A STABILITY-ENSURING PROCEDURE FOR DESIGNING HIGH CONVERSION-GAIN FREQUENCY DOUBLERS

Ingo Schmale (*student member, IEEE*), Günter Kompa (*member, IEEE*)

University of Kassel, Fachgebiet Hochfrequenztechnik
Wilhelmshöher Allee 73, D-34121 Kassel, Germany,Tel: +49-561-804-6535, Fax: -6529
E-mail: ingo@hfm.e-technik.uni-kassel.de, http://www.uni-kassel.de/fb16/hft/schmale.html

Abstract

This paper presents a new general procedure for designing optimum conversion gain class B FET frequency doublers. For the first time, the two key design variables, i.e. the reflection coefficients of the input and output matching networks, $\Gamma_{IMN,2fo}$ and $\Gamma_{OMN,fo}$, can be independently swept without risking device oscillation and hence simulator non-convergence. This permits the designer to directly select the best parameters for maximum but insensitive conversion gain. Exemplary conversion gain contours typical for HEMTs and MESFETs are finally presented.

Introduction

Today's world witnesses a never seen increase of communication demand that can only be satisfied by opening up new bandwidths at higher frequencies. Frequency multipliers are ideal in this respect since they can extend the operation range of communication devices to frequencies where fundamental oscillation is not achievable with a given technology [1].

The design of a frequency doubler is a non-linear problem with a large number of independent variables, for which no general solution has yet been presented [2]. Some rough guidelines exist [1], but they lead to sub-optimal circuit realisations [3]. The unconstrained usage of optimisers in harmonic balance (HB)-simulators [4,5], on the other hand, leads to simulator convergence problems, as soon as some parameters approach a region of instability [6]. For certain terminations, doublers can oscillate at the fundamental frequency, which mathematically corresponds to an infinite conversion gain [7,8].

The aim of this paper is therefore to deliver a general procedure to the designer that permits to attain the optimum *single-transistor* doubler, without subjecting him to the drawbacks of optimisation. When broadband doubling is required, balanced structures are recommended [16], that have been demonstrated up to W-band [17].

Limitations of past doubler design methods

The fundamental frequency source impedance $Z_{SOURCE,fo}$ and the doubled frequency load impedance $Z_{LOAD,2fo}$ (see Fig. 3) are chosen such that maximum power is delivered at the respective frequencies [6,9]. To this end, small-signal conjugate matching is only a first estimate since we have a large-signal drive into a non-linear system [10,11].

Therefore, the remaining two variables, the reflection factors $\Gamma_{IMN,2fo}$ and $\Gamma_{OMN,fo}$ (see Fig.

3), are the truly independent variables for which $Z_{SOURCE,fo}$ and $Z_{LOAD,2fo}$ have to be determined that give maximum conversion gain. These reflection factors are generally assumed to be purely reactive, since no losses should occur [6-12]. The results shown in Fig. 1 prove this assumption for the first time by a fundamental load-pull simulation complementing experimental results [13].

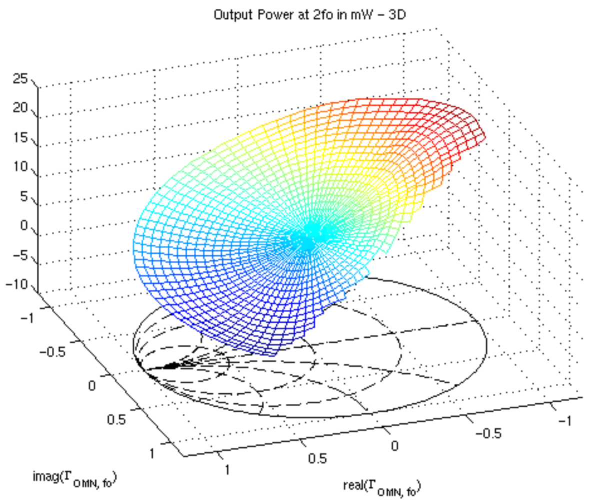

Figure 1: Simulated output-power at the doubled frequency for an 0.2µm HEMT. Load-pull with readapted $Z_{SOURCE,fo}$-values for every $\Gamma_{OMN,fo}$ -termination. $\Gamma_{OMN,fo}$- values that potentially lead to instability are excluded.

