A DOUBLE-PUMPED LOW-NOISE PARAMETRIC DOWN-CONVERTER*

by

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Introduction

It is well known in the theory of single-pumped parametric amplifiers[1] that the parametric down-converter is inherently very noisy if there is no cooling in the output circuit. This is largely responsible for its limited application in converting a microwave frequency into a low intermediate frequency. In this paper a theoretical discussion is given of a low-noise uncooled parametric down-converter which is realised by using two unsynchronised pump generators at different frequencies.

A Double-Pumped Parametric System

Consider a nonlinear capacitance pumped by two sources at frequencies f_{p1} and f_{p2}. The double-pumped varactor capacitance is assumed to be of the form

$$C(t) = C_0 + \frac{\bar{C}_1}{2} e^{j\omega_{p1} t} + \frac{\bar{C}_1^*}{2} e^{-j\omega_{p1} t} + \frac{\bar{C}_2}{2} e^{j\omega_{p2} t} + \frac{\bar{C}_2^*}{2} e^{-j\omega_{p2} t} \qquad (1)$$

Here $\bar{C}_1 = C_1 e^{j\phi_1}$ and $\bar{C}_2 = C_2 e^{j\phi_2}$ are phasors.

Because the varactor is pumped by two independent generators of different frequencies, the number of intermodulation products and hence the number of possible modes of operation is increased many times over the single pumped case. Let us consider a particular system having a frequency scheme as shown in Fig. 1. The system is characterised by: (a) f_1, f_{p1} and f_{p2} which are the input

* Work supported by the Australian Research Grants Committee and the Colombo Plan.

signal frequency and the two pump frequencies respectively; (b) $f_3 \triangleq f_{p2} - f_{p1} + f_1$ (c) $f_2 \triangleq f_{p1} - f_1$ and (d) there is no power flow at frequencies other than f_{p1}, f_{p2}, f_1, f_2 and f_3.

The extended Manley-Rowe relations [2] for multiple pump generators when applied to this system reveal that the time-varying capacitance supplies power at f_2 and f_3 as well as at the signal frequency f_1, rather than absorbing it. This of course gives rise to a regeneration condition.

With the simplifying assumptions that: (a) signals at f_1, f_2 and f_3 are regarded as "small signals", (b) $C(t)$ is given by relation (1), and (c) all other unwanted harmonics are short-circuited, then the small signal currents and voltages of the nonlinear capacitance are related by the "small signal admittance" matrix via the following[3].

$$\begin{bmatrix} I_1 \\ I_2^* \\ I_3 \end{bmatrix} = \begin{bmatrix} j\omega_1 C_0 & \frac{j\omega_1 \bar{C}_1}{2} & 0 \\ \frac{-j\omega_2 \bar{C}_1^*}{2} & -j\omega_2 C_0 & \frac{-j\omega_2 \bar{C}_2^*}{2} \\ 0 & \frac{j\omega_3 \bar{C}_2}{2} & j\omega_3 C_0 \end{bmatrix} \cdot \begin{bmatrix} V_1 \\ V_2^* \\ V_3 \end{bmatrix} \qquad (2)$$

where I_n and V_n (n=1, 2, 3) represent the current and voltage phasors at f_n respectively.

The Down-Conversion Operation

The double-pumped parametric system described can be operated as a down-converter provided that $f_{p1} > f_{p2}$ so that $f_3 < f_1$. Then f_3 is taken to be the output frequency and the remaining frequency f_2 is termed the "idler frequency". The circuit arrangement is shown in Fig. 2 where each external admittance Y_n (n=1,2,3) at frequency f_n has a real part G_n representing the combined circuit and diode loss associated with f_n, and an imaginary part B_n being the external susceptance which matches the fixed susceptance, associated with $C(t)$, at the midband frequency of f_n.

Three circuit equations, one for each port, can be readily written for the linear time-invariant part of the circuit which together with equation (2) completely permit the determination of all the small-signal characteristics of the converter.

Before presenting the various results obtained, it is convenient to define certain symbols as follows:

$$a_{12} \triangleq \frac{\omega_1\omega_2 C_1^2}{4(G_1+G_g)(G_2+G_I)} ; \qquad a_{23} \triangleq \frac{\omega_2\omega_3 C_2^2}{4(G_2+G_I)(G_3+G_L)}$$

$$b \triangleq (G_1+G_g)/(G_2+G_I); \quad c \triangleq (G_1+G_g)/(G_3+G_L) ; \quad T_0 = 290°K$$

Then the circuit characteristics of interest are

Input Conductance: $G_{in} = -a_{12}(G_1+G_g)/(1-a_{23})$ at centre band.

