

Full-Wave Design and Optimization of MM-Wave Diode-Based Circuits in Finline Technique

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ABSTRACT

This paper presents a full-wave design and optimization of a quasi planar frequency doubler and a balanced mixer in finline technique by applying the extended finite difference time domain method (FDTD). The structures are based on the junction of a coplanar waveguide and a finline using two Schottky diodes mounted across this junction. The diodes are represented by their large signal device circuit model. The specific problem of embedding the lumped elements in the FDTD mesh at mm-wave frequencies is discussed. A new method for the inclusion of the device into the grid is developed avoiding unphysical reactances. The frequency doubler is designed for optimal conversion loss at 0 dBm input power in a frequency band from 20 to 25 GHz and 40 to 50 GHz, respectively. The operation frequency of the balanced mixer is 30 GHz. The simulation results are validated by the measurements.

INTRODUCTION

The FDTD method [1],[2] is successfully applied to the design and optimization of linear structures. In recent years also nonlinear structures have been analyzed at microwave frequencies, and several methods for incorporating nonlinear devices into FDTD or modeling the device itself by finite difference methods have been proposed [3],[4],[6]. Especially with nonlinear problems, like in this case a frequency doubler or a balanced mixer, an analysis with standard CAD tools gets rather difficult. So full-wave time domain methods have to be employed. In this case, the extended FDTD method using equivalent current source technique is applied to model the complex circuitry including quasi planar structures as well as the diodes. The two diodes are described with their equivalent circuit and are embedded in the FDTD mesh in such a way that unphysical parasitic effects are avoided. The influence of these effects in the mm-wave range will be discussed later.

DESCRIPTION OF THE CIRCUIT

For broadband operation, e.g. measurement systems, a balanced/unbalanced diode configuration has proven to be a useful concept for frequency multiplication of even order and for frequency conversion [7],[10]. Such a structure can easily be implemented in the junction of a coplanar waveguide and a finline as shown in Fig. 1. The coplanar waveguide is placed in a waveguide channel of reduced cross section to reject the slot mode excited at the diodes. In the area of the junction and the finline, a shielding with standard waveguide dimensions is used. In [5] such a junction was analyzed with the extended FDTD method. In this paper, an optimization of this junction for a multiplier operation is presented.

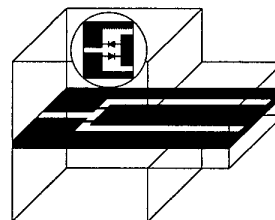


Figure 1: Basic structure of the doubler

DEVICE CIRCUIT MODEL

As an active device HP HSCH5330 silicon low barrier Schottky diodes are chosen. The large-signal circuit model of these diodes is shown in Fig. 2. This type of diodes offers the advantage of a reasonable conversion loss even with low input power. The elements in the circuit were determined accurately by measurements, so that the model can be used over a wide frequency range (up to 80 GHz). The element values are given in Fig 2. The circuit includes two nonlinear elements, the Schottky capacitance $C_D(U)$ and the current source $I_D(U)$, described

by:

$$C_D(U) = \frac{C_{j0}}{\sqrt{1 - \frac{U}{\Phi_0}}}; I_D(U) = I_0(e^{\frac{qU}{kT}} - 1)$$

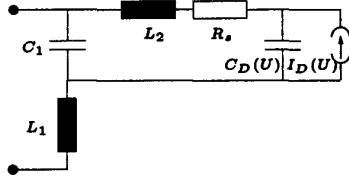


Figure 2: Equivalent circuit of the diode; Element values: $L_1 = 0.1nH$, $L_2 = 0.04nH$, $C_1 = 30fF$, $C_{j0} = 60fF$, $R_s = 10\Omega$, $I_0 = 10nA$.

SIMULATION OF NONLINEAR STRUCTURES

Analyzing linear structures, a Gaussian pulse can be used for the incident signal, and with one simulation the scattering parameters for the whole frequency band can be calculated. With nonlinear devices, a pulse excitation results in a rather complex harmonic spectrum not relevant for multiplier and mixer LO operation, thus a harmonic excitation has to be chosen. So for each frequency point and for each power level, an extra simulation is necessary. To calculate the quasi linear conversion loss of a mixer, however, a modulated Gaussian pulse with a small bandwidth can be used as RF signal as soon as a steady state has been achieved for the harmonic LO excitation. The bandwidth of the pulse has to be chosen in such a way that a single sideband operation of the mixer is guaranteed.

