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COMPUTER-AIDED DESIGN OF MULTIPLE-VARACTOR BROADBAND VCO's BY A NOVEL OPTIMISATION ALGORITHM

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Abstract. The paper introduces a novel approach to broadband nonlinear oscillator optimisation, making use of the harmonic-balance (HB) technique as the basic circuit analysis algorithm. The key idea is give the optimizer direct control of the magnitude of one harmonic (usually the output fundamental), and to replace the latter by a circuit parameter in the inner analysis loop. In this way the degenerate solution(s) of the HB system are suppressed, and the number of iterations required to achieve a prescribed performance is drastically reduced. The resulting CAD tool is particularly well-suited for systematically tackling complex problems such as broadband multiple-varactor VCO design.

1. INTRODUCTION

The traditional approach to nonlinear microwave circuit design by numerical optimisation normally relies upon the nesting of two search loops [1]: the inner one is a harmonic-balance analysis based on the Newton iteration, and the outer one is a minimisation loop driven by a gradient-based algorithm. Although this scheme is quite efficient and well behaved for applications to non-autonomous (forced) circuits such as amplifiers and mixers, it suffers from a major drawback when it comes to autonomous (e.g., oscillator) circuit design [2]. Autonomous circuits are fed by DC bias sources only, and normally do not include any RF forcing generator. Thus the HB solving system for such circuits always admits at least one degenerate solution, for which only the DC components of the state variables (and thus of all the voltages and currents supported by the circuit) are nonzero, and no oscillation exists. When designing a broadband circuit such as a VCO, this may lead to serious ill-conditioning of the numerical optimisation process in a twofold way: i), it is very difficult to find by some simple criterion (such as negative-resistance considerations) a starting-point circuit topology such that the first Newton iteration converges to an oscillatory state at all the (discrete) design frequencies selected across the prescribed tuning band; ii), even though i) may be overcome, at any point during the subsequent optimisation the oscillator analysis may converge to a degenerate solution, so that lengthy one-dimensional searches may become necessary to recover the oscillation at all design frequencies. In this paper we introduce a novel design strategy for broadband tunable oscillators whereby the above difficulties can be neatly eliminated, and a well-conditioned optimi-sation can be systematically started and efficiently performed without any special a priori knowledge of the circuit topology nor of the state-variable (SV) harmonics.

2. THE OPTIMISATION STRATEGY

The concept underlying the new optimisation approach will be referred to as the *substitution algorithm*. The key idea may be explained as follows. In an ordinary optimisation the minimisation algorithm directly controls the circuit topology, and the circuit state is obtained by nonlinear HB analysis. From here the electrical performance is derived and fed back to the optimiser for the generation of the next topology update through a comparison with the design goals. With the substitution algorithm this closed-loop architecture is partly replaced by an open-loop structure. A state component directly related to the output power, usually the magnitude of a suitable harmonic, is treated as a design variable and is replaced by a circuit parameter in the state vector. In this way the optimiser gains direct control of one of the key performance indexes, and at each step the circuit topology is *tuned* to match the prescribed performance by solving a modified harmonic-balance system by an efficient Newton iteration. The essential point is that the modified HB system does no longer admit any degenerate solution, because one of the SV harmonics is forced to be nonzero. Thus the problems of the traditional approach are effectively suppressed while fully preserving the numerical efficiency of the HB-based optimisation.

3. APPLICATION TO MULTIPLE-VARACTOR VCO's

In order to gain a clearer insight into the computer implementation of the substitution algorithm, let us refer to the case of a dual-varactor broadband VCO of the kind illustrated in fig. 1. No fully automated CAD procedure for this important class of circuits has been available until now in the technical literature, although the use of HB simulation in support of linearized or empirical design approaches has been reported [3] - [6]. On the other hand, this case allows an effective exploitation of our novel optimisation technique. At each frequency of oscillation, the unknowns of a conventional HB analysis would be the real and imaginary parts of the SV harmonics. However, since the circuit is autonomous, the phase of a reference harmonic (e.g., the fundamental of the drain voltage) is undetermined, and can be set to an arbitrary value, such as zero. Furthermore, with the substitution algorithm the magnitude of the drain voltage, say M, is also extracted from the state vector, and is treated as an optimisation variable, in order to suppress the degenerate solutions, as explained above. This leaves us with a harmonic-balance solving system with a number of equations exceeding the number of unknowns by two. In order to reobtain a well-posed system, we treat the gate and source varactor tuning voltages as additional unknowns, so that the correct number of unknowns is restored. The nonlinear system may then be solved by an efficient Newton iteration for any prescribed frequency and value of M. The optimisation variables are the linear circuit parameters and the values of M associated with all the design frequencies. Each Newton iteration simultaneously produces the oscillatory steady state and the varactor bias voltages required to tune the oscillator to the prescribed frequency and magnitude of the drain voltage harmonic.