However, it was not possible in the past to sweep both angles from $\Gamma_{IMN,2fo}$ and $\Gamma_{OMN,fo}$ from 0 to 360°, and to perform HB-optimisations for $Z_{SOURCE,fo}$ and $Z_{LOAD,2fo}$, since instability can occur. Using conventional small-signal load stability circles at f_0, unstable $\angle\Gamma_{OMN,fo}$-values had to be cautiously excluded from HB-simulations [9], but instability risks remained.

We have found that this concept has to be extended when the FET is not only potentially unstable at f_0, but also at $2f_0$. Then, small-signal source stability circles at $2f_0$ have to be employed to avoid unstable $\angle\Gamma_{IMN,2fo}$-values. Furthermore, since we have simultaneous single-sided matching at both frequencies (at opposite sides), Edwards' extended stability criteria [14] developed for conditionally stable amplifiers have to be used.

The general stability-ensuring procedure

The following newly-developed procedure can be repeated for various input power levels, bias points, and fundamental frequencies:

1) **Calculation of the stability contours for $\Gamma_{IMN,2fo}$ and $\Gamma_{OMN,fo}$.** These contours correspond to the nearest intersection of a ray drawn from the origin of the Smith-chart with either the Smith-chart boundary or the stability circle defined by Edwards [14].

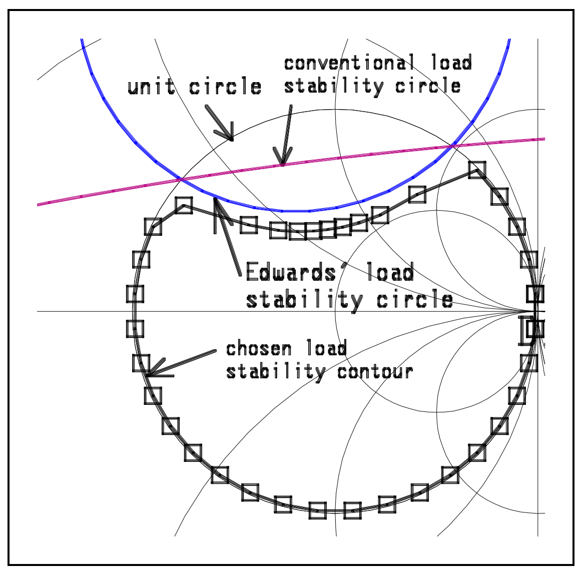

Figure 2: Construction of the load-stability contour

2) **HB-determination of the large-signal input reflection factor LS-$\Gamma_{IN,fo}$** for every $\angle\Gamma_{OMN,fo}$, with mag($\Gamma_{OMN,fo}$) limited by the stability contour determined in 1). Especially for class B doublers biased in or near pinch-off, the LS-$\Gamma_{IN,fo}$ is sensitive to the input power level and differs noticeably

from the small-signal value [12], which is the reason for the additional stability margin visible in Fig. 2. Since the LS-$\Gamma_{IN,fo}$ is fairly independent of the terminations at higher harmonics, they are all set to 50 Ω.

3) **Nested HB-simulations for all $\angle\Gamma_{IMN,2fo}$ /$\angle\Gamma_{OMN,fo}$-combinations,** using an appropriate non-linear model (e.g. [15]) with the following terminations at the respective frequencies (see Fig. 3):
   - $\Gamma_{IMN,2fo}$ and $\Gamma_{OMN,fo}$ are limited in their magnitude by the stability contours from 1).
   - $Z_{SOURCE,fo}$ is conjugately matched to the LS-$Z_{IN,fo}$ determined in 2), to guarantee maximum power transmission.
   - $Z_{LOAD,2fo}$ is more difficult to fix, because no LS-$Z_{OUT,2fo}$ can be meaningfully defined to which it could be conjugately matched. However, we have observed that the best $\Gamma_{LOAD,2fo}$ is related to the conjugate-complex of the small-signal $\Gamma_{OUT,2fo}$: It has approximately the same angle while the magnitude is reduced by a factor of between 0.9 and 0.7. We perform the HB-simulations for several reduction factors and chose the best.
   - All higher harmonics are terminated in 50 Ω, temporarily neglecting their influence [2].
   - The terminations at the higher harmonics are set to 50 Ω. While they noticeably affect the conversion gain [2], it is extremly difficult to precisely synthesise them, especially in hybrid circuits, and for higher frequencies.

