $f = f_1$ are valid

$$C_1 < C_{\max}$$
$$\mathrm{Re}(Z_R) < -5\Omega \tag{6}$$

then f_1 is decreased progressively until one of the conditions of (6) is violated.

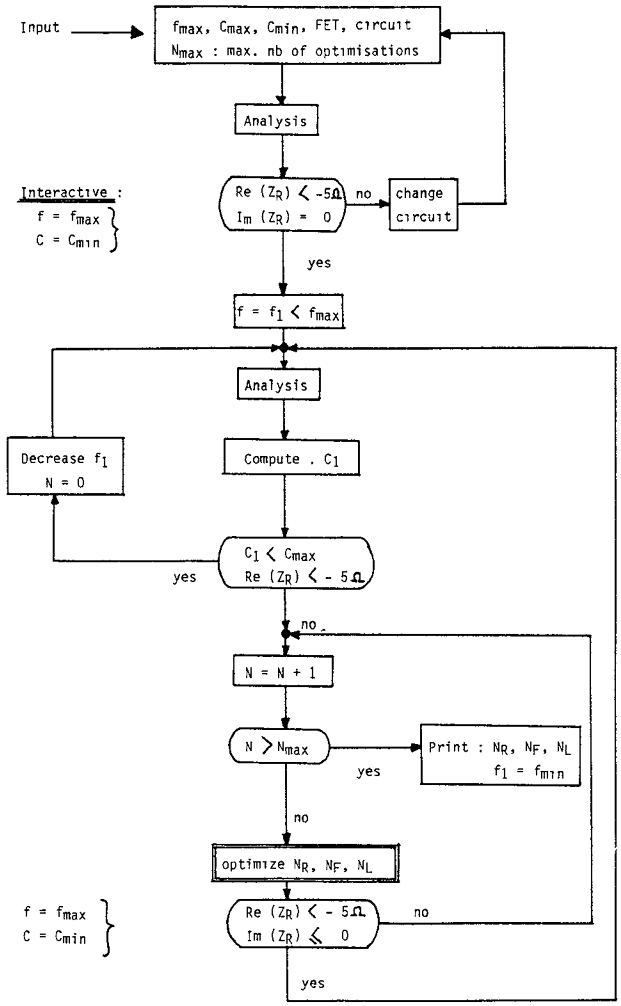
3) In that case, an optimization of the overall circuit (networks N_R, N_F, and N_L) is undertaken in order to satisfy conditions (6) at $f = f_1$ and (7) at $f = f_{\max}$, $C = C_{\min}$.[2]

$$\mathrm{Re}(Z_R) < -5$$
$$\mathrm{Im}(Z_R) \leqslant 0. \tag{7}$$

4) If realistic values for N_R, N_F, and N_L, given for any particular technology, can be found in 3), then f_1 is further decreased and we execute operation 2).

[1]Negative resistance of the active part mu. t be at least twice as great as the losses. Higher values introduce larger shifting between starting conditions frequency (calculated) and steady-state frequency (measured). In our case, a difference of 70 MHz for $-5\ \Omega$ is observed.

[2]In case of multiple-varactor VCO's, the circuit is calculated with capacitances $C = C_{\min}$ at $f_{\max}$ and $C = C_{\mathrm{opt}}$ at f_1.



C. End of Optimization

The optimization ends if no values of N_R, N_F, and N_L can be found that satisfy conditions (6) and (7) for a given maximum number of optimization cycles.

This method allows us to find the maximum tuning bandwidth of the VCO once the active device, varactor(s), highest tuning frequency $f_{\max}$, and physical limitations of the considered technology[3] are specified.

The flowgraph illustrates the described computing and optimization strategy.

Some principal design rules of general validity should be respected for designing VCO's in order to avoid parasitic oscillations at low frequencies and frequency jumps within the effective bandwidth.

Parasitic oscillations can be avoided if care is taken during the choice of the load and the feedback circuit in order to force $\mathrm{Re}(Z_R) \geqslant 0$ outside of the band as far as possible.

Frequency jumps are due to phase loops within the band. In order to avoid such effects, we design the circuit

[3]It is, for instance, well known that spiral MMIC inductors do not allow $Z_{\mathrm{ind}} = \omega_L \geqslant 150\ \Omega$, which automatically limits L to around 1.5 nH at 18 GHz [4].

TABLE I
DESIGN PARAMETERS OF REALIZED VCO'S

VCO Type	FET parameters	Varactor parameters
6-12 GHz	CA 18 (LEP); Z = 2x100 um, Lg=0.8um g_m = 35 mS; C_{gs} = 0.23 pF $R_g + R_i + R_s$ = 6.6 ; C_{gd} = 17 fF	MA/COM : MA 46572 C (Epitaxial GaAs) C_{max} : 2.5 pF C_{min} : 0.15 pF RV : 6
12-18 GHz	MGFC 1403 (Mitsubishi) Z = 4 x 75 um, Lg = 0.5 um gm = 63 mS ; C_{gs} = 0.39 pF $R_g + R_i + R_s$ = 18 ; C_{gd} = 24 fF	" "

TABLE II
COMPARISON OF PREDICTED AND MEASURED VALUES OF REALIZED FET VCO'S

VCO Type		Predicted	Measured values
6 - 12 GHz	f_{max}/f_{min}	1.6	1.67
	f_{max}	12.5 GHz	11.93 GHz
	f_{min}	7.8 GHz	7.055 GHz
12 - 18 GHz	f_{max}/f_{min}	1.38	1.33
	f_{max}	18 GHz	18 GHz
	f_{min}	13 GHz	13.5 GHz

so that the phase at the Z_R' plane *decreases monotonically* with frequency.