4. AN EXAMPLE OF APPLICATION

Some preliminary results obtained by the above technique for the topology shown in fig. 1, are reported in this section. Fig. 2 shows the measured varactor capacitance and series resistance [4], that are directly taken into account in the numerical design process. The two varactors are assumed to be identical. Figs. 3 and 4 show the results of a broadband optimisation in the 7.5 - 12 GHz band, for an output power $\geq$ +12 dBm. The DC components of the varactor voltages are plotted in fig. 3 as a function of frequency, and the fundamental output power is given in fig. 4. The overall optimisation time is about 1200 seconds on a SUN SPARCstation 10.

REFERENCES

[1] V. Rizzoli, A. Lipparini, A. Costanzo, F. Mastri, C. Cecchetti, A. Neri, and D. Masotti, "State-of-the-art harmonic-balance simulation of forced nonlinear microwave circuits by the piecewise technique", *IEEE Trans. Microwave Theory Tech.*, Vol. 40, Jan. 1992, pp. 12-28.

[2] V. Rizzoli, A. Costanzo, A. Lipparini, C. Cecchetti, and A. Neri, "Opimization-oriented design of free-running and tunable microwave oscillators by fully nonlinear CAD techniques", *Int. Journal Microwave Millimeter-Wave Computer-Aided Eng.*, vol. 7, Jan. 1997, pp. 52-74.

[3] B.N. Scott and G. E. Brehm, "Monolithic voltage controlled oscillator for X- and Ku-bands", *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-30, Dec. 1982, pp. 2172-2177.

[4] E. Reese and J. M. Beall, "Optimized X & Ku band GaAs MMIC varactor tuned FET oscillators", *1988 IEEE MTT-S Int. Microwave Symp. Digest*, New York, NY, May 1988, pp. 487-490.

[5] J. E. Andrews, T. J. Holden, K. W. Lee, and A. J. Podell, "2.5 - 6.0 GHz broadband GaAs MMIC VCO", *1988 IEEE MTT-S Int. Microwave Symp. Digest*, New York, NY, May 1988, pp. 491-494.

[6] K. Kamogawa, K. Nishikawa, C. Yamaguchi, M. Hirano, I. Toyoda, and T. Tokumitsu, "A very wide-tuning range 5-GHz-band Si bipolar VCO using three-dimensional MMIC technology", *1997 IEEE MTT-S Int. Microwave Symp. Digest*, Denver, CO, June 1988, pp. 1221-1224.