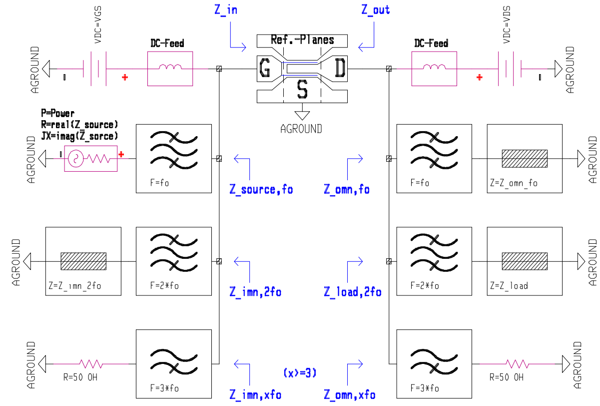

Figure 3: Schematic representation of the HB-simulator set-up with denominations of terminations.

Results

Fig. 4 shows for the first time the mutual influence of the two key design variables $\angle\Gamma_{IMN,2fo}$ and $\angle\Gamma_{OMN,fo}$. It proofs that the design requirements at the two frequencies are fairly independent [7]. The best $\Gamma_{IMN,2fo}$-termination is near to a SHORT at the intrinsic device [1,2,7,12] which corresponds to a nearly purely capacitive $\Gamma_{OUT,2fo}$. The worst $\angle\Gamma_{IMN,2fo}$ is near to 100^o, where $\Gamma_{OUT,2fo}$ moves towards the centre of the Smith-chart, corresponding to maximum losses [3,6].

The best $\Gamma_{OMN,fo}$-termination is also near to a SHORT at the intrinsic device [1-3, 6-12], where the class B doubler utilises maximally the g_m-nonlinearity. The worst $\angle\Gamma_{OMN,fo}$ at 60^o corresponds to an effective OPEN seen by the transistor's current generator, brought about by the parallel resonance of C_{ds} and C_{gd} with $Y_{OMN,fo}$, which prevents any I_{ds}-swing.

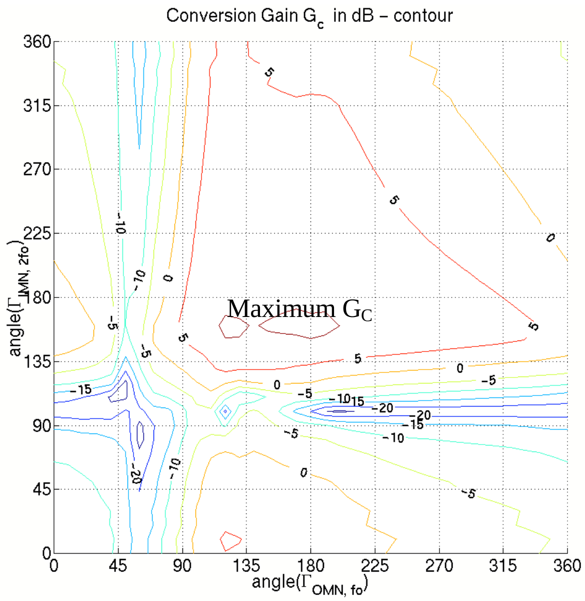

Figure 4: Contours showing the conversion gain attainable for every combination of $\angle\Gamma_{IMN,2fo}$ / $\angle\Gamma_{OMN,fo}$ when $Z_{SOURCE,fo}$ and $Z_{LOAD,2fo}$ are optimally adapted. Simulation data for an 0.2 µm HEMT device.

The best point in Fig. 4 with respect to conversion gain is dangerously near to the minima valleys, which has been observed for both HEMTs and MESFETs. It also involves nearly purely capacitive $\Gamma_{IN,fo}$ and $\Gamma_{OUT,2fo}$-values with high Q-factors, leading to small bandwidths of the respective matching networks. For an optimum design, a trade-off has to be made between these factors.

