Simulation of a Nonlinear Frequency Multiplier using the FDTD Technique

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Abstract **─** Nonlinear circuits are a key component in RF transceivers. Efficiency and power requirements for 5G communication are creating new challenges in simulation and modeling of nonlinear devices. An application of the finite-difference time-domain (FDTD) method to nonlinear circuits comprising diodes is demonstrated. A frequency multiplier is constructed from a diode and a low-pass filter. The diode is simulated in the context of this circuit to demonstrate the formation of harmonics.

Index Terms **─** FDTD, frequency multiplier, nonlinear.

I. INTRODUCTION

Frequency multipliers are often employed in microwave communications devices operating at high frequencies, including those in the millimeter-wave region. Moreover, other devices share in the harmonic-generating property of a frequency multiplier, including nonlinear amplifiers and mixers. While harmonic-balance analysis has been a mainstay for the analysis of such devices, we demonstrate that the finite-difference time-domain (FDTD) simulation technique has merit for certain types of nonlinear problem.

A. Frequency multiplier theory of operation

The voltage-current relationship for an ideal diode is [1]:

$$I_D(V_D) = I_s\left(e^{\frac{V_D}{\eta V_T}} - 1\right). \quad (1)$$

Where V_D is the voltage across the diode, I_s is the saturation current, V_T is the thermal voltage of the diode, and η is an ideality factor. This equation may be rewritten to remove the exponential, by:

$$I_D(V_D) = I_s \sum_{n=1}^{\infty} \frac{\left(\frac{V_D}{\eta V_T}\right)^n}{n!}. \quad (2)$$

If V_D is a sinusoidal signal given by $V_D = a\cos(\omega t)$, then (2) may be written as:

$$I_D(t) = I_s \sum_{n=1}^{\infty} \frac{\left(\frac{a\cos(\omega t)}{\eta V_T}\right)^n}{n!}. \quad (3)$$

Taking only the terms $n = (1,2,3)$, and using trigonometric identities to simplify the exponents [2], the current may be approximated as:

$$I_D(t) \approx I_s \begin{pmatrix} \frac{a\cos(\omega t)}{\eta V_T} + \frac{a^2(\cos(2\omega t)+1)}{4\eta^2 V_T^2} \\ + \frac{a^3(\cos(3\omega t) - 3\cos(\omega t))}{24\eta^3 V_T^3} \end{pmatrix}. \quad (4)$$

From this expression, it is possible to see how a sinusoidal voltage across a diode is transformed into both even and odd harmonics of the fundamental frequency. Thus, the diode may be used in this capacity as a frequency multiplier.

B. FDTD simulation

Problems in this work are simulated using the well-known FDTD algorithm, based on discretizing the problem into a grid of Yee cells, and solving differential forms of Maxwell's equations in the time domain. All results presented here are generated based on the code developed in [3].

Simulation of the diode is performed by solving a modified form of (1) in order to update the values for electric fields in the region of the diode. This equation is solved iteratively using the Newton-Raphson method [3, Ch. 4].

II. SIMULATIONS AND RESULTS

To demonstrate FDTD simulation of a diode in the context of a frequency multiplier, we simulate two configurations. First, the diode is connected in series with a voltage source and a 50Ω resistor. Second, the diode is connected as a shunt device after a low pass filter. The configurations were simulated as circuit schematic models using the Transient simulation in Keysight's ADS software [4], with ADS results plotted alongside the FDTD results for comparison.

A. Diode in series with resistor

To test the diode updating equation in the context of a simple circuit, a diode was placed in series with a 50Ω resistor as shown in Fig. 1 (a). Conductors between lumped elements were modeled using thin-wire approximations. The voltage source was configured to produce a 5 GHz cosine wave with a peak-to-peak voltage of 3 V, and an internal resistance of 50Ω.