LUMPED ELEMENTS IN THE MM-WAVE RANGE

In the literature, several approaches for an inclusion of lumped elements in the FDTD mesh can be found. In [3] the elements are regarded as dimensionless devices and are placed on the edge of a FDTD cell. In [4] the lumped element is a one dimensional device between both conductors so that the device is distributed over several edges of the FDTD cells cascaded one by another. Dealing with low frequencies, up to 20 GHz, such a way of inclusion does not have a remarkable influence on the electric behaviour of the nonlinear microwave structure. Going up to the mm-wave range, e.g. the V-band or even the W-band, unphysical parasitic effects due to such an incorporation of lumped elements will occur, resulting in erroneous computation results. The main problem at higher frequencies is that the devices become as big as the passive discontinuity, so that the size plays an important role. The device, shown in Fig. 3, covers more than one FDTD

cell, and also most of the area of the junction. This has to be incorporated in the mesh structure. Four possible

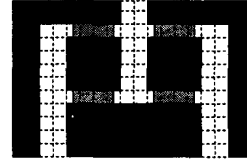


Figure 3: Junction with the diodes in real size; dashed lines show the grid

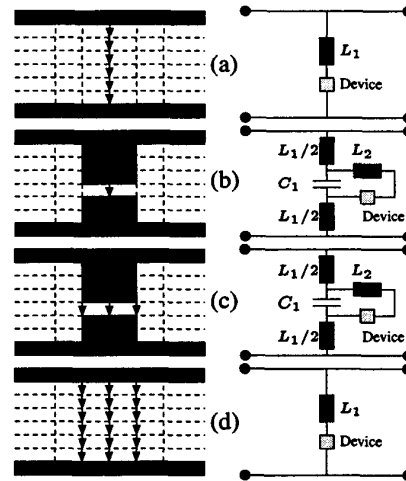


Figure 4: Possibilities of incorporation of lumped elements; test structure: 220Ω slotline with $300\mu m$ slotwidth and V-band shielding; dashed line represents the grid $50\mu m \times 100\mu m$ used for FDTD simulation; a) $L_1 = 0.204nH$; b) $L_1 = 0.110nH$, $L_2 = 0.034nH$, $C_1 = 8.45pF$; c) $L_1 = 0.110nH$, $L_2 = 0.013nH$, $C_1 = 8.45pF$; d) $L_1 = 0.123nH$

ways of including a diode into the FDTD mesh are indicated in Fig. 4. Version (a), distributing the device linearly over several edges of cells, results in an unphysical increased inductance twice as big as in reality. In (b) and (c), metal pads are used to better model the physical size of the diodes. Typically, however, the equivalent circuit of the diode already includes the capacitance between the two diode leads; thus this approach leads to an overestimation of capacitance. The best solution therefore is a distribution of the diode over the complete device area (d). The inclusion of the nonlinearities is done as discussed in [5]. A test structure was fabricated to validate this specific modelling of lumped elements. The diode is mounted across a finline slot in a V-band waveguide. The measurements at 0 V bias

and the small signal scattering parameters are compared to the simulation results of the four approaches according to Fig. 4. In the V-band the transmission reaches a minimum as the parasitic effects of the diode are in resonance. The transmission coefficient at resonance depends on the value of the resistance R_s . If the arrangement according to Fig.

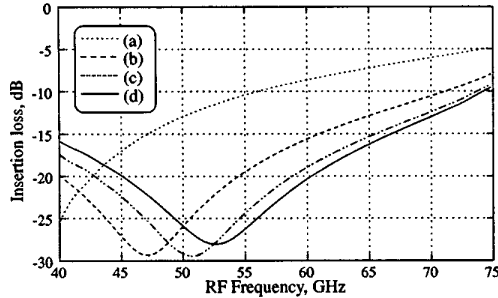


Figure 5: Simulation of the test structure with four approaches for lumped element inclusion (see Fig. 4).

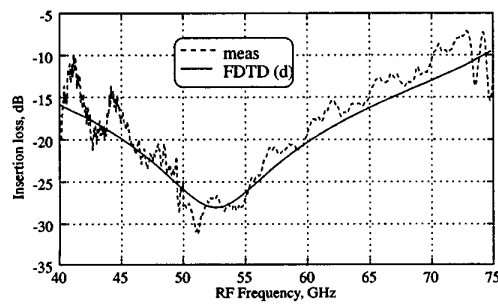


Figure 6: Comparison of the new approach with measurements.

4d) is used, a good agreement between the measurements and simulation is achieved.

OPTIMIZATION OF A FREQUENCY DOUBLER

For a better return loss, i.e. an improved conversion loss of the multiplier, a matching network was designed. The operation frequency should be 20 to 25 GHz and 40 to 50 GHz, respectively. The input power of the frequency doubler is chosen to 0 dBm. The characteristic impedances of coplanar waveguide is 50Ω and of the finline 110Ω . First simulations showed that the smaller the characteristic impedance of the finline the better is the conversion loss. The value of 110Ω is the limit due to the fabrication. For impedance models a Chebyshev type filter with 5 GHz bandwidth is applied. The junction with the two diodes is the first element of the three section filter. This leads to a bandwidth of 3.6 GHz with an equal

ripple response of the return loss of -9.4 dB. In a CAD

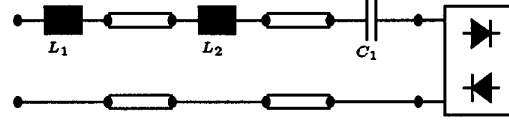


Figure 7: Filter circuit: $L_1 = 0.33nH$, $L_2 = 0.83nH$, $C_1 = 1.8pF$

tool, the filter circuit according to Fig. 7 is used for a preliminary design of the inductances and capacitance of the inverters, which then are used as starting values for the next optimization step using FDTD. The matched doubler as a whole is analyzed with FDTD, and the return loss is compared to the expected one. In Fig. 8 the matching

