Global stability analysis of a broadband MMIC frequency divider in millimetric band

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Abstract

The global stability of a broadband MMIC frequency divider in the millimetric range has been analyzed by determining its bifurcation loci on a two-parameter plane. Some important characteristic to be satisfied by broadband designs are provided by these loci. The circuit bias range for operation as harmonic injection divider is also obtained by means of a very simple new approach. The new algorithm allows an easy selection of any bifurcation parameter and it is short time consuming. An excellent agreement has been obtained between simulation and experimental results.

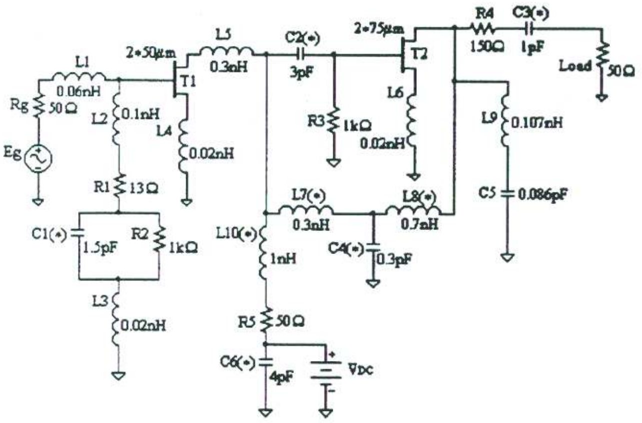

Figure 1. MMIC frequency divider schematic

Introduction

Two main phenomena may lead to frequency division by two: second harmonic synchronization [1], from a quasi-periodic regime, and I-type bifurcation [2], from a multiplying regime. For the first type of division, the circuit should behave as a free running oscillator, obtaining a so called harmonic injection divider. The advantage of this sort of divider is its capability to perform the frequency division from very low input power.

Harmonic injection dividers operate thus as free running oscillators in the absence of input power. For low injected input power there will be, in general, two independent fundamentals: the autonomous frequency ω_a, now modified under the influence of the input source, and the external frequency ω_{in}. As the input frequency ω_{in} approaches $2\omega_a$, a synchronization phenomenon will take place from a certain ω_{in} value. A divided regime of fundamental $\omega_{in}/2$ will be thus obtained in the synchronization band. Larger synchronization bands will be obtained for increasing input power. However, outside these bands, as the input power is increased, the autonomous frequency may be extinguished (inverse Hopf bifurcation), obtaining a multiplying regime of fundamental ω_{in}. As the input frequency is now modified, frequency division will be due to an I type bifurcation (two natural frequencies $\sigma \pm j\omega_{in}/2$ cross the imaginary axis [2]). As it can be gathered, the synchronization phenomenon allows frequency division from minimum input power.

Harmonic injection dividers exhibit thus three different operation modes: divider, multiplier and self-oscillating mixer. Hysteresis phenomena might take place in the transformation from one into another and this is why, for a good prediction of the circuit behavior, the simulation tools should be able to cope with every possible regime. The most demanding will be the autonomous quasi-periodic one, since two fundamentals must be considered and the autonomous one must be re-evaluated for every input generator value. This analysis is performed here by means of harmonic balance, after introducing a measuring probe [3] into the circuit, operating at the autonomous frequency to be determined.

The input generator conditions for each operating mode may be determined by tracing the circuit bifurcation loci on a two-parameter plane (generally, input power and frequency). Through the analysis of these loci, some basic characteristic for a broadband and efficient design will be derived.

The bias range for free running oscillation, and thus for harmonic injection behavior, may be obtained by tracing the evolution of the free running response as a function of the DC-voltage. In the new approach for bifurcation diagrams proposed here, it is not necessary to include the parameter dependence in the harmonic balance HB system, which makes it very easily implementable on the computer.

These approaches will be applied to the simulation of a broadband MMIC frequency divider by two with 28 GHz input frequency. This divider has been designed under a broadband configuration, based on the chain connection of two transistor stages.