III. EXPERIMENTAL RESULTS

We have applied the described method in designing GaAs FET VCO's in the *C*-, *X*-, and *Ku*-bands to be realized in integrated and in hybrid form. Presented here are the results of the hybrid realizations. We have investigated mostly the following circuit configurations: a) series capacitive feedback in the source with the varactor connected to the gate, output at the drain; and b) series inductive feedback in the drain, output at the source, and the varactor connected to the gate.

Using the same varactor and FET, both configurations have shown identical bandwidth capability. The series capacitive feedback is easier to operate at lower frequencies, while the series inductive feedback should be preferred for higher frequencies.

We have designed two families of VCO's, one from 6 to 12 GHz and the other at 12 to 18 GHz. According to our design method, the maximum obtainable bandwidth for the given FET and varactor is 7–12 GHz and 13–18 GHz, correspondingly.

Table I shows the important parameters of the FET's and varactors used in these circuits.

Following the proposed design and using the parameters given in Table I, we have designed VCO's in the above-mentioned frequency bands.

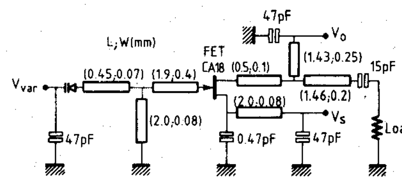


Fig. 2. The 7–12-GHz VCO, realized on 0.25-mm-thick Al_2O_3.

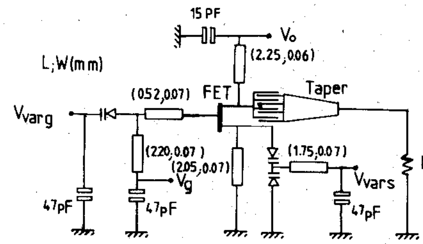


Fig. 3. The 13–18-GHz VCO, realized on 0.25-mm-thick Al_2O_3.

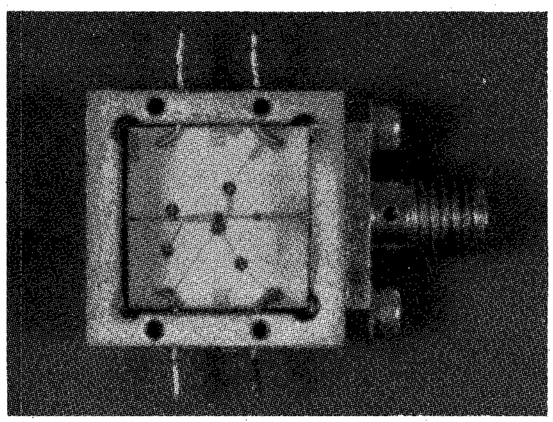


Fig. 4. The *X*-band VCO.

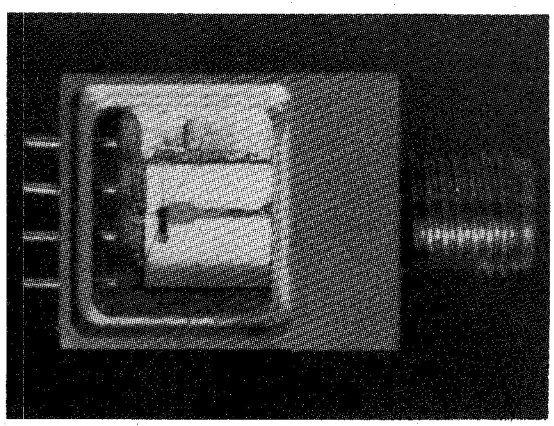


Fig. 5. The *Ku*-band VCO.

Table II gives a comparison between predicted optimum tuning bandwidths and obtained results. It must be emphasized that no adjusting of the circuits has been foreseen, such measures being almost impossible to employ due to the miniature size of the circuits. The active part of the 7–12-GHz VCO, shown in Fig. 2, is 7×7 mm^2, while the same part of the 13–18-GHz VCO, shown in Fig. 3, is 5×5 mm^2, including all the bias circuitry (see Figs. 4 and 5).

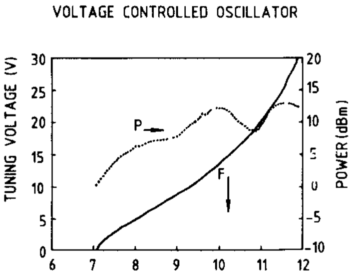


Fig. 6. Tuning characteristic of the 7–12-GHz VCO.

