

FDTD ANALYSIS OF A QUASI-PLANAR MM-WAVE FREQUENCY DOUBLER

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ABSTRACT

A quasi-planar frequency doubler based on the junction of a coplanar waveguide and a finline using two silicon Schottky diodes mounted across this junction is analyzed. The extended Finite Difference Time Domain (FDTD) method is used with a newly developed excitation scheme for harmonic waves feeding a defined power with the proper field distribution into the circuit. This harmonic signal is fed to the diodes via the coplanar line. The output signal containing even harmonics only, is analyzed on the finline and compared to measurements. Operating frequencies are 20 to 25 GHz and 40 to 50 GHz, respectively.

INTRODUCTION

Recent development of faster computers and progress on the original algorithm [1] have made FDTD attractive to analyze complex microwave circuits including nonlinear elements. Commercial CAD tools possess an extensive library for various microwave structures and semiconductor elements. With respect to short computation and optimization times, passive and active elements mostly are cascaded one to another. Typically, no higher order mode coupling and no parasitic coupling between adjacent circuit parts are included. The limitations of standard CAD procedures are even more severe if - like for frequency doubler reported here - the semiconductor elements are placed directly into a major discontinuity. As a consequence, a reliable analysis and optimization of the complete structure with standard CAD tools becomes rather difficult. Therefore, an extended FDTD method [3] using an equiv-

alent current source technique is applied to compute the complex circuitry including quasi-planar structures as well as the diodes. The two diodes are described as concentrated non-ideal lumped elements represented by their equivalent circuit. With the full-wave features of the FDTD algorithm, the circuit performance can be visualized, and the interaction between the components can be taken into account. As the structure requires a harmonic excitation with defined power, a new accurate excitation method has been developed to enable a correct determination of conversion loss. Comparing the measurements with the theoretical results, it is shown that this approach is valid.

DESCRIPTION OF THE CIRCUIT

For broadband operation, e.g. in measurement systems, a balanced/unbalanced diode configuration has proven to be a useful concept for frequency multiplication of even order [5]. Such a structure easily can be implemented in the junction of a coplanar waveguide and a slotline or finline, as shown in Fig. 1. The coplanar line is placed in a waveguide channel of reduced cross section, thus higher harmonics, generated by the diodes are reflected. In the area of the junction and the finline, a shielding with standard waveguide dimensions is used.

THEORY

Diode Modelling

The two diodes are placed directly in the junction between the coplanar waveguide and the finline (Fig. 1). As active device, a HP HSCH 5330 Silicon Low Barrier Schottky diode is chosen. In the presented approach, the diodes are modeled by their equivalent

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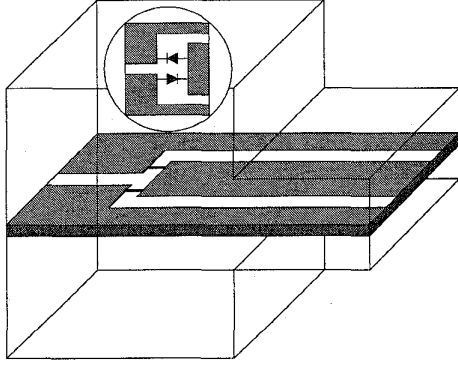


Figure 1: Basic structure of the doubler

circuit given by the manufacturer (Fig. 2). Investigations have shown that the diode capacitance very sensitively affects the whole electrical behavior and had to be taken into account. Because a wide range is given for the capacitance by the manufacturer, the actual value had to be determined accurately by measurements. The capacitance of the diode, in this case 50 fF at 0 V, is voltage dependent and is modeled with the following equations [4]:

$$C = \begin{cases} \frac{C_{j0}}{(1-\frac{U}{\Phi_0})^m} & U < \Phi_0/2 \\ \frac{C_{j0}(1-FC(1+M)+M\frac{U}{\Phi_0})}{(1-FC)^{1+m}} & U \geq \Phi_0/2 \end{cases} \quad (1)$$

where Φ_0 is the built-in voltage, C_{j0} the capacitance at 0 V and m , M , and FC are constants, each chosen as 0.5 in this case. First tests showed that the non-ideal capacitance has to be considered as it increases the output power of about 1 to 2 dB.