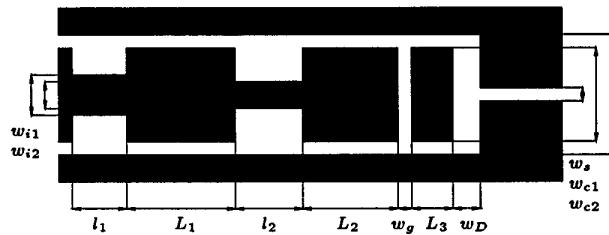


Figure 8: Layout of the matching network; Dimensions: $w_{c1} = 1.2mm$, $w_{c2} = 1.45mm$ (coplanar waveguide); $w_s = 0.05mm$ (slotline); $w_D = 0.35mm$, $L_3 = 1.732mm$ (first section); $w_g = 0.08mm$ (capacitive inverter); $L_2 = 4.803mm$ (resonator) $l_2 = 1.2mm$, $w_{i2} = 0.1mm$ (inductive inverter); $L_1 = 5.961mm$ (resonator) $l_1 = 0.4mm$, $w_{i1} = 0.2mm$ (inductive inverter)

network and its geometry are given. Comparing the measurement and the simulation result (Fig. 9), the conversion loss and the return loss show a good agreement. The bandwidth is larger than predicted. In a 5.5 GHz range, the return loss is below -10 dB. The conversion loss could be improved by about 3 dB, and the return loss by about 7 dB (Fig. 9). The frequency shift is caused by fabrication tolerances of both the passive structure and the diodes.

ANALYSIS OF A KA-BAND MIXER

For the design of a finline mixer, a similar concept can be applied [8], [9]. The local oscillator is matched to the diodes in the same way as with the doubler. Matching the LO port, less power is required to achieve the optimal operation point of the diodes. For this mixer, a RF matching network was not required because the junction already shows a good return loss over a wide frequency range. Fig. 11 and Fig. 12 show the return and the conversion loss of

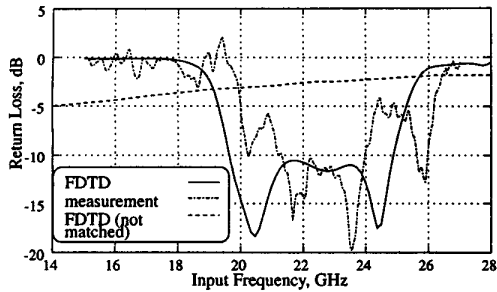


Figure 9: Return loss at 0 dBm input power

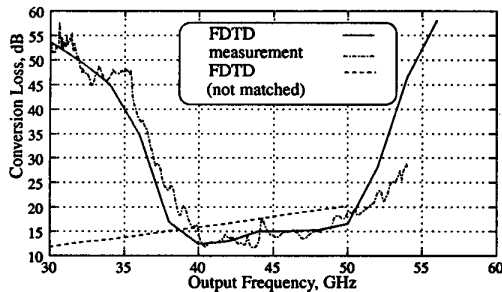


Figure 10: Conversion loss at 0 dBm input power

the mixer. The LO frequency is 30 GHz, and the RF return loss at about 30 GHz is -6 dB. A conversion loss of about 8 dB could be achieved. There is a good agreement between the measurements and the simulation results.

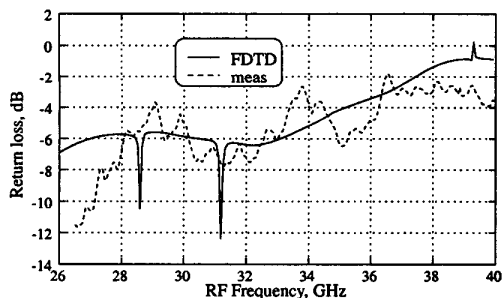


Figure 11: Return loss at -5 dBm input power

CONCLUSION

In this paper, an optimization of mm-wave diode based circuits is presented. As an example, a frequency doubler was designed for optimal conversion loss at 0 dBm input power. The FDTD method has proven to be a useful tool for the design of nonlinear components even in the mm-wave range. For higher frequencies, e.g. in the V- or W-band, a concept for the incorporation of lumped elements

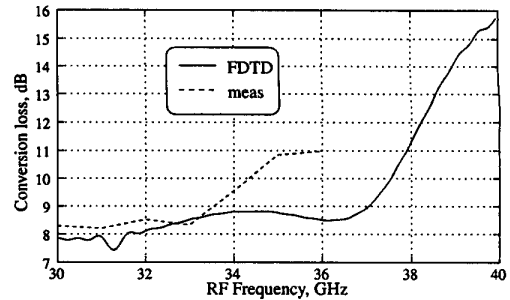


Figure 12: Conversion loss at -5 dBm input power

in the FDTD mesh without generating unphysical reactances has been presented. Presently, this approach is used for the design of a subharmonic mixer with both LO and RF matching networks at 60 GHz.

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