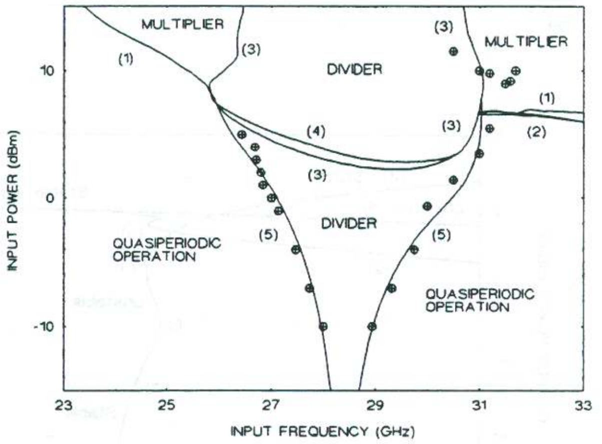

Figure 2 Bifurcation loci. (1) Hopf - locus. (2) Turning points locus in quasi-periodic regime. (3) I - locus. (4) Turning points locus in periodic regime. (5) Synchronization locus.

Global stability of frequency dividers

The harmonic balance (HB) method is applied here for the analysis of frequency dividers. Their autonomous and synchronized states are analyzed by means of the introduction into the circuit of a measuring probe. This probe must satisfy a non perturbation condition, provided by the voltage to current ratio equal to zero, for a current probe, or the reverse ratio, for a voltage probe. In an autonomous regime, the probe variables $\overline{p}$ to be determined are its amplitude and frequency. In synchronized and divided states, the probe variables $\overline{p}$ are its amplitude and phase. The total system to be solved will be:

$$HB\left(\overline{p},\overline{X}\right)=0 \qquad (1)$$

$$S\left(\overline{p},\overline{X}\right)=0$$

where HB is the harmonic balance system and S=0 is the probe non-perturbation condition. $\overline{X}$ are the harmonic balance independent variables.

Instead of considering the partial dependence of each set of equations on $\overline{X}$ and $\overline{p}$, we propose obtaining solving $\overline{X}$ as a function of $\overline{p}$ through the harmonic balance set of equations. Thus $\overline{X}=\overline{X}(\overline{p})$ may be introduced in the probe system S:

$$S\left(\overline{X}(\overline{p}),\overline{p}\right)=0 \qquad (2)$$

The total dependence of the probe equations on its own variables, as expressed in (2), has been proved to be very advantageous for obtaining the circuit bifurcation diagrams and bifurcation loci.

a) Bifurcation diagrams

Sometimes it may be desirable to obtain the circuit bifurcation diagram as a function of a parameter different from input power or frequency. This parameter, in a traditional approach, should be added to the circuit independent variables, calculating the derivatives of the HB function with respect to it, in a highly demanding computer approach. Here the parameter μ is introduced in (2):

$$S\left(\mu,\overline{p}\right)=0 \qquad (3)$$

In general, the solution path will be multivalued and a continuation method must be applied. This is done here in a local way, involving only the two probe single equations and their 2x2 jacobian matrix. The derivatives of S with respect to the probe variables and the parameter are calculated in a numerical way. Since the parameter is not introduced into the HB equations, the algorithm is external to this HB calculation and can be easily implemented on any existing software. Due to its local nature, this algorithm allows also an easy selection of the bifurcation parameter.

This algorithm has been applied here for obtaining the evolution of the free running oscillation as a function of the DC-bias. The DC-bias voltage is thus introduced into the probe equations:

$$S\left(A_p,\omega_p,V_{DC}\right)=0 \qquad (4)$$

where A_p and ω_p are the probe amplitude and frequency, the latter corresponding in this case to the unknown autonomous frequency ($\omega_p=\omega_a$).

Due to the intimate relation between the probe and the autonomous component, as the probe amplitude tends to zero, the primary Hopf bifurcation is approached.

b) Bifurcation loci

The bifurcation loci of harmonic injection dividers compose a qualitatively similar pattern (see [1] and figure 2). Divider operation is obtained both inside the I-type and synchronization locus, without any physical change taking place when crossing from one to another region.

