BIFURCATION ANALYSIS OF SYNCHRONIZED MICROWAVE CIRCUITS USING COMMERCIAL SOFTWARE

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ABSTRACT

In this paper a new method is proposed for obtaining the complete synchronization curves of injected oscillators or analog frequency dividers, using harmonic balance (HB) commercial simulators. The bifurcation loci on the *input power-input frequency* plane, globally providing the circuit operating bands can also be obtained. The new method offers an invaluable aid to microwave designers, avoiding the need for specific in-house simulation tools and taking advantage of the flexibility and friendliness of standard commercial software. The method is illustrated by means of its application to the design of a frequency divider by two, obtaining for the first time, to our knowledge, complete synchronization curves and bifurcation loci from a commercial simulator. Under some modifications, the method is applicable to tuned circuits. Simulation and measurements of a MMIC VCO are shown for experimental validation.

INTRODUCTION

Circuits in synchronized operation often exhibit multi-valued responses, specially for low input generator power [1], [2], for which the synchronous solutions coexist with unstable ones, forced by the external generators. As will be shown, the HB commercial simulators converge by default to the latter, with no synchronization actually observed. In this paper, this undesired convergence is avoided by means of a new method that also enables the tracing of the whole synchronization curves from HB commercial simulators. The analysis technique is based on the minimization, using the commercial software optimization tools, of the total immittance function at the synchronized or subharmonic frequency, taking the amplitude and phase at the observation port as the optimization variables. This is done through the use of an auxiliary generator. When tracing the immittance diagrams on a polar plot, the intersection with the origin will provide the synchronized solutions. The solution is estimated from these diagrams and then corrected through optimization of the auxiliary generator amplitude and phase, in order to minimize the immittance absolute value.

When varying the input frequency, the solution curves will be closed for low input generator power and will often exhibiting hysteresis phenomena for medium input power [3]. Here they are obtained by means of a new continuation technique, that takes advantage of the use of this auxiliary generator and is easily applicable to commercial HB simulators. In this technique, from a given solution point, previously determined, the next point of the path is obtained by the optimization of two of three possible variables, constituted by the auxiliary generator amplitude and phase and the *physical* parameter (usually the injection generator amplitude or frequency). The variable among the three showing the biggest variations will be considered as the *analysis* parameter, thus limiting its increment and assuring the convergence through turning points. This reduction in the number of variables, allowed by the use of the auxiliary generator and the control that it provides over the circuit solution, enables the easy application of this technique to commercial software. This continuation technique can also be combined with simple optimization conditions in order to obtain the circuit bifurcation loci [2],[3], which on the plane defined by the input frequency and input power will provide, at a glance, the circuit operating bands.

A frequency divider by two is analyzed in this paper, obtaining, for the first time (to our knowledge), its closed synchronization curves and bifurcation loci from a HB commercial simulator. The method can also be applied to tuned circuits, when the analysis is carried out as a function of auxiliary generator frequency instead of its phase. Excellent agreement between measurement and simulation has been obtained in a MMIC VCO.

ANALYSIS METHOD

The analysis method here proposed is based on the use of immittance diagrams [4], which provide the variation of the circuit total immittance as a function of the amplitude and phase at the observation port. Here an admittance analysis will be presented, although a dual one could also be carried out in terms of impedance. The admittance diagrams are obtained by means of an auxiliary voltage generator connected in parallel at the observation port, operating at the injection generator frequency in oscillators or at the subharmonic frequency in frequency dividers. For each amplitude value, as the phase varies from 0 to $2\pi/k$, with k the subharmonic rank, closed curves will be obtained, the possible synchronized solutions being given by the intersections with the origin. When this happens, the generator is no longer perturbing [2] and its value corresponds to that of the circuit voltage at the observation port, obtaining a phase relationship with the injection generator. Estimated solutions can be improved by optimization, using the commercial software standard tools, which, due to the reduced number of optimization variables, is a short time procedure.

