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A novel evolutionary approach for the analysis and optimization of THz nonlinear circuits

M. Bozzi, M. Saglam, M. Rodriguez–Girones, L. Perregrini, H. L. Hartnagel

Abstract – This paper presents a novel approach for the analysis of the nonlinear circuits derived from the modeling of THz frequency multipliers. This method combines the rapidity of the Harmonic Balance technique with the reliability of the Genetic Algorithm. For this reason, it has been used within an fully automatic optimization procedure, which determines the maximum conversion efficiency attainable with a device for a given pump power level, as well as the optimal impedance needed at all the harmonic. As an example, we report the analysis and design of frequency triplers based on Heterostructure Barrier Varactors, and operating at 255 GHz.

I. INTRODUCTION

The design of frequency multipliers operating in the mm–wave region requires circuit simulators: they are codes able to analyze lumped–element nonlinear circuits, derived from the electromagnetic analysis of frequency multipliers (see Fig. 1) [1].

Many analyses are required in the design process of a frequency multiplier, in order to determine the most suitable device and the optimal embedding impedance Z_L, for given operating frequency and pump power level. Since a large number of analyses is required, such nonlinear simulators should be fast and reliable. The reliability is mandatory if the design is based on automatic optimization procedures, where no human intervention is possible.

Many methods have been proposed for the analysis of nonlinear circuits [2,3]: most of them are based on the Harmonic Balance (HB) technique [4–6]. Even if they are typically fast, their use requires the tuning of a number of parameters for each specific nonlinear device. Therefore, these simulators can hardly be used in a completely automatic optimization tool.

Recently, a genetic approach to the analysis of nonlinear circuits has been proposed [7]: the application of the genetic algorithm (GA) leads to circuit simulators very stable and not device–dependent, but usually quite slow.

A novel method for the analysis of nonlinear circuits, derived from the modeling of THz frequency multipliers, was recently proposed [8]. It is based on a hybrid approach, which combines the standard HB technique with the GA. This method takes advantage from both the reliability of the evolutionary approach and the rapidity of the HB technique.
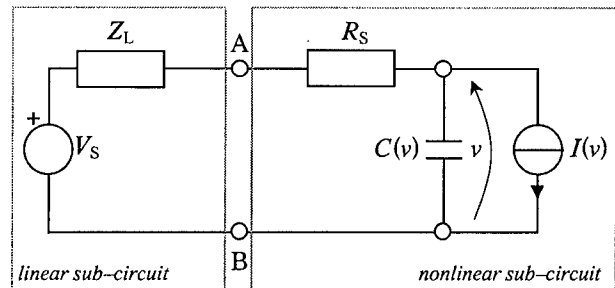

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Fig. 1: Lumped element equivalent circuit of a frequency multiplier operating in the mm–wave range.

This method has been applied to the analysis and design of frequency triplers, operating at 255 GHz. Such triplers are based on Heterostructure Barrier Varactors (HBVs), fabricated and measured at the Technical University of Darmstadt. The optimization process of the multiplier and the optimal performance are discussed in this paper.

II. STANDARD HARMONIC BALANCE ANALYSIS

The HB technique is a well–established iterative method for the analysis of nonlinear circuits operating in the mm–wave range [2–6]. This technique is based on the splitting of the circuit into two parts, one containing the nonlinear elements and the other only linear components, modeled by a Thevenin equivalent circuit (Fig. 2). The analysis of the linear sub–circuit is performed in the spectral domain, whereas a time–domain analysis is applied to the nonlinear sub–circuit.

The aim of this analysis is the calculation of the voltage V_N across the terminals of the nonlinear device and of the current I_N flowing through the same device (Fig. 2). The source voltage V_S at the fundamental frequency ω_0 and the linear impedance Z_L are known, as well as the characteristics of the nonlinear device.
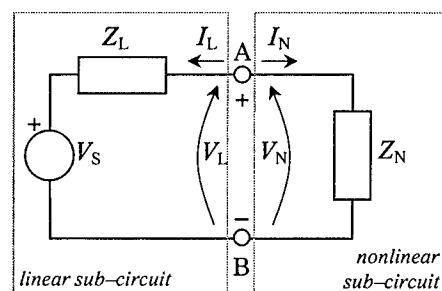

Fig. 2: Nonlinear circuit considered in the Harmonic Balance analysis. Z_N represents the impedance of the nonlinear sub–circuit.