The I-type bifurcation locus is, in general, a closed curve, showing two turning points on the parameter plane. For large band and efficient operation, the input power corresponding to these turning points should be similar and not very high. Also the synchronization locus should join the I-type division locus the nearest possible from these turning points. Otherwise, as it has been shown in a recent paper [1], coexistence of I-bifurcated and quasi-periodic branches may take place, this giving rise to hysteresis and other undesirable phenomena.

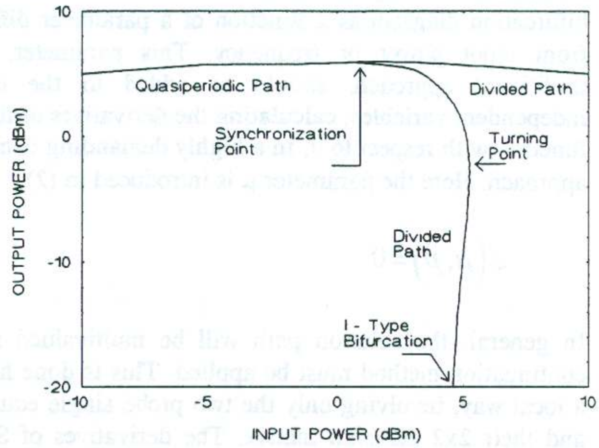

Figure 3. Transition between autonomous quasi-periodic and divided regimes for 27 GHz input frequency. Output power at autonomous component in both regimes has been traced.

The different bifurcation loci are obtained here by making use of the measuring probe method [1],[5]. The bifurcation diagrams as a function of input power or frequency are traced using the analysis method proposed above.

MMIC frequency divider with 28 GHz input frequency

The circuit schematic of a MMIC frequency divider by two with 28 GHz input frequency is shown in fig. 1 [4]. This divider was realized on a 0.25 μm HEMT technology. The substrate is GaAs (ε_r = 12.8), and each transistor is composed of two parallel cells, being the total gate width 2*50 μm for T1 and 2*75 μm for T2. The nonlinear elements taken into account for the FET model are, in each case, the Schottky barrier current Igs, the drain current Ids and the input diode capacitance Cgs. For the inductors and capacitors indicated with (*), the MMIC models provided by the THOMSON foundry have been used. The fixed DC bias used in the global stability analysis is 5.0 V (The gates are self-biased).

The bifurcation loci corresponding to this divider have been traced in fig.2. Frequency division is obtained inside the synchronization locus and the I-locus. The two border lines between these loci respectively correspond to I-type bifurcation points and divided branch turning points, occurring in an unstable periodic regime (see fig.3). They do not have thus a physical existence. From the bifurcation loci, it can be gathered that the second harmonic synchronization is responsible for the frequency division for most of the practical input power range. For input power levels corresponding to this synchronized operation, closed divided paths are obtained. I-type division provides divided branches from the multiplying regime, as in fig. 3. The success of the broadband design technique [4] is confirmed by the wide operation bands resulting from the loci.

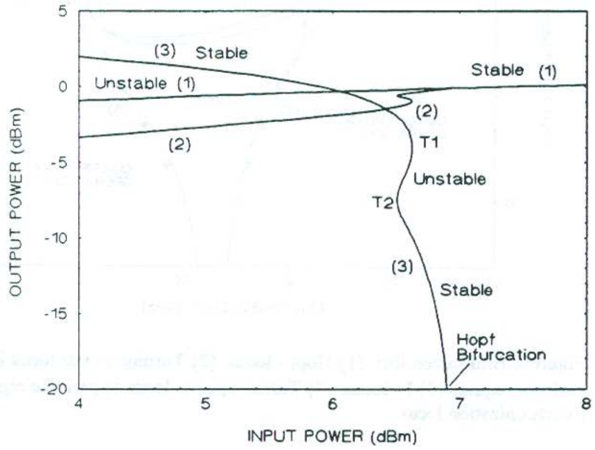

Figure 4. Quasi-periodic hysteresis phenomenon. **(1) External component in multiplier operation. (2) External component in quasi-periodic regime. (3) Autonomous component in quasi-periodic regime.**