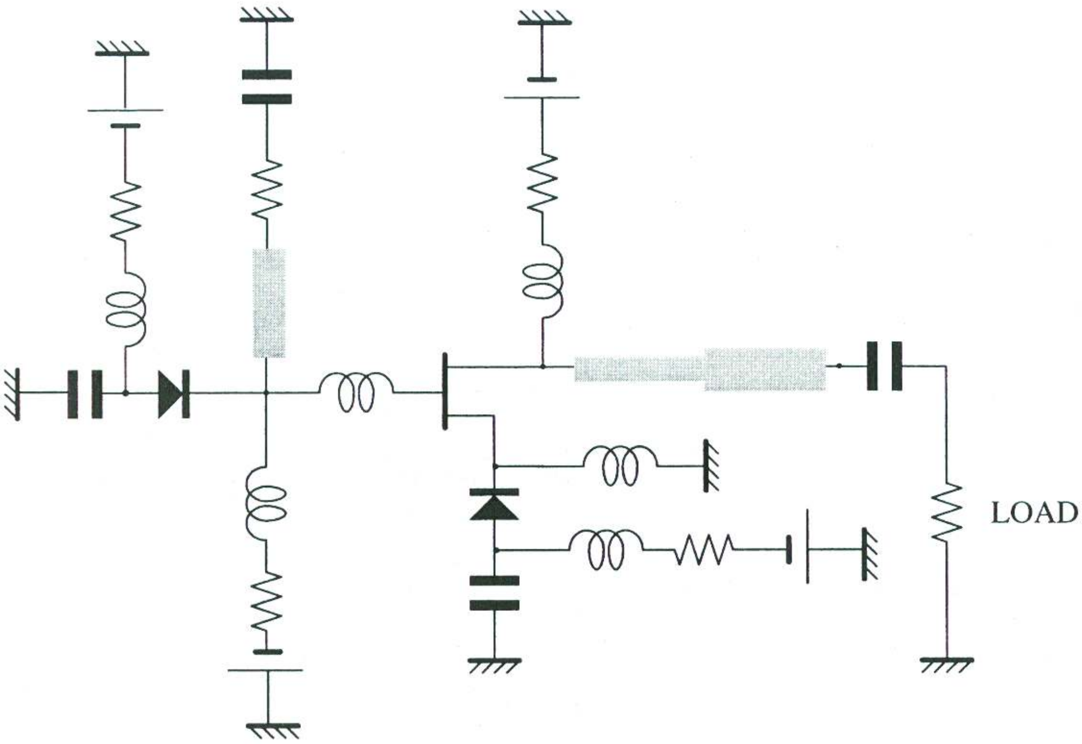

Fig. 1 - Schematic topology of a dual-varactor broadband VCO

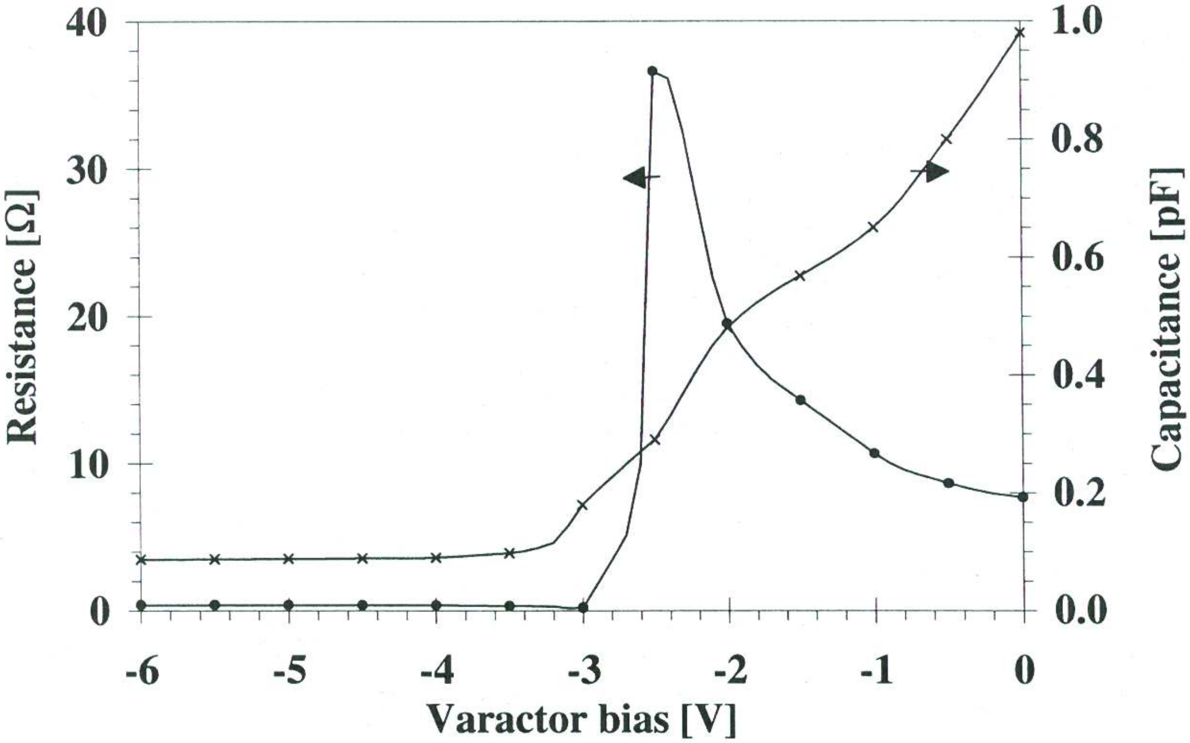

Fig. 2 - Measured varactor capacitance and series resistance

