Oscillator Design for Maximum Added Power

Brian K. Kormanyos and Gabriel M. Rebeiz, *Senior Member, IEEE*

Abstract—**We report on a linearized technique for the determination of embedding networks that maximize the added power in a two-port oscillator design. The embedding networks are similar to the optimum networks presented by Kotzebue [1], but they are determined without the assumption of a constant voltage at the input port of the active device. The method presented here will result in a more accurate determination of the embedding networks for maximum power output from a device with a given set of two-port parameters.**

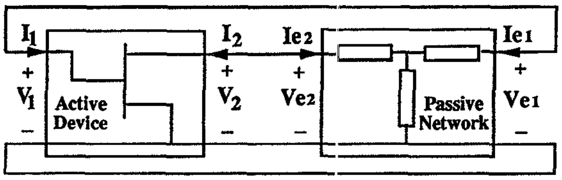

Fig. 1. Equivalent circuit for generalized two-port oscillator design.

I. Introduction

IN THE generalized problem of oscillator design using a two-port active device (Fig. 1), it has been shown [2], [3] that the embedding networks for oscillating systems are those that result in net power flow out of the active device.

The total power delivered to the device is given by:

$$P = \tfrac{1}{2}Re(\mathbf{V}_1^*\mathbf{I}_1 + \mathbf{V}_2^*\mathbf{I}_2), \tag{1}$$

where P is negative for net power flow out of the device. The complex ratio of the port 2 voltage ($\mathbf{V}_2$) and the port 1 voltage ($\mathbf{V}_1$) is defined as:

$$\mathbf{A} = A_r + jA_i = \mathbf{V}_2/\mathbf{V}_1 \tag{2}$$

The active device is described by a Y-parameter matrix:

$$\begin{bmatrix}\mathbf{I}_1\\ \mathbf{I}_2\end{bmatrix} = \begin{bmatrix}\mathbf{y}_{11} & \mathbf{y}_{12}\\ \mathbf{y}_{21} & \mathbf{y}_{22}\end{bmatrix}\begin{bmatrix}\mathbf{V}_1\\ \mathbf{V}_2\end{bmatrix} \tag{3}$$

The total power delivered to the active device can be expressed in terms of $\mathbf{V_1}$, A_r, A_i and the Y-parameters:

$$P = [g_{11}+g_{22}(A_r^2+A_i^2)+(g_{12}+g_{21})A_r-(b_{12}-b_{21})A_i]\cdot|\mathbf{V}_1|^2, \tag{4}$$

where g_{ij} and b_{ij} are the real and imaginary parts, respectively, of $\mathbf{y}_{ij}$. When $|\mathbf{V}_1|$ is assumed to be a constant, the values of the real and imaginary parts of $\mathbf{A}$ that result in the negative minimum of P correspond to the maximum power output from the device. The value of $\mathbf{A}$ that corresponds to this optimum point can be found from the partial derivatives of (4) with respect to A_r and A_i. This value is given by [2], [3]:

$$\mathbf{A}_{opt} = -\frac{\mathbf{y}_{21} + \mathbf{y}^*{}_{12}}{2g_{22}} \tag{5}$$

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The authors are with the NASA/Center for Space Terahertz Technology, Electrical Engineering and Computer Science Department, University of Michigan, Ann Arbor, MI 48109-2122 USA.

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When the value of $\mathbf{A}$ is chosen, an embedding network may be synthesized in any one of three series or three shunt configurations given by Kotzebue [1] and shown in Fig. 2. This is possible because an oscillator at steady state will have the following relationships between the voltages and currents of the active device and the voltages and currents of the embedding network:

$$\begin{aligned}\mathbf{V}_1 &= \mathbf{V}_{e1} \quad \mathbf{V}_2 = \mathbf{V}_{e2}\\ \mathbf{I}_1 &= -\mathbf{I}_{e1} \quad \mathbf{I}_2 = -\mathbf{I}_{e2}\end{aligned} \tag{6}$$

Johnson [4] has indicated that a good starting point for designing the embedding network for an oscillator is to use the Y-parameters of the active device at the gain compression point corresponding to the maximum oscillator power. This value of gain is given by:

$$G_{ME}(\text{max oscillator power}) = \frac{G_o - 1}{\ln G_o} \tag{7}$$

where G_o and G_{ME} are the small signal uncompressed and large signal compressed values, respectively, of the maximum efficient gain defined by Kotzebue [5]. The Y-parameters at this point can be estimated by reducing the transconductance in the equivalent circuit of the active device or by simply reducing the magnitude of the S-parameter $\mathbf{S}_{21}$ until the desired value of gain is obtained [4].