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In the HB analysis, a set of tentative voltages $V_N = (v_{N,1}, ..., v_{N,P})$ at P harmonic frequencies (at ω_0, $2\omega_0$, ..., $P\omega_0$) is arbitrarily chosen and applied to the terminals A–B of the nonlinear sub–circuit. By using a time–domain analysis and the Fourier transform, the set of currents $I_N = (i_{N,1}, ..., i_{N,P})$ entering the nonlinear sub–circuit is determined. The same current set (apart from the sign) $I_L = -I_N$ is applied to the linear sub–circuit, and the set of voltages $V_L = (v_{L,1}, ..., v_{L,P})$ is determined. This set of voltages V_L is compared with the tentative voltage V_N, and an error ε is calculated as the Euclidean distance between V_L and V_N

$$\varepsilon = \frac{|V_N - V_L|}{|V_N|}$$

If the error ε is larger than a prescribed value ε_{MAX}, the iteration proceeds with the estimation of a new V_N, which is obtained as a weighted summation of V_L and the old V_N.

$$V_N^{new} = p\, V_N + (1-p)\, V_L$$

This weight p, called "convergence parameter," determines the convergence rate and must be properly chosen.

The HB technique typically permits to obtain a rapidly converging algorithm, but presents some drawbacks: an initial guess of the voltage V_N is required, and the criterion for the choice of the convergence parameter p is not easy. Moreover, the optimal convergence parameter is typically device–dependent and the convergence often depends on the initial guess.

These drawbacks reduce the effectiveness of this method, especially when the analysis code is embedded in an automatic routine for the optimization of nonlinear circuits. In this case, the aim of the design is the determination of the most suitable nonlinear device, for given operation frequency and pump power level. Therefore, different devices are considered, with different embedding impedance Z_L. Since no human intervention is possible, the analysis code must be reliable, so that the solution is found in any operation condition.

III. NOVEL GENETIC ALGORITHM/ HARMONIC BALANCE TECHNIQUE

To overcome these drawbacks, a novel algorithm was recently proposed [8]: it is based on the combination of the GA [9] with a standard HB technique [4]. The structure of our method is sketched in the block diagram of Fig. 3.