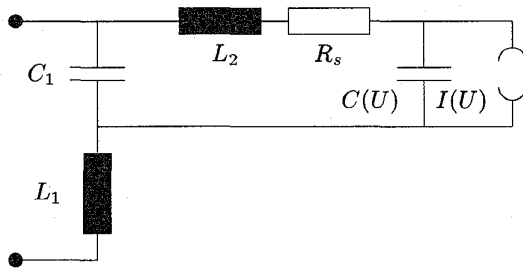


Figure 2: Equivalent circuit of the diode

Implicit algorithm

To include the diode circuit into the FDTD scheme, an equivalent circuit model with a current source and a capacitance for the FDTD cell is used. An interface to the diode circuit is the Ampere's current law:

$$-C_{eq} \frac{\partial U}{\partial t} + I_{eq} = I_{dev} \quad , \quad (2)$$

where C_{eq} is the equivalent capacitance of the cell, and I_{dev} represents the current through the device. I_{eq} is determined each time step from the integration of the H field. If the diode is extended over more than one cell, the equivalent circuits of the FDTD cells together with the equivalent circuit of the diode lead to a system of differential equations:

$$\frac{\partial \vec{x}}{\partial t} = \vec{f}(\vec{x}) + \vec{g}(t) \quad , \quad (3)$$

where \vec{x} is the state vector of voltages and currents in the diode network, and $\vec{g}(t)$ is the vector including the current sources, according to the integral over the H field known at discrete time steps.

Explicit algorithms like that of Runge-Kutta of second order, which can easily be implemented and fits to this time scheme, cause instability after several thousand time steps. So, a fully implicit algorithm, unconditionally stable under Courant condition, had to be implemented. The derivation with respect to time in equation (3) is solved by the backward Euler method, and the state vectors are interpolated at half time steps to get an algorithm of second order accuracy. This leads to a nonlinear system of equations, which is solved by the Newton Raphson method.

Harmonic Excitation

For doubler operation, a harmonic signal has to be chosen, while the signals generated by the diodes will contain harmonic frequencies and possibly other frequencies generated by parametric effects. For such a harmonic excitation of the circuit, difficulties may occur to separate the injected signal not limited in time from the reflected ones. Normally, the input line is fed at its end by a concentrated source

including a matched load. On one hand, this approach requires a sufficiently long feeding line, only then the fields converge to the correct field distribution of the specific transmission line. This however, leads to increased computation times. On the other hand, at millimeter wave frequencies, the transition from the concentrated source to the transmission line already represents a discontinuity, resulting in unwanted reflections, increased errors and partly stability problems. Another important point is the possibility to feed the transmission line with a defined power, which is necessary for the determination of the conversion loss. In this contribution, therefore, a different excitation method was chosen. Opposite to the diodes, the input line is loaded by absorbing boundary conditions [2]. Then a precomputed field according to the natural field of this transmission line is excited in a plane between the structure under test and the absorbing wall (Fig. 3). In this way, only a short section of transmission line is required, and reflections from the source can be avoided. This excitation generates two waves propagating in two directions from this plane. The equations for the field components tangential to the excitation plane, here only E_x is given, are determined in the following way:

$$E_x^{n+1} = E_x^n + \frac{\Delta t}{\epsilon \Delta y \Delta z} \text{rot} \vec{H}^{n+1/2} * \vec{e}_x - \frac{2\Delta t}{\epsilon \Delta z} H_{inc,y} \quad (4)$$

where H_{inc} is the magnetic field of the basic mode of the transmission line. With the value of the H field, the power propagating on the transmission line can be accurately adjusted and is independent of the spatial or time steps as well as of frequency.

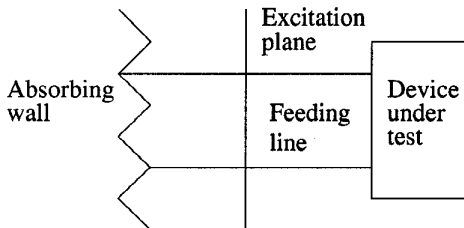


Figure 3: Excitation

For the calculation of the return loss of the doubler, the injected field easily can be subtracted from the reflected signal.

RESULTS

The operating frequency band of the doubler was chosen from 20 to 25 GHz and 40 to 50 GHz. The overall structure is divided into 250000 cells, and 5000 time steps are necessary for an evaluation of the doubler parameters. One simulation is necessary to investigate the behaviour at one power level and at one frequency point which takes about two hours computation time on a Sun workstation. In a first investigation, the conversion loss versus the input power at 20 GHz is compared to the measurement showing a good agreement (Fig. 4). In contrast to this, simulations done with a commercial CAD system showed deviations of up to 6 dB. The minimum of the conversion loss is achieved both in the theory and in the experiment at the same power level. The output spectrum is given in Fig. 5. The advan-