II. Maximum Two-Port Added Power

Unfortunately, it is not clear that the magnitude of the port 1 voltage ($\mathbf{V}_1$) will remain constant for all values of $\mathbf{A}$. A better way to maximize the output power is to determine the value of $\mathbf{A}$, which gives the maximum two-port added power (8) for the oscillating system. The two-port added power is defined as:

$$\text{Added Power} = P_{out} - P_{in} \tag{8}$$

The added power in a two-port oscillator design can be maximized by the method described below:

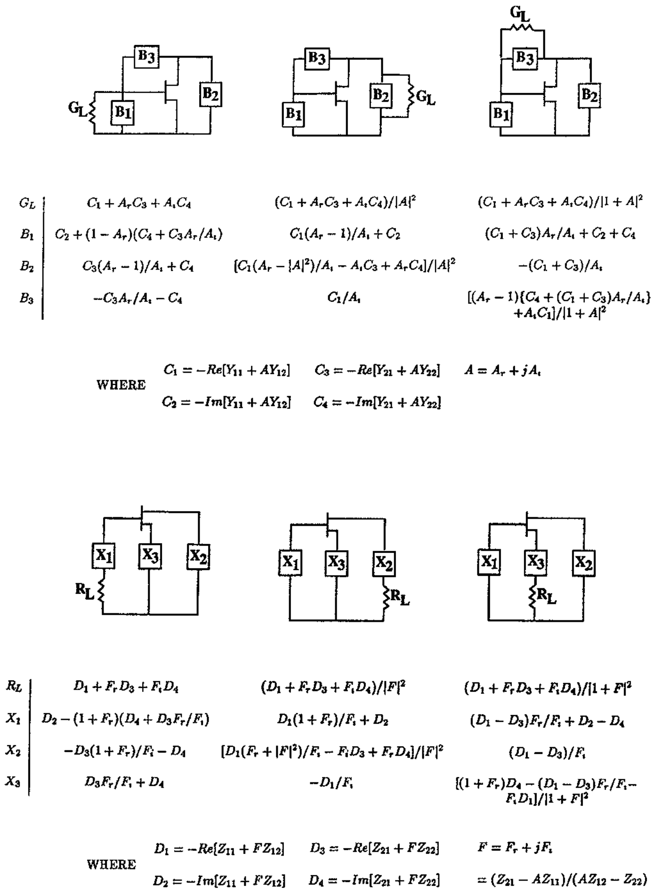

Fig. 2. Embedding networks for three shunt and three series configurations.

The power delivered to port 2 ($P_2 = -P_{out}$) is taken to be any arbitrary negative constant (power is going out), and the power delivered to port 1 ($P_1 = P_{in}$), which is positive (power is going in), is minimized. Since the phase in the oscillating system is arbitrary, we can select the phase angle of $\mathbf{V}_2$ to be zero ($\mathbf{V}_2 = V_{2r}$). This establishes a relationship between the real part of $\mathbf{I}_2$ (denoted by I_{2r}) V_{2r} and the negative power delivered to port 2 (P_2).

$$P_2 = \tfrac{1}{2}Re(\mathbf{V}_2^*\mathbf{I}_2) = \tfrac{1}{2}V_{2r}I_{2r} \qquad \text{and} \qquad I_{2r} = 2P_2/V_{2r} \tag{9}$$

The imaginary part of $\mathbf{I}_2$ (denoted by I_{2i}) and V_{2r} are taken as independent variables. The real part of $\mathbf{I}_2$ is a function of P_2 and V_{2r} given by (9). The imaginary part of V_2 has been set to zero. The current and voltage at port 1 ($\mathbf{V}_1$, $\mathbf{I}_1$) are functions of the port 2 variables as determined from the Y-parameter matrix (3). The power delivered to port 1 is given by:

$$P_1 = \frac{1}{2}Re(\mathbf{V}_1^*\mathbf{I}_1) \tag{10}$$

where

$$\mathbf{V}_1 = \frac{\mathbf{I}_2 - \mathbf{y}_{22}\mathbf{V}_2}{\mathbf{y}_{21}} \qquad \mathbf{I}_1 = \mathbf{y}_{11}\left(\frac{\mathbf{I}_2 - \mathbf{y}_{22}\mathbf{V}_2}{\mathbf{y}_{21}}\right) + \mathbf{y}_{12}\mathbf{V}_2 \tag{11}$$

