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NUMERICAL ANALYSIS OF SUBHARMONIC MIXERS USING A BILINEAR DIODE MODEL

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Abstract

Using a bilinear approximation of the Schottky barrier diode characteristic, conversion loss peaks were accurately determined for a typical millimeter-wave subharmonically-pumped mixer. This approach requires significantly less computer time than a full nonlinear analysis.

Introduction

Accurate analyses of subharmonically pumped mixers have been widely reported in the literature, for the identical diode case by Kerr[1] and for the more general case of unequal diodes by Faber and Gwarek[2] and Hicks and Khan[3]. All three methods require substantial amounts of computer time for the following reasons, viz: (i) the large number of calculations involved in the numerical integration of the nonlinear differential equations representing the junction varactor capacitance and Schottky barrier resistance; (ii) the number of iterations required to ensure the linear embedding-circuit constraints at the pump frequency and its harmonics are satisfied.

Investigations[1,3] have shown that the conversion loss performance of a subharmonic mixer depends primarily on the diode parasitics, especially the lead inductance - junction capacitance resonant frequency. It is thus imperative that this property be incorporated into any model of such a mixer.

Simplified bilinear diode models have been proposed in the literature. Barber[4] first proposed such a model for the single-diode mixer, with the mixer properties being chiefly determined by the pulse duty ratio of the switch.

Bordonskiy et.al.[5] expanded on Barber's switch model by extending the number of sidebands under consideration together with making an allowance for broadband non-zero terminating impedances at both the image and sum frequencies. Both Barber and Bordonskiy commented on the diode cutoff frequency as being a parameter of fundamental importance. Zabyshnyi et.al.[6] extended the work of Bordonskiy to the case of subharmonic mixers, using the assumption of identical diodes. However, the approach of Zabyshnyi fails to account for the crucial effect of the parasitic lead inductance which, at resonance, induces multiple conductions in each local-oscillator voltage waveform cycle[1,3].

It is clear that the present analytical subharmonic mixer models lack vital information on the parasitic lead inductance to make accurate predictions. It is equally clear that analyses of this type are attractive in terms of their greater ease of calculation, an attractive characteristic in laboratory and design work where results are required expeditiously.

This paper sets out an accurate bilinear subharmonic mixer model enabling both loss performance and input noise temperature to be calculated. Results are given for both equal and unequal diode cases.

Bilinear Model

The analysis of a millimeter-wave subharmonic mixer, using a bilinear model which incorporates all the important parasitic elements, involves a large-signal analysis followed by small-signal calculations.

The large-signal analysis is carried out using the simplified model, shown in Fig. 1, for each diode in the anti-parallel pair. In this model C_j is taken to be the zero-bias capacitance value, and the turn-on voltage is taken to be equal to the d.c. bias voltage which gives rise to the required d.c. bias current. Assuming an ideal pump source having zero source impedance, with the diode parameters specified and with zero d.c. bias voltage, the conduction angle is found from a Laplace transform analysis. The switch is closed for the period during which the current is such that the voltage across C_j is equal to $V_{turn-on}$. The conduction angle, and the pump voltage amplitude, are determined by specification of the d.c. bias current; in practice, a rapid iteration gives the required pump voltage value to provide the specified bias current. Care must be taken with multiple conductions to ensure they are properly characterized by the computer program.

The small-signal analysis involves determination of the conductance and capacitance waveforms, from which harmonic components are readily found by Fourier analysis. This analysis is carried out with the diode model shown in Fig. 2, which differs from that of Fig. 1 in provision of elements C_{j2} and R_j when diode conduction is occurring and the switch is closed. R_j is the diode conductance and $C_{j1} + C_{j2}$ the diode capacitance for the specified d.c. bias current value; both are found from the exact diode I-V and C-V relations. C_{j1} now denotes the zero-bias capacitance. Using this model, together with θ found from the large signal analysis, conductance and capacitance waveforms are readily found and a small-signal conversion matrix constructed for each diode. An overall mixer admittance matrix may then be formed using the two diode conversion matrices plus the diagonal matrix representing the embedding admittance network and external load admittances. This combined overall system matrix enables the calculation of the output i.f. impedance and conversion loss.

The noise analysis proceeds in two steps. Firstly, the thermal noise emanating from the diode series resistances and the embedding network is determined using the theory of Twiss[7]. The shot noise contribution of the two diodes, each represented as an ideal switch, may be determined using the following theorem[1]. A two-diode mixer, using ideal exponential diodes mounted in a lossless circuit, has the same output noise as a lossy multiport network maintained at a temperature $\eta T/2$, where T is the physical temperature of the diodes and η is their ideality factor. For the switch bilinear model, it is assumed that the switch in the model contributes an equivalent amount of shot noise to that of the ideal exponential diode referred to in the above theorem.