For the analysis of the frequency divider, two different kinds of curves should be traced: the synchronization curves, as a function of the input generator frequency, and the bifurcation loci, on the plane *input power-input frequency*. The latter must include the synchronization locus and I-type bifurcation locus [3].

a) Synchronization curves

The synchronization curves provide the output power variation as a function of the input frequency ω_{in}. For tracing them through the new method, the admittance value is minimized by optimizing the auxiliary generator amplitude A and phase ϕ, for each ω_{in} value. However, the HB convergence is difficult near the turning or infinite slope points of the solution curve, which satisfy $\partial A/\partial\omega_{in}=\infty$. This is solved here by switching the optimization variables from (A, ϕ) to (ϕ, ω_{in}), sweeping A instead of ω_{in} and thus inverting the solution curve. The turning points of the curves A-ω_{in} generally provide the borders of the operating bands for low and medium input power [3].

b) Bifurcation loci

The I-type bifurcation locus, providing the parameter values for the onset of a frequency division by two [5], [6], can be directly obtained using the new optimization technique. A negligible amplitude value is imposed to the auxiliary generator, operating at $\omega_{in}/2$, using as possible optimization variables ϕ, ω_{in} and P_{in}. The admittance minimization will be initially carried out on ϕ and ω_{in}, although near the locus turning points these should be switched to ϕ and P_{in}.

Using the new method, the turning point locus can be obtained by taking advantage of the good convergence properties of the (ϕ, ω_{in}) optimization. This allows an accurate determination of the synchronization band borders, satisfying $\partial\omega_{in}/\partial A=0$. In the locus tracing, the border generator values $(A^n, \phi^n, \omega_{in}^n)_{1,2}$, corresponding to the input power P_{in}^n, are used as the initial estimate for P_{in}^{n+1}. At present, this locus cannot be obtained imposing, as in the former case, a single condition in HB commercial simulators, as it involves a derivative calculation of the admittance function [7].

APPLICATIONS

The new simulation technique has been applied to a frequency divider by two, with the schematic shown in fig.1. The transistor that has been used is a HEMT with four 50µm fingers, from the technological process D02AH-PHILIPS. It has been designed for input frequency 18.2 GHz.

For tracing the admittance diagrams the auxiliary generator is connected in parallel with the transistor gate. For P_{in} = 0 dBm and $\omega_{in}/2$=9.1 GHz, the resulting closed diagrams are shown in fig.2. Each curve corresponds to an auxiliary generator amplitude, with phase variations 0 and π. The intersection with the origin provides the synchronized solution, here obtained for A=1.59 V and ϕ=57.3°. The synchronization curves, showing the output power at the divided frequency, for several input power levels are shown in fig.3. The band borders are in each case provided by the left and right turning points of the synchronization curves. No division would be obtained with an standard simulation, as can be gathered from figure 4. There the output power curves at the generator frequency obtained from conventional simulation and through the new method can be compared. Finally, the division region, obtained from the turning point and I-type loci, is shown in fig. 5. Stable frequency division will be obtained inside the loci.

The validity of the simulation method has been proven by its application, under some modifications, to a monolithic Ku band VCO (fig.6). With the aid of the new method it has been possible to predict its multi-valued response. Measurements and simulations showed an excellent agreement. As an example, the simulated and measured output power versus the tuning voltage is shown in fig. 7.

CONCLUSIONS

In this paper a new method is presented to obtain the multi-valued solution curves and bifurcation loci, characteristic of circuits with synchronized behavior, through the use of standard HB simulators. The method is based on the use of immittance diagrams, as a function of the amplitude and phase of an auxiliary generator. A frequency divider by two is analyzed in detail, presenting its closed synchronization curves and bifurcation loci, which, to our knowledge, have been obtained here for the first time from a HB commercial simulator. The method can be adapted to the simulation of tuned circuits. Measurements and simulations of a monolithic VCO showed excellent agreement.

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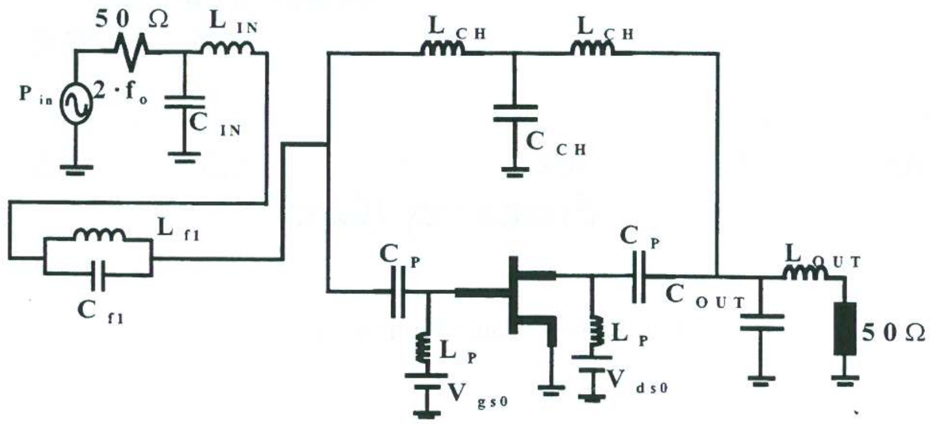