The input power can be minimized by taking the partial derivatives of P_1 in terms of V_{2r} and I_{2i}, and setting them equal to zero. The corresponding values of the independent port 2 variables for maximum added power are:

$$I_{2_i} = -\frac{V_2(g_{12}b_{21} + g_{21}b_{12} - 2g_{11}b_{22})}{2g_{11}}$$

$$V_{2r} = 2 \cdot \sqrt[4]{\frac{P_2^2 g_{11}^2}{N}} \tag{12}$$

where:

$$N = 4g_{11}g_{22}(g_{11}g_{22} + b_{12}b_{21} - g_{12}g_{21}) - (g_{12}b_{21} + g_{21}b_{12})^2$$

The port 1 variables ($\mathbf{V}_1$, $\mathbf{I}_1$) can be calculated from these optimum port 2 variables through the Y-parameters (11). The value of $\mathbf{A}_{opt}$ is given by $\mathbf{V}_2/\mathbf{V}_1$:

$$\mathbf{A}_{opt} = \frac{-2g_{11}\mathbf{y}_{21}}{\sqrt{N} + 2g_{11}g_{22} + j \cdot (g_{12}b_{21} + g_{21}b_{12})} \tag{13}$$

The embedding networks may then be synthesized as before. The ratio of the arbitrary constant $P_2 = -P_{out}$ and the minimum input power at port 1 (P_1) is equal to the maximum power gain of the active device. This optimization of $\mathbf{A}$ is equivalent to simultaneously matching the input and output ports for maximum added power in the feedback loop.

The gain-compressed Y-parameters for maximum oscillator power described by Johnson [4] should be used in the calculation of $\mathbf{A}_{opt}$. Oscillator start up should be carefully checked since there may be a phase shift between the small signal Y-parameters and the large signal (gain-compressed) Y-parameters. In general, the uncompressed power gain of the device will be higher at oscillator start up and the amplitude of the signal in the system will increase until the power gain compresses to the point given by the Y-parameters used in deriving the embedding network. Gain compression beyond this point will be impossible because the power feedback through the embedding network will be insufficient for operation at any lower gain value. Thus, maximum oscillator power will be delivered to the load because the minimized port 1 input power (P_1) will insure operation at the gain compression value for maximum oscillator power (7), and any power not fed back to the input must be dissipated in the embedding network that includes the load. Numerical examples (Table I) using the 20-GHz gain-compressed Y-parameters of typical GaAs MESFET's show that the values of $\mathbf{A}_{opt}$ determined with this new optimization method are

TABLE I

VALUES OF $\mathbf{A}_{opt}$ CALCULATED AT G_{ME}(MAX OSCILLATOR POWER) FOR TWO GaAs MESFET'S AT 20 GHZ. THE FLR016XV IS A MEDIUM-POWER DEVICE. THE NE32100 IS DESIGNED FOR SMALL SIGNAL LOW NOISE APPLICATIONS

Device	G_{ME} (at max osc. power)	$\mathbf{A}_{opt}$ (constant $\lvert\mathbf{V}_1\rvert$)	$\mathbf{A}_{opt}$ (max added power)
FLR016XV (Fujitsu)	5.5 dB	2.28 + j 13.05	3.19 + j 10.73
NE32100 (NEC)	6.3 dB	-1.00 + j 1.26	-1.10 + j 0.478

different from those determined from (5). The differences are not extremely large, which accounts for the experimental success of oscillators constructed under the assumption that $|\mathbf{V}_1|$ is constant [1,3,4,6]. This new method, however, is expected to result in more accurate determination of the embedding networks for maximum output power.

At a constant DC bias point, with a given set of two-port parameters, the point of maximum output power is also the point of maximum DC-RF efficiency [6]. For a given device under varying DC bias, however, the point of maximum power and maximum DC-RF efficiency are likely to be different. The magnitude of the port 2 RF voltage ($\mathbf{V}_2$) and current ($\mathbf{I}_2$) for the device in the optimum embedding network should be iteratively calculated to determine if voltage or current limits set by the DC bias conditions [3] will prevent the oscillator from reaching its maximum power output. If this occurs, it may be helpful to choose a different value for **A** or appeal to a simple load line analysis [7].

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