The Hopf bifurcation locus is the border between self-oscillating mixer and multiplier operation modes. In this locus an autonomous frequency appears or disappears [2], according to the transformation sense. Possible turning points are often responsible for an hysteresis phenomenon in the mixing region. This happens here at the right side of the quasi-periodic operation region, in which two turning point curves, plus the Hopf bifurcation locus are obtained. If one of these turning point curves had been placed above the Hopf locus, the hysteresis phenomenon would have involved the transformation to periodic regime [1]. At the right side, only Hopf bifurcation points are obtained.

A bifurcation diagram as a function of input power for 32 GHz input frequency has been traced in fig. 4. For low input power, the multiplier branch is unstable, the solution being autonomous quasi-periodic. From a quasi-periodic simulation, two different solution branches are obtained, each corresponding to a different fundamental. In each branch, two turning points (T1 and T2) are encountered, the section T1-T2 being unstable. Thus, when the turning point T1 is reached, a jump takes place to the lower stable path (from T2 to the Hopf bifurcation). When the input power is modified in the reverse sense, another jump takes place when reaching the point T2, to the upper stable path. This hysteresis phenomenon confirms the prediction of the bifurcation loci.

The bifurcation diagram of fig. 5 provides the bias range for harmonic injection behavior (Experimental points superimposed). The primary Hopf bifurcation, at which the free running oscillation builds up from the DC bias point, is indicated in fig. 5(a). This bifurcation takes place for about 2V.

Conclusions

In this paper, some analysis techniques for global stability analysis of frequency dividers are provided. By introducing a measuring probe into the circuit, a simple approach is obtained in order to determine the circuit bias range for operation as harmonic injection divider. The proposed method has been successfully applied to the analysis of a MMIC frequency divider by two.

Acknowledgments

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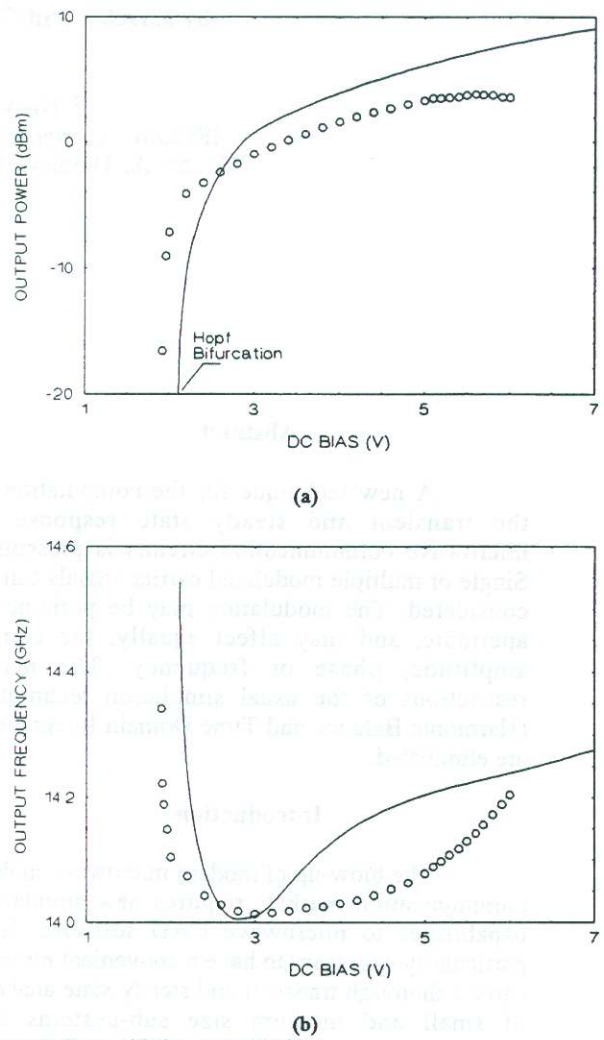

Figure 5. Free oscillation versus DC bias.