Application of the Analysis

Comparative studies were carried out on the subharmonic balanced mixer examined by Kerr, given as example 1 in his paper[1]. This particular circuit presents zero coupling between the two diodes at frequencies above the signal frequency. At lower frequencies, the load seen by the diodes is 50Ω. The diode parameters used were as follows: R_s = 10Ω, C_o = 7.0 fF, L_s = 0.4 nH, η = 1.12, ϕ = 0.95 V, γ = 0.5, i_{sat} = 8.0

x 10^{-17}A. The signal, pump and i.f. frequency are set at 103 GHz, 50 GHz and 3 GHz respectively. In the case of the equal-diode analyses, the bias current for each diode was set at 2 mA; with unequal diodes, one diode was fixed and held at 2 mA bias current.

Fig. 3 shows the variation of mixer performance with lead inductance, for the case where the diode lead inductances are constrained to be equal. The exact-analysis results[1] are shown for comparison. Fig. 4 is similar to Fig. 3, but is for the case where the lead inductance of diode 1 is fixed with that of diode 2 allowed to vary as shown. Fig. 5 depicts typical calculated voltage and current waveforms (using the bilinear model) for the case of double conduction, leading to a conversion loss peak.

Discussion

It is clear that the peaks given by the more complete analysis of Kerr[1] are also predicted by the simplified bilinear model. This close correspondence applies to all three properties of the mixer, namely conversion loss, i.f. output impedance and the input signal noise temperature. However, it is equally apparent that there is a systematic horizontal displacement of the conversion peaks. Elementary LC resonance calculations using the zero bias capacitance (based on resonance at the second pump harmonic) predict the largest peak to occur at 0.36 nH in Fig. 3. As the average pumped capacitance is higher than the zero bias capacitance, it is to be expected that the nonlinear analysis of Kerr[1] will shift the peak to the left of 0.36 nH. The bilinear model analysis will naturally shift the peaks still further to the left as the forward conduction region is effectively modelled as an infinite capacitance (short circuit), thus further increasing the average capacitance. An improvement in the bilinear model for the large signal analysis would be to replace the switched short circuit with a switched capacitance (as has been done for the small signal analysis). Its value would be such as to make the total "on" capacitance equal to that of the capacitance calculated at the d.c. bias current (from the exact I-V and C-V relationships), thereby reducing the average capacitance. As may be expected, the bilinear model predicts sharper resonances than that found by Kerr[1], a consequence of the absence of diode-junction damping resistance implicit in the Schottky-barrier diode model. Although still quite satisfactory, the noise analysis probably contains the greatest discrepancy between the complete nonlinear analysis and bilinear model predictions. This may be attributed to the additional assumption required for the noise analysis, namely the equivalence between an ideal Schottky barrier diode with ideality factor η and the perfect switch used in the diode bilinear model.

The unequal diode results reinforce statements made previously in the literature[3]. It is clear that should one diode be at a resonant condition, the total mixer performance will suffer, irrespective of the condition of the other diode.

Conclusions

The bilinear model proposed offers the following advantages:

(i) the important addition of the lead inductance to the existing bilinear subharmonic diode models;

(ii) an allowance for the effect of bias current on the performance calculated by such a model;

(iii) calculations which account for both the resistive and parametric mixing;

(iv) excellent correlation with the more detailed nonlinear analysis of Kerr[1];

(v) the speed of computation, being an order of magnitude smaller than a full nonlinear analysis; and

(vi) the simplified analytical bilinear model facilitates intuitive understanding of the mixing process.

Acknowledgements

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Appendix

The following linear differential equations describe the large signal operation of the bilinear diode:

Off State:

$$v = R_s i + L_s \frac{di}{dt} + v_{capacitor}$$

$$v_{capacitor} = \int \frac{i}{C_j} \, dt$$

On State:

$$v = R_s i + L_s \frac{di}{dt} + v_{capacitor}$$

$$v_{capacitor} = V_{turn\text{-}on} = \text{constant}$$

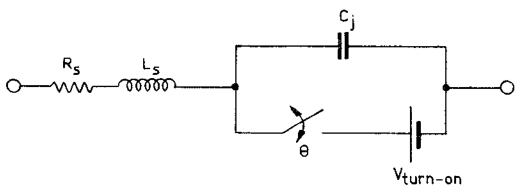

Figure 1: Bilinear model of the mixer diode to be used in the approximate large signal nonlinear analysis. R_s is the series resistance, L_s is the lead inductance, C_j is the zero-bias capacitance, $V_{turn-on}$ is the forward bias turn-on voltage, θ is the conduction angle of the switch. Two of these diodes are connected in antiparallel to form a subharmonic mixer.