As a first step, we apply the GA: an initial population of C chromosomes [9] is generated. The chromosomes are coded as strings of real genes, each of them containing the real part or the imaginary part of the voltages V_N at all the harmonics of interest $\omega_p, p = 1, ..., P$. The number C of chromosomes is related to the number P of harmonics considered in the simulations: as a rule of thumb, we used $C = 20 \div 30\, P$. The initial value contained in the genes is randomly generated, typically in the range $\pm 3 V_S$.
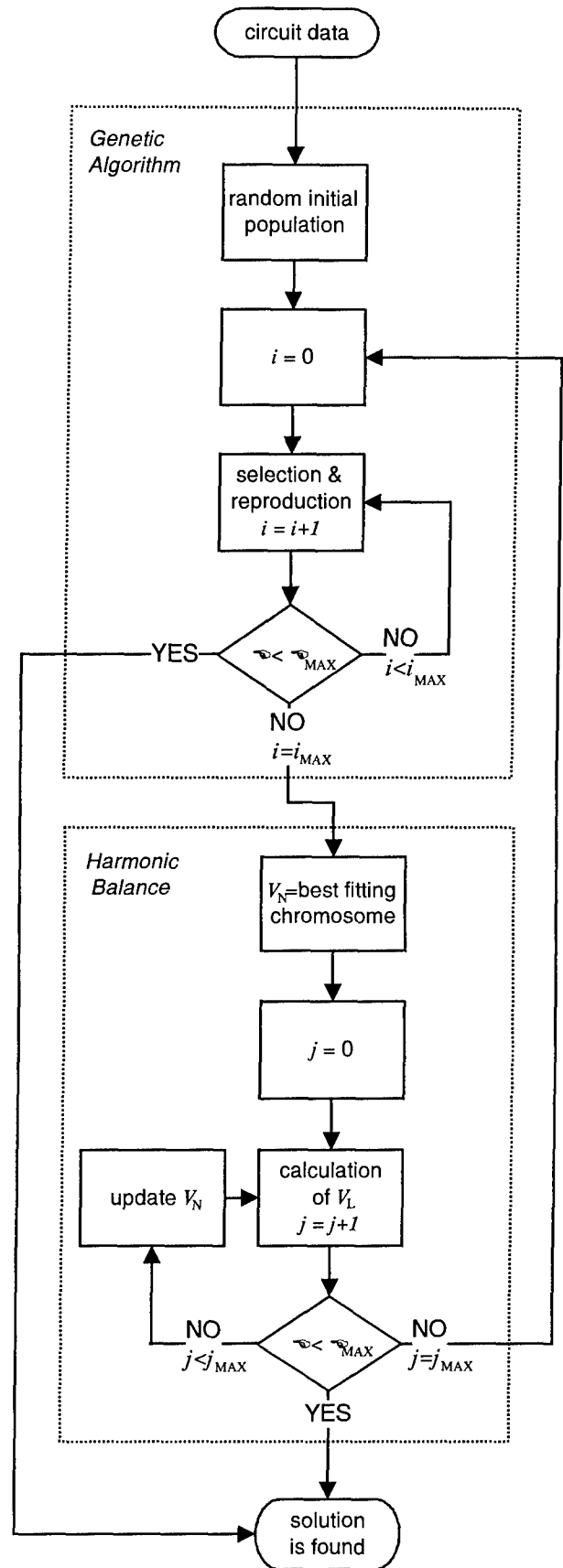

Fig. 3: Block diagram of the combined Genetic Algorithm/Harmonic Balance technique: the algorithm repeatedly switches between GA and HB, until the convergence is reached.

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New generations of the population are then created: the survivors are the best fitting chromosomes, selected through a binary tournament, while the new chromosomes are obtained by applying both crossover and mutation [9]. The "fitness" of a chromosome depends on the Euclidean distance ε between the voltage V_N (represented by the chromosome) and the voltage V_L, determined in the same way as previously described for the HB technique. Of course, the lower is the value of ε, the better the fitness of the chromosome.

The algorithm stops and the solution is found if a chromosome of the current population satisfies the requirement in fitness ($\varepsilon < \varepsilon_{MAX}$); otherwise, a new population is generated.

If the GA does not find the solution in a fixed number i_{MAX} of generations (say $i_{MAX}=500 \div 1000$), the code switches to the HB technique. The best fitting chromosome is taken as the initial guess V_N for the HB technique. Since the values of the best chromosome are taken as initial guess, this typically represents a reasonably good choice; moreover, the user is not required of providing any information.

If the HB fails to converge after a fixed number j_{MAX} of iterations (say $j_{MAX}=100 \div 200$), the algorithm switches again to GA and proceeds for additional generations. This procedure continues, repeatedly switching between GA and HB, until the convergence is reached.

IV. OPTIMIZATION OF A 255 GHz HBV FREQUENCY TRIPLER

The analysis method presented above was applied to the optimization of a frequency tripler operating at 255 GHz based on Heterostructure Barrier Varactors (HBVs).

HBV diode is a suitable device for direct tripling since the C–V characteristic is evenly symmetric and I–V characteristic is anti–symmetric, so that only odd harmonics are generated [10]. Therefore, one of the applications where HBV diodes show a great potential is quasi–optical tripler arrays [11]: in fact, these varactor devices require less design complexity compared to Schottky diode tripler circuits since no DC bias circuitry and no idler circuit at second harmonic is required.