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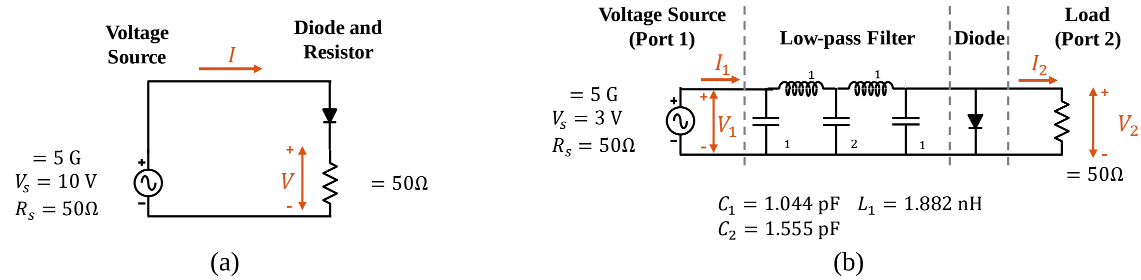

Fig. 1. Circuit schematics for diode simulations. (a) Diode in series with resistor and (b) diode with low-pass filter.

Time-domain results from this simulation are plotted in Fig. 2, where the diode is seen to rectify current traveling through the 50Ω resistor. The voltage across this resistor is plotted in the frequency domain in Fig. 3. In this plot, harmonics may be seen every 5 GHz, as a result of the diode's clipping effect.

B. Diode with low-pass filter

From the previous results, we see that the diode produces numerous harmonics above 5 GHz. To make use of these harmonics for the function of frequency multiplication, it is necessary to place filters before and after the diode [5]. In this simulation, a low-pass filter is placed before the diode to prevent harmonics from reaching the source, as shown in Fig. 1 (b). Results from this simulation are plotted in Fig. 4: at port 1, only the excitation at 5 GHz may be seen. At port 2, following the diode, we see harmonics every 5 GHz as a result of the diode. Extension of this work to the FDTD simulation of transistors, as described in [6], is in progress.

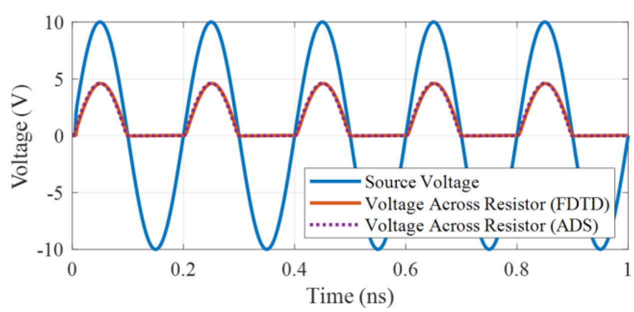

Fig. 2. Measured voltages for circuit with diode in series with resistor shown in Fig. 1 (a).

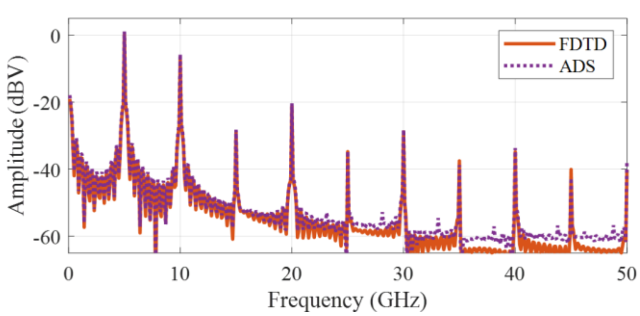

Fig. 3. Frequency domain plot of voltage measured across series diode and resistor from Fig. 1 (a).

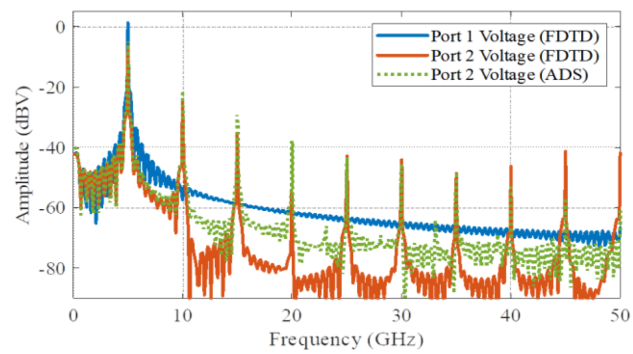

Fig. 4. Frequency-domain plot of voltages at port 1 and port 2 of network with low-pass filter shown in Fig. 1 (b).

III. CONCLUSION

As a proof-of-concept, we demonstrate an application of FDTD simulation to a circuit incorporating passive devices and a diode as a nonlinear circuit to analyze harmonics in microwave devices. From this result, we conclude that FDTD can be a useful method for modeling 3-D structures incorporating nonlinear devices.

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