Fig. 1: Frequency divider schematic

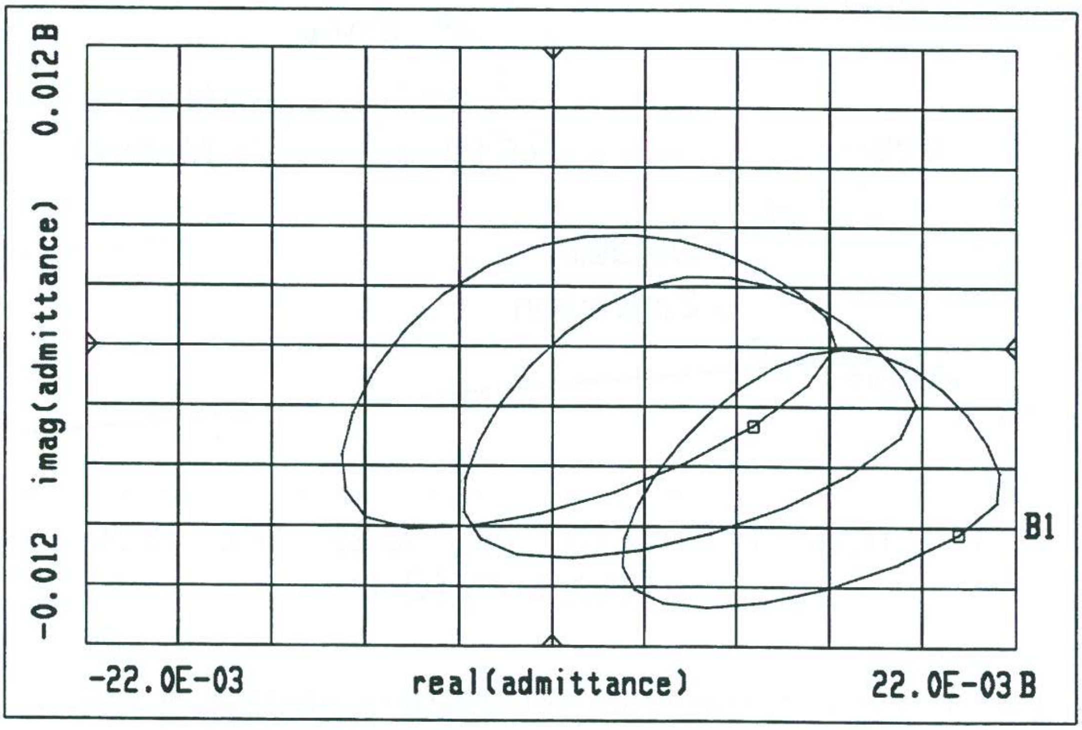

Fig. 2: Admittance diagrams obtained from phase and amplitude variations.