Conclusion

In this paper we have presented a new procedure for designing optimal frequency doublers. It allows for the first time the independent exploration of the influence of the two key circuit terminations $\Gamma_{IMN,2fo}$ and $\Gamma_{OMN,fo}$, while guaranteeing stable, non-oscillating operation. The provided well-annotated conversion-gain contours are a valuable reference for future designs.

References

[1] S.A. Maas, "Nonlinear microwave circuits", Artech House, 1988, Chapter 10: "FET frequency multipliers", pp. 397-416

[2] D.G. Thomas, Jr. and G.R. Branner, "Optimization of active microwave frequency multiplier performance utilizing harmonic terminating impedances", *IEEE Transactions on MTT*, vol. 44, no. 12, December 1996, pp. 2617-2624

[3] J.S. Augusto, M.J. Rosário, J.C. Vaz, and J.C Freire, "Optimal design of MESFET frequency multipliers", *Proceedings of the 23rd European Microwave Conference*, Madrid 1993, pp. 402-404

[4] C. Guo, E. Ngoya, R. Quere, M. Camiade, and J. Obregon, "Optimal CAD of MESFETs frequency multipliers with and without feedback", *IEEE MTT-S Int. Microwave Symp. Dig.*, 1988, pp. 1115-1118

[5] S. El-Rabaie, J.A.C. Stewart, V.F. Fusco, and J.J. McKeown, "A novel approach for the large signal analysis and optimisation of microwave frequency doublers", *IEEE MTT-S Int. Microwave Symp. Dig.*, 1988, pp. 1119-1122

[6] F. Giannini, G. Leuzzi, E. Limiti, and M. Tricarico, "Non-linear design of microwave active frequency doublers", *4th International Workshop on Integrated Nonlinear Microwave and Millimeterwave Circuits*, INMIC, University of Duisburg, Germany, October 1996, pp. 53-57

[7] C. Rauscher, "High-frequency doubler operation of GaAs field-effect transistors", *IEEE MTT Transactions*, vol. 31, no. 6, June 1983, pp. 462-473

[8] T. Hirota and H. Ogawa, "Uniplanar monolithic frequency doublers", *IEEE MTT Transactions*, vol. 37, no. 8, August 1989, pp. 1249-1254

[9] R. Gilmore, "Concepts in the design of frequency multipliers", *Microw. J.*, March 1987, pp. 129-139

[10] I. Schmale, F. van Raay, and G. Kompa, "Dispersive table-based large-signal FET-model validated in analysis of MMIC frequency doubler", *Proceedings of the 26th European Microwave Conference*, Prague 1996, pp. 260-263

[11] P. Colantonio, F. Giannini, G. Leuzzi, and E. Limiti, "On the optimum design of microwave active frequency doublers", *IEEE MTT-S Int. Microwave Symp. Dig.*, 1995, pp. 1423-1426

[12] E. Camargo, R. Soares, R.A. Perichon, and M. Goloubkoff, "Sources of non-linearity in GaAs

MESFET frequency multipliers", *IEEE MTT-S Int. Microwave Symp. Dig*., 1983, pp. 343-345

[13] Robert Larose, F.M. Ghannouchi, and R.G. Bisisio, "Multi-harmonic load pull: a method for designing MESFET frequency multipliers", *IEEE Military Communications Conference 1990*, Conference Record Cat. n. 90CH2831-6, pp. 466-469

[14] M.L. Edwards, S. Cheng, and J.H. Sinsky, "A deterministic approach for designing conditionally stable amplifiers", *IEEE MTT Transactions*, vol. 43, no. 7, July 1995, pp. 1567-1575

[15] I. Schmale and G. Kompa, "A physics-based non-linear FET model including dispersion and high gate-forward currents", *Int. IEEE Workshop on Experimentally based FET device modelling and related nonlinear circuit design*, University of Kassel, Germany, July 1997, pp. 27.1-27.7

[16] Pekka Kangaslahti, P. Alinikula, and V. Porra, "Monolithic artificial transmission line balanced frequency doublers", *Proceedings of the 27th European Microwave Conf.*, 1997, pp. 219-224

[17] H. Zirath, I. Angelov, N. Rorsman, C. Karlsson and E. Kollberg, "A balanced W-band HFET doubler", *Proceedings of the 23rd European Microwave Conference*, Madrid 1993, pp. 837-839