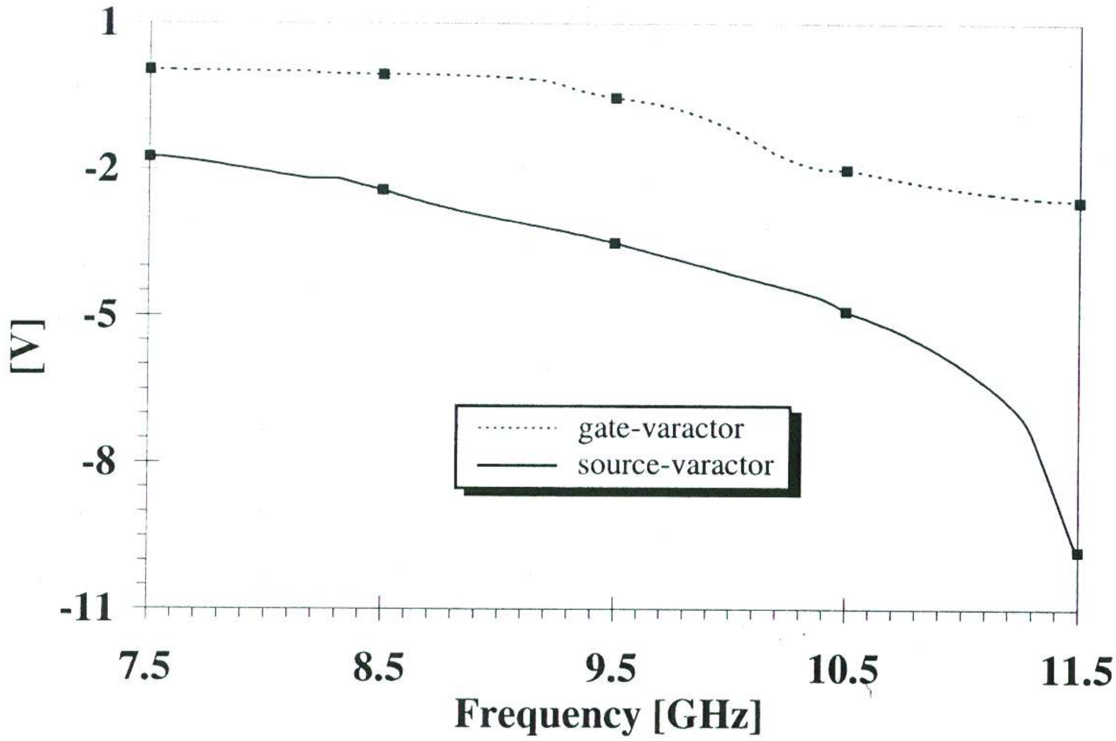

Fig. 3 - DC components of the varactor voltages

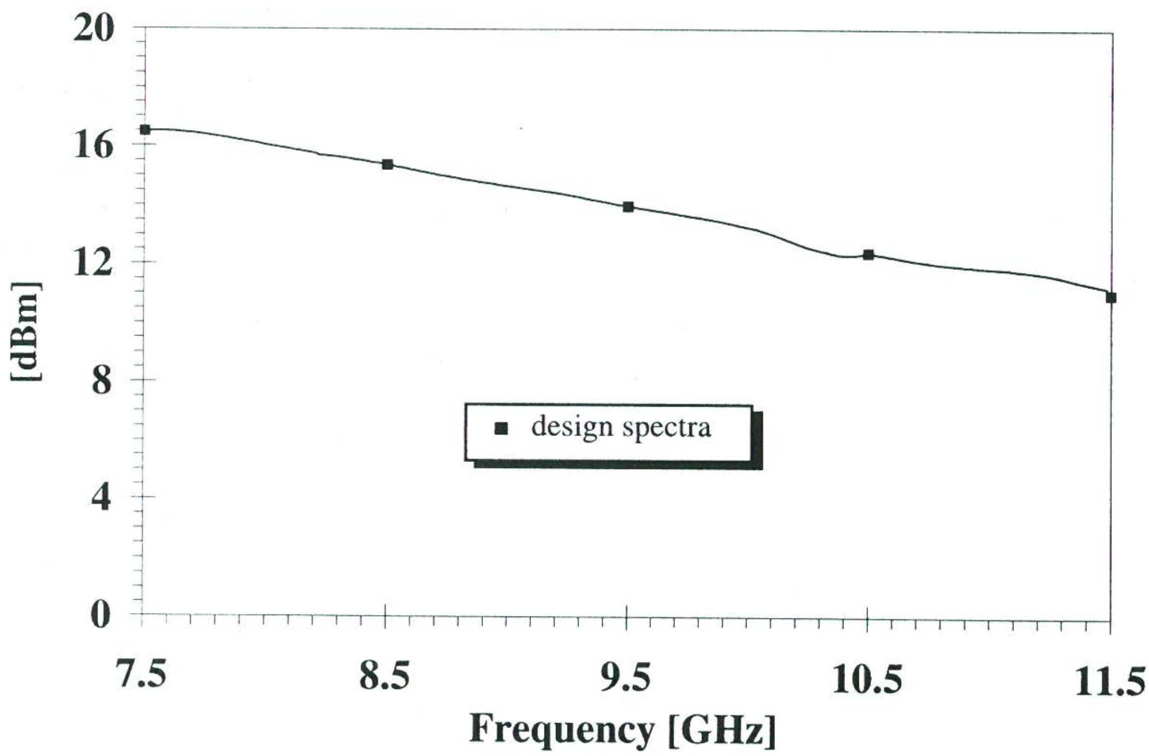

Fig. 4 - Optimized VCO output power