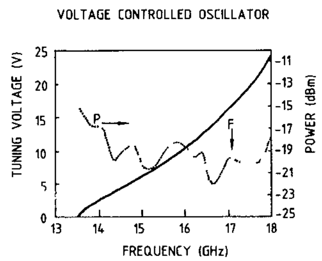


Fig. 7. Tuning characteristic of the 13–18-GHz VCO.

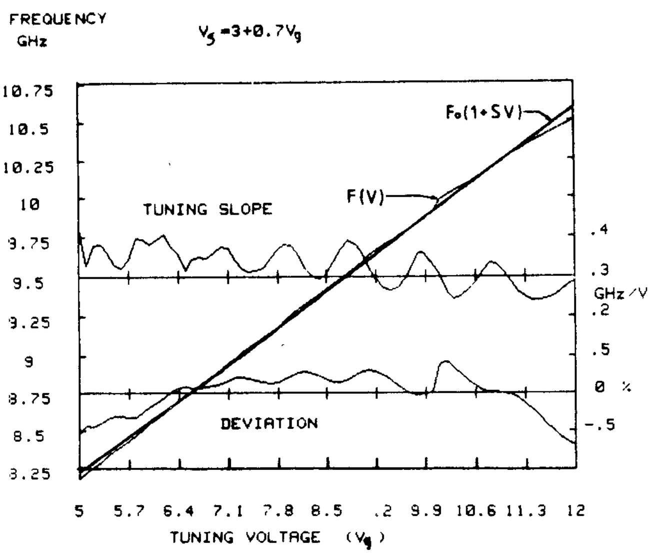


Fig. 8. Linearity for the 7–12-GHz VCO.

An important point to notice is that the measured value of 1.67 for f_{max}/f_{min} is higher than the predicted value of 1.6; this is not necessarily a contradiction concerning bandwidth since we deal with different f_{max} values. In fact, the predicted bandwidth was 4.9 GHz and the measured bandwidth was 4.875 GHz.

Figs. 6 and 7 illustrate the measured tuning characteristics of these two VCO's.

IV. Tuning Linearity

Up to now, we have presented a VCO design method without paying attention to the tuning linearity. The second varactor is used to increase the tuning bandwidth. However, it can also improve the linearity.

Let us consider two varactors of the same type but with different sizes, the voltages V_g and V_s applied to the two varactors being linear functions of the input voltage V

$$V_g = V_{go} + K_g \cdot V$$
$$V_s = V_{so} + K_s \cdot V.$$

Such relations can easily be realized with a simple resistor circuit which is integrable.

The capacitances are given by $C_g(V_g) = C_{go} \cdot C(V_g)$, $C_s(V_s) = C_{so}(V_s)$. The function $C(V)$ depends on the doping profile of the varactors, and is the same for both varactors. The VCO is linear if any frequency F can be obtained with an input voltage $V = F + V_o$. We introduce the $C(V)$ curve in our program and ask it to optimize the values of C_{go}, C_{so}, V_{go}, V_{so}, K_g, and K_s and of the other elements of the circuit in order to obtain the maximum linearity over a given bandwidth. As starting values, we use the results of the optimization described in Section II (maximum tuning bandwidth).

Applied to the *Ku*-band VCO, this optimization has shown that C_{so} has to be much smaller than C_{go}. Finally, putting two identical varactors in series at the source improved linearity without degrading bandwidth.

The 7–12-GHz VCO has been optimized with C_{go} and C_{so} held constant (Fig. 8). We obtained a frequency deviation from the linear tuning law of ± 30 MHz from 7 to 10 GHz. This value is comparable to the linearity of YIG-tuned oscillators (typical value of *X*-band YTO: ± 10 MHz). Expressed in tuning sensitivity variation terms, the linearizing method contributes an improvement from a ratio of 0.23 GHz/V to 0.11 GHz/V (≈ 2.1) to a ratio of 0.23 GHz/V to 0.15 GHz/V (≈ 1.5).

V. Conclusions

We present a simple method that allows us to design maximum-bandwidth VCO's. Its main advantages are 1) the avoidance of time consuming iterations for frequency determination, 2) easy determination of starting conditions, and 3) an optimization strategy that allows us to find the maximum tuning bandwidth for a given active device and varactor. Using this method, we have designed and realized a 7–12-GHz and a 13–18-GHz FET VCO in hybrid technology. Using a second varactor in the feedback network of these VCO's, we have been able to reduce the tuning nonlinearity to ± 30 MHz for a 3-GHZ tuning bandwidth at 10 GHz.

Acknowledgment

The authors acknowledge the contribution of J. C. Meunier and P. Talbot for the MIC realizations. P. Huguet and J. Bellaiche supplied the CA18 GaAs FET's.

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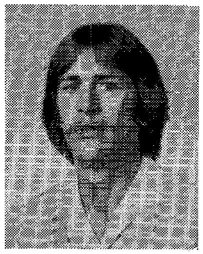

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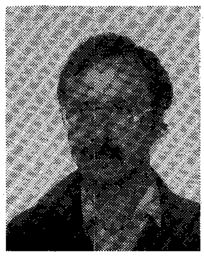

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