Output Conductance: $G_0 = -a_{23}(G_3+G_L)/(1-a_{12})$ at centre band.

Transducer Gain: $$g_t = \frac{\omega_3}{\omega_1} \cdot \frac{G_g}{(G_g+G_1)} \cdot \frac{G_L}{(G_L+G_3)} \cdot \frac{4a_{12}a_{23}}{(1-a_{12}-a_{23})^2}$$

Voltage Gain - Fractional Bandwidth Product:

$$\sqrt{g_t}\text{-}B = (\omega_2\omega_3/\omega_1)(C_1C_2/2C_0)(G_gG_L)^{\frac{1}{2}}\{(G_2+G_I)(G_3+G_L)(1-a_{23}-ca_{12}+b+c)\}^{-1}$$

Noise Figure:

$$F = 1 + \frac{T}{T_0} \cdot \frac{G_1}{G_g} + \frac{\omega_1}{\omega_2} \cdot \frac{T}{T_0} \cdot \frac{G_g+G_1}{a_{12}G_g} + \frac{\omega_1}{\omega_3} \cdot \frac{T}{T_0} \cdot \frac{G_1+G_g}{G_g} \cdot \frac{a_{23}}{a_{12}}$$

for high gain condition, i.e. $(1-a_{12}-a_{23}) \doteq 0$, and all circuit components are assumed for simplicity, to be at the same ambient temperature T.

Discussion

It is readily recognised that in the noise figure expression, the first two terms are the contribution from the input circuit; the third term is that from the idler circuit, one which is not present in the single-pumped case; and the last term is from the output circu including the load - the most significant term of all.

Now for a high gain condition and with a_{12} made almost unity and a_{23} very small, the noise due to the idler circuit can be made rather small, because the idler frequency f_2 can be made several times the signal frequency f_1. Considerably more important is the fact that the large noise component due to the load circuit is now not so significant compared with the single-pumped case because of the small factor a_{23}/a_{12}. Thus the strong dependence on the output frequency f_3 of the noise figure is roughly reduced by the factor a_{23}/a_{12} making low-noise down-conversion with reasonably good voltage gain-bandwidth product a highly likely proposition without cooling the output circuit.

References

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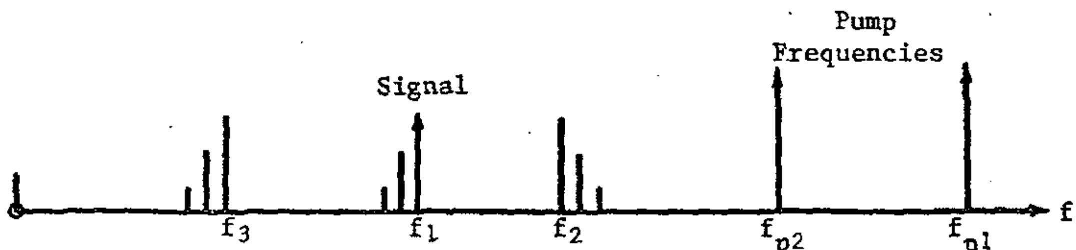

Fig. 1. Frequency Spectrum of the Double-pumped Parametric System

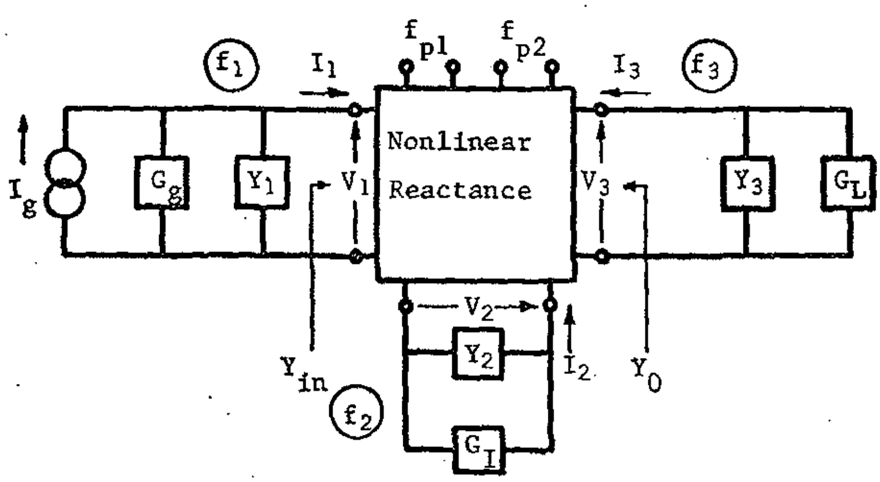

Fig. 2. Circuit Model for the Double-Pumped Down-Converter