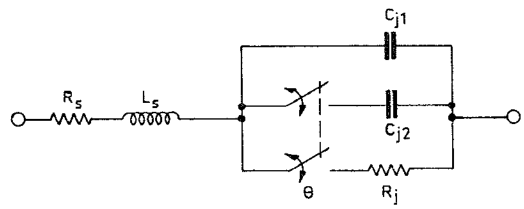

Figure 2: Equivalent circuit of the diode used in the small signal analysis. This circuit features both a switched capacitance and a switched conductance. C_{j1} is the zero-bias capacitance, R_j is the diode conductance and $C_{j1} + C_{j2}$ the diode capacitance for the specified d.c. bias current.

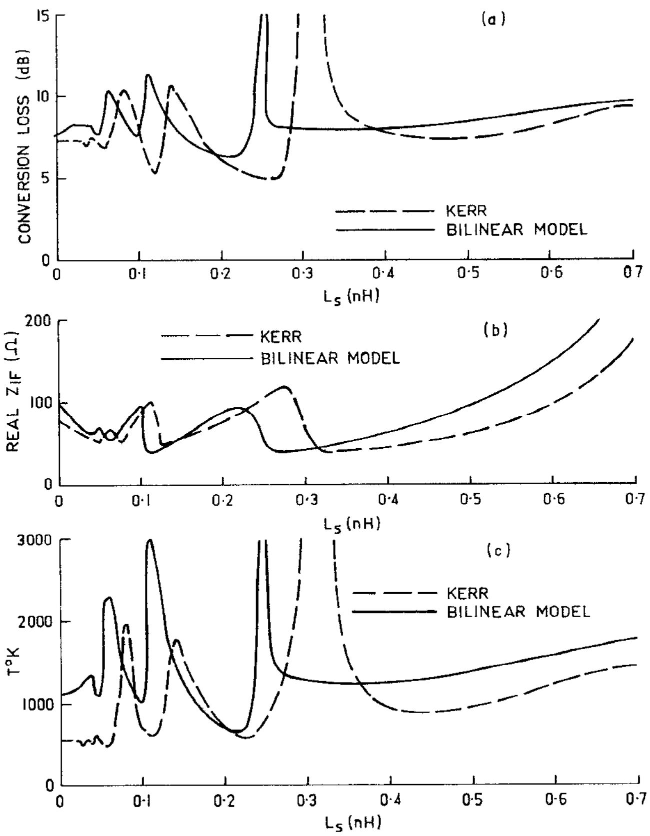

Figure 3: Comparison of: (a) calculated conversion loss, (b) i.f. output impedance and (c) input noise temperature values given by the full nonlinear analysis reported by Kerr[1] and the bilinear model described in this paper. Identical diodes were used. Pump frequency = 50 GHz, signal frequency = 103 GHz, i.f. frequency = 3 GHz, bias current = 2 mA, R_s = 10 Ω, C_j = 7.0 fF.

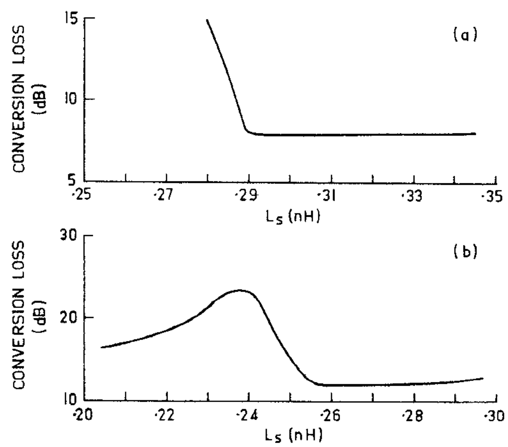

Figure 4: Conversion loss versus diode 2 lead inductance for 2 different unequal diode situations: (a) diode 1 lead inductance = 0.30 nH, (b) diode 1 lead inductance = 0.25 nH. Other diode parameters (for both diodes) are: R_s = 10 Ω, C_o = 7 fF. Diode 1 bias current = 2.0 mA. Note in (b) the conversion loss is always high as diode 1 is resonant at the signal frequency.

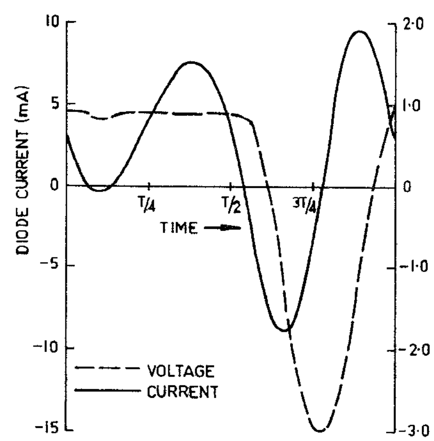

Figure 5: Typical voltage and current waveforms calculated by the bilinear model where the phenomenon of multiple conduction is occurring. Bias current = 2 mA, R_s = 10 Ω, C_j = 7.0 fF, L_s = 0.25 nH. The two diodes are identical in this case.