$Al_{0.7}Ga_{0.3}As/GaAs$ HBV structures were grown with Molecular Beam Epitaxy on SI GaAs substrate at the University of Darmstadt [12]. HBVs with diameters of 10, 20 and 40 μm were fabricated in the form of two columns with a total of four barriers. The measured C–V and I–V characteristics of the HBVs are shown in Fig. 4.

The design of the frequency tripler requires the choice of the most suitable device among the available ones, and the determination of the optimal embedding impedance, which depends on the pump power available at the fundamental frequency.

In the analyses of the HBVs, the maximum conversion efficiency of the devices was calculated, with the pump power ranging from 1 to 30 mW. For each pump power level, the optimal embedding impedance Z_L was determined.

As an example of the GA/HB technique, the analysis of the HBV with 10 μm diameter, with 20 mW pump power, is reported: Fig. 5 shows the error ε vs. the number of

iterations: after 1000 GA iterations, the HB analysis was inserted and reached the convergence in 104 additional steps.

From the optimization process resulted that the most suitable device in the considered pump power range was the HBV with 10 μm diameter, which achieved a conversion efficiency better than 4% and an output power larger than 1.2 mW (Fig. 6). The optimal embedding impedance at the fundamental frequency (85 GHz) and at the output harmonic (255 GHz) is reported in Fig. 7.
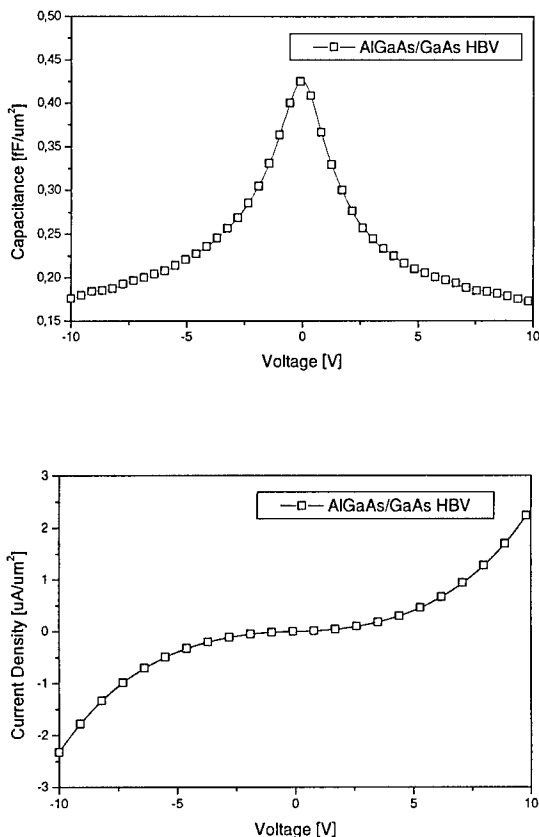

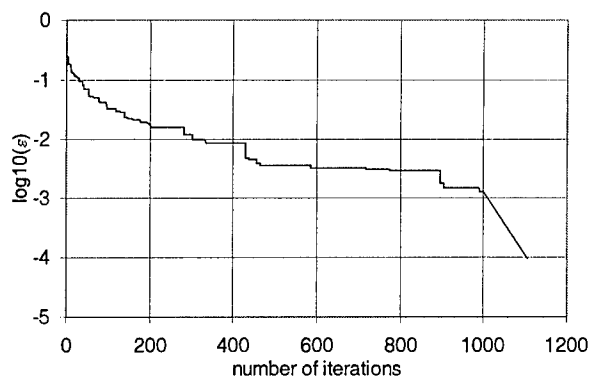Fig. 4: Measured C–V and I–V characteristics of the $Al_{0.7}Ga_{0.3}As/GaAs$ HBVs.