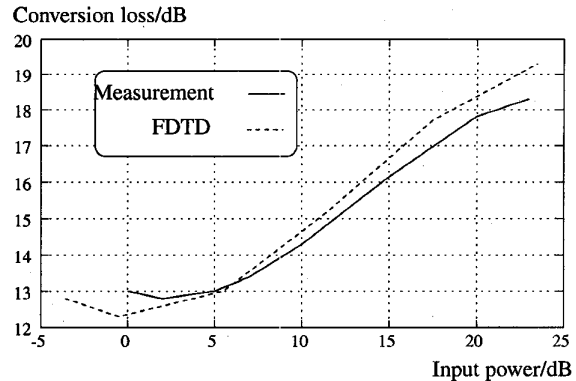


Figure 4: Conversion loss at 20 GHz

tage of this balanced/unbalanced doubler clearly can be seen: no output signals appear at 60 or 100 GHz. In Fig. 6 the field distribution is shown in the junction illustrating the diode operation. Finally, it has to be stated that the electric behaviour of the doubler very strongly depends on both: on placement of the diodes in the junction and the exact value of the diode capacitance.

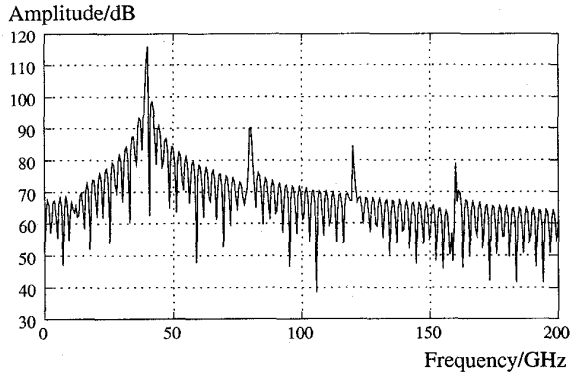


Figure 5: Output spectrum for an input frequency of 20 GHz

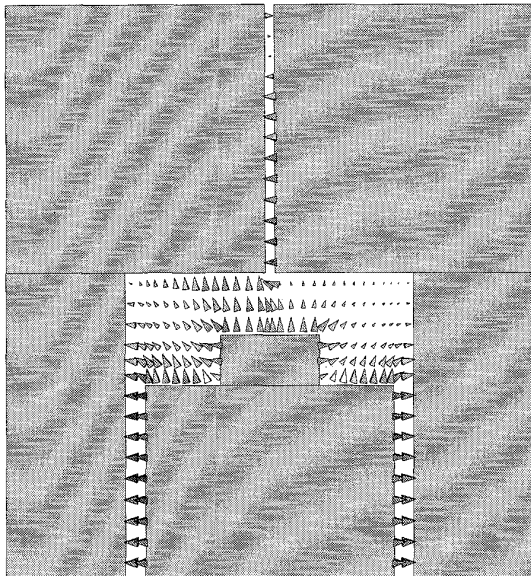


Figure 6: Snapshot of the field distribution in the junction (The diodes are not shown here; For their location see Fig. 1)

CONCLUSION

In this paper, a doubler has been analyzed using an extended FDTD method and a new concept for an accurate harmonic excitation. The theoretical predictions could be verified by measurements. Summarizing the results presented above, the FDTD method has turned out to be a suitable tool for complex non-

linear circuits, and equally could be applied to similar problems, e.g. finline mixers, which include a comparable circuit arrangement [6].

REFERENCES

- [1] K.S. Yee, *Numerical Solution of Initial Boundary Value Problems Involving Maxwell's Equation in Isotropic Media*, IEEE Trans. Antennas Propagation, vol. 14, pp. 302-307, May 1966
- [2] Fang Jiayuan, *Absorbing Boundary Conditions Applied to Model Wave Propagation in Microwave Integrated Circuits*, IEEE MTT, vol. 42, pp. 1506-1513, August 1994
- [3] Melinda Piket-May, Allen Taflove, John Baron, *FD-TD Modeling of Digital Signal Propagation in 3-D Circuits With Passive and Active Loads*, IEEE MTT, vol. 42, no. 8, pp. 1514-1523, August 1994
- [4] P. Ciampolini, P. Mezzanotte, L. Roselli, D. Sereni, R. Sorrentino, P. Torti, *Simulation of HF Circuits with FDTD Technique Including Non-Ideal Lumped Elements*, IEEE MTT-S, pp. 361-364, 1995
- [5] J. Koehler, B.Schiek, *Broadband microwave frequency doublers*, The Radio and Electronic Engineer, Vol. 48, Jan./Feb. 1978, pp. 29-32
- [6] W. Menzel, *Integrated Fin-Line Components for Communication, Radar, and Radiometer Applications*, Infrared and Millimeter Waves, Vol. 13, Academic Press, 1985, pp. 77-121