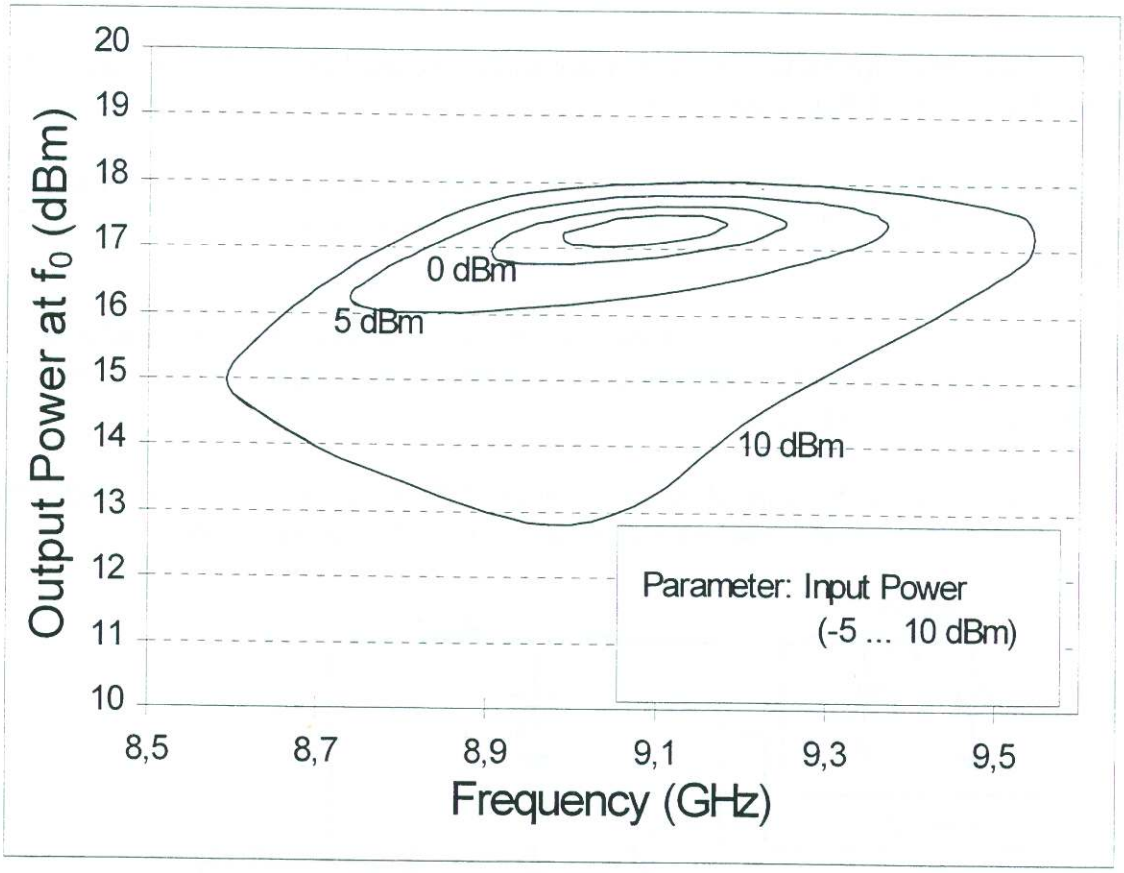

Fig. 3: Synchronization curves.

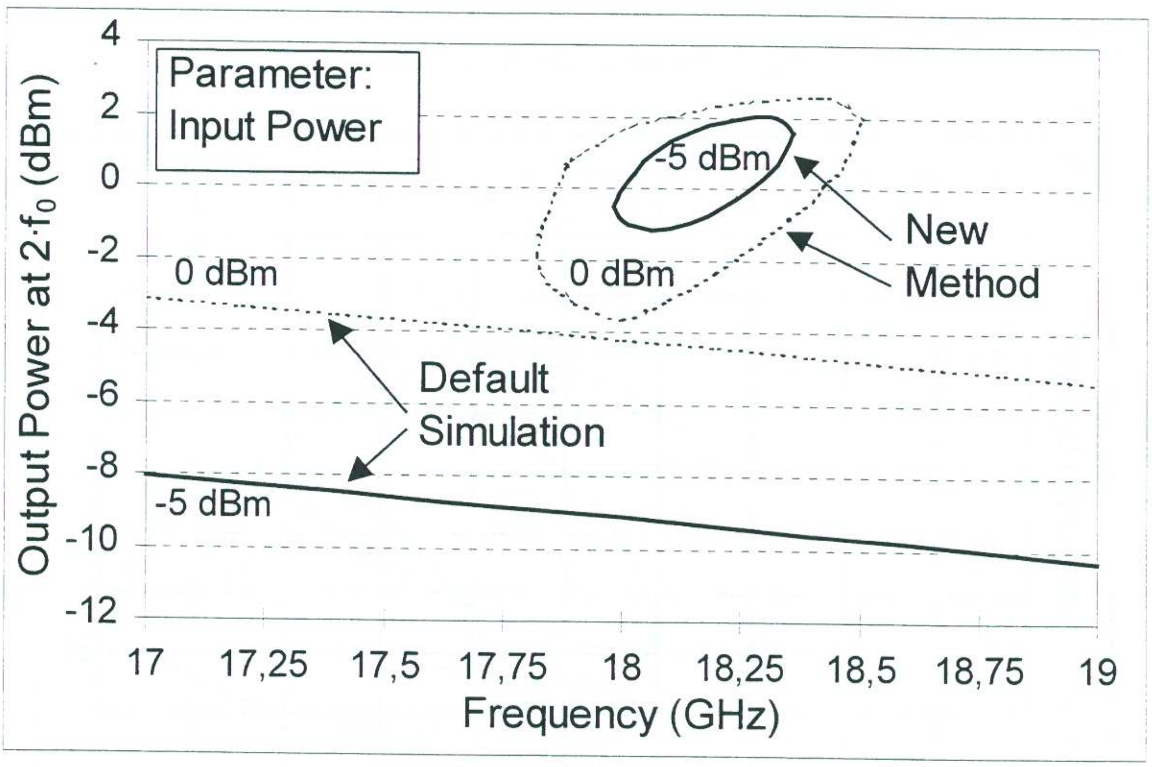

Fig. 4: Comparison between the new method and the standard simulation results.