Fig. 5: Variation of the residual error e vs the number of iteration in the GA/HB analysis of the 10 μm HBV. The convergence limit is fixed at $\varepsilon_{MAX}=10^{-4}$. The convergence is obtained in 1000 GA iterations and 104 HB additional steps.
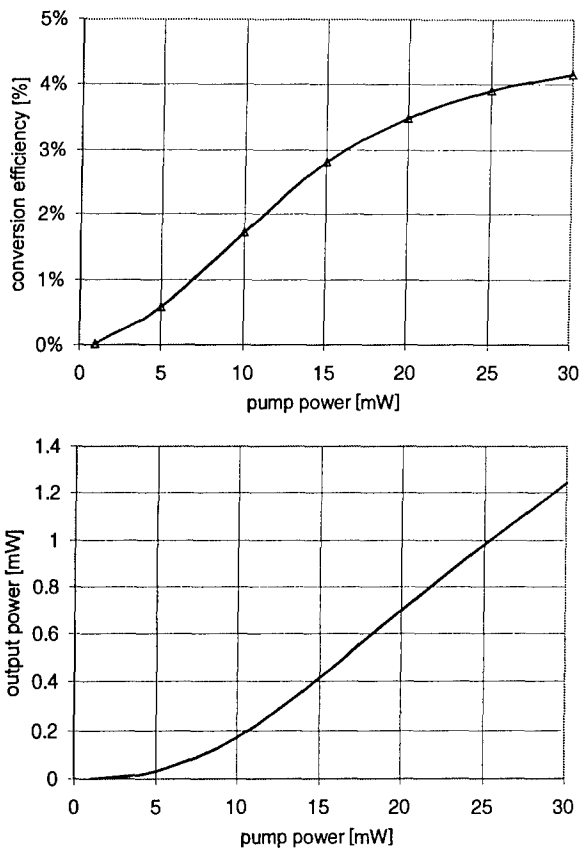
V. CONCLUSION

We presented a novel approach for the analysis and optimization of the nonlinear circuits operating as frequency multipliers in the THz region. The method, which is an hybrid between the Harmonic Balance technique and the Genetic Algorithm, is very reliable, reasonably fast and does not require any human intervention. It was applied to the analysis and design of 255 GHz frequency triplers based on HBVs with diameters ranging from 10 to 40 μm. The results showed that the HBV with the smaller diameter exhibits good conversion performance in the considered pump power range (up to 30 mW). Conversely, HBVs with larger diameters are not suitable for operation with limited pump power level.

Fig. 6: Maximum conversion efficiency and output power at 255 *GHz* of the HBV versus the pump power level at the fundamental frequency (85 *GHz*).
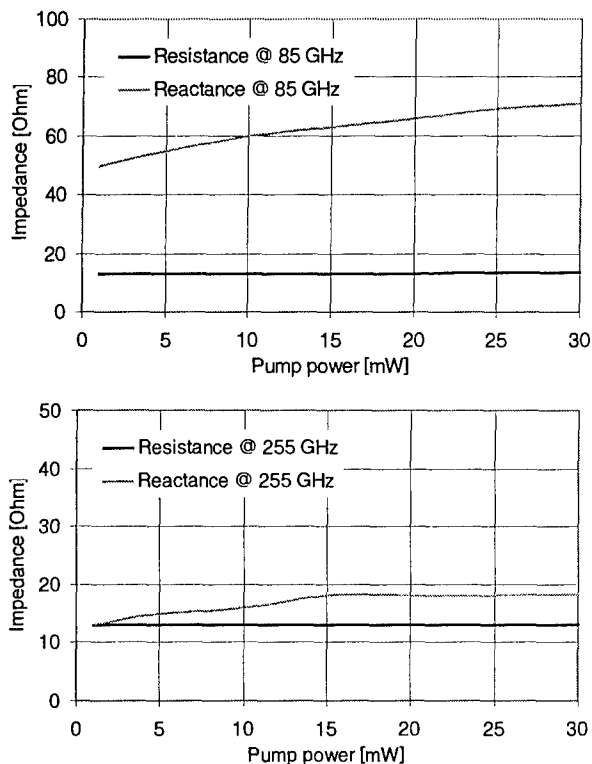

Fig. 7: Optimal embedding impedance of the 10 μm HBV vs the pump power level, at 85 GHz (fundamental frequency) and 255 GHz (output frequency)

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