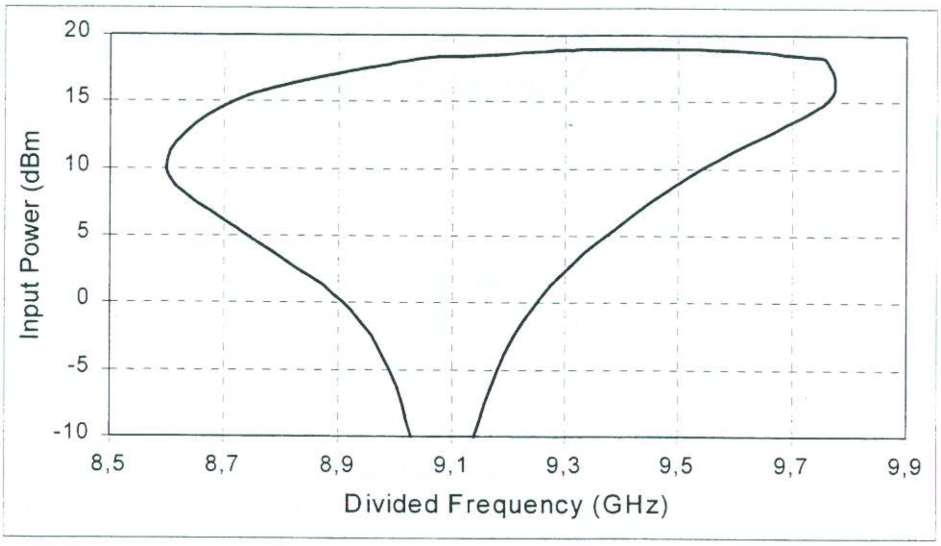

Fig. 5: Frequency division region: inside the loci.

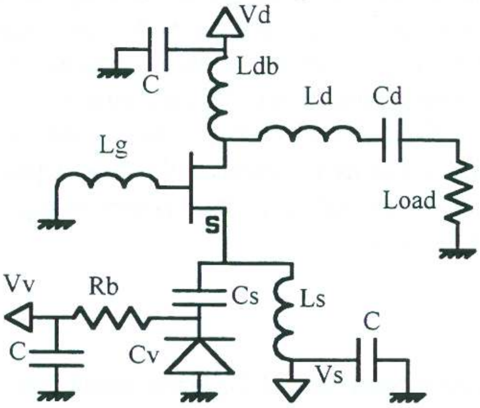

Fig. 6: MMIC VCO schematic.

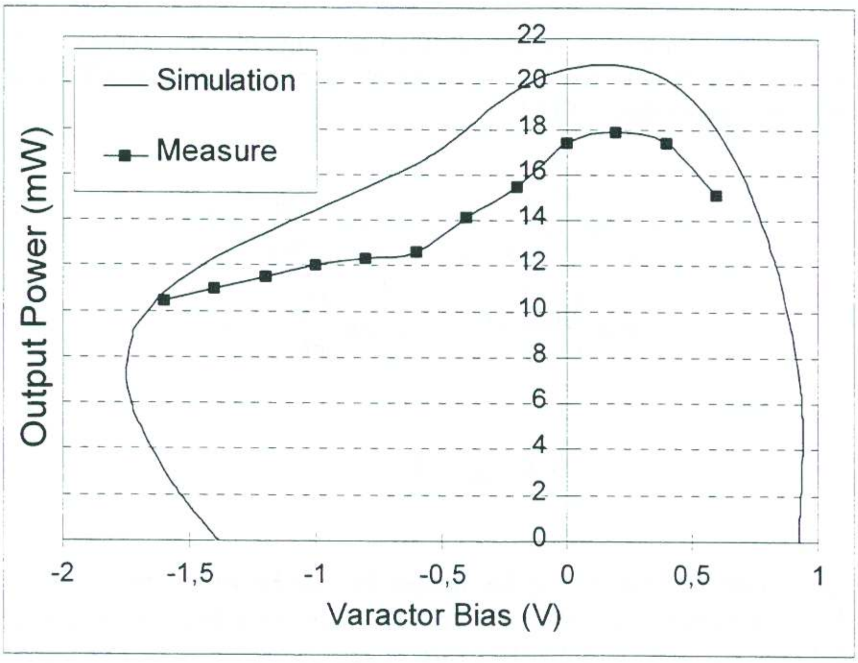

Fig. 7: VCO measured and simulated output power versus tuning voltage.