Global Time-Domain Full-Wave Analysis of Microwave FET Oscillators and Self-Oscillating Mixers

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ABSTRACT

The global time-domain nonlinear analysis of microwave FET oscillators and self-oscillating mixers using the extended FDTD technique is presented. Employing the concept of equivalent current/voltage sources, the device-wave interaction is characterized and incorporated into the FDTD time-stepping algorithm. Consequently, investigation of highly nonlinear phenomena, such as injection locking and intermodulation, can be accomplished by utilizing a large-signal device circuit model. Theoretical results are validated by experiments.

INTRODUCTION

Oscillator has been an interesting problem in nonlinear circuit analysis. Being an autonomous system, it can find its own oscillation frequency and power level. Furthermore, as far as two-port GaAs FET oscillators are concerned, they can function as injection-locked oscillators or self-oscillating mixers with the presence of an injection signal [1].

Two most commonly used techniques, i.e., Harmonic-balance and Volterra-series methods, for nonlinear circuit analysis have been applied to this kind of problem [2]-[4]. Both of them conduct the simulation in frequency domain by dividing the whole circuit into subcircuits and cascading the frequency characteristics of each subcircuit to determine the overall circuit performance. However, as the trend of microwave circuit designs moves toward highly integrated system and higher frequency range, circuit designs have to deal with the problems caused by electromagnetic effects, such as radiation, surface wave leakage and coupling between different subcircuits. Since the interaction between the nonlinear behaviors and electromagnetic mechanism can affect the system performance, the entire circuit needs to be characterized as a whole by a full-wave analysis incorporating the nonlinear active device.

Among available full-wave approaches, the finite-difference time-domain (FDTD) method has attracted much interest because of its electromagnetic time-domain analysis and versatile simulation capacity. The FDTD method has been demonstrated to be able to analyze microwave circuits including lumped semiconductor devices by employing the equivalent current or voltage sources [5]-[7]. The applications of this extended FDTD algorithm to the large-signal analysis of a FET amplifier [6] and a diode mixer [7] have been reported. However, they are either theoretical in nature [6] or involved with a two-terminal device [7].

In this work, we devote our effort to the application of the extended FDTD method for global simulation of highly nonlinear FET circuits, which are traditionally difficult to analyze. Examples under discussion include a frequency-stabilized oscillator, an injection-locked oscillator and a self-oscillating mixer. These circuits are not designed for optimal performance, but rather to demonstrate the capability of this technique applied to highly non-linear circuits. Experimental results are presented for validation of the theory.

INCORPORATION OF FET DEVICE IN THE FDTD ALGORITHM

The active device used for the circuits in this paper is a packaged FET NE76038. Assuming that the active device is electrically small, then the active device can be treated as dimensionless and represented by its equivalent circuit model. Fig. 1(a) shows the manufacturer's nonlinear circuit model of NE76038. The transistor in Fig. 1(a) is implemented by the TriQuint's Own Model (TOM) [8] in Fig. 1(b). The passive elements in Fig. 1(a) account for the parasitic effects. In addition, the DC bias is applied to the drain and gate ports through a RF-choke inductor in our simulation. In measurement, the biasing is provided via an external bias network HP11612A.

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The device-wave interaction in each FDTD time-stepping process is established through the employment of equivalent current or voltage sources. Detailed description of the equivalent current/voltage sources can be found in [6], [7]. Upon applying the equivalent sources at the three terminals of the FET, the nonlinear state equation of the resulting circuit is derived. The state equation can be solved by finite-difference scheme and an iterative multidimensional root-finding algorithm, e.g., Newton-Raphson method, in each time step. The terminal voltages of the FET can thereby be determined and fed back to the FDTD simulation. All the results reported in this paper are obtained by applying the equivalent voltage-source scheme.

RESULTS

The first circuit under consideration is a frequency-stabilized oscillator composed of a ring resonator coupled to the input line as shown in Fig. 2. The source port of the FET is connected to a microstrip stub to provide negative resistance. The ring resonator is designed to have the fundamental resonance at around 5.8 GHz. Table I shows the theoretical and experimental values of the oscillation frequency and power level. The power level with respect to each frequency component is determined by a Fourier transform in our analysis. Because of the 3-D time-domain modeling feature, the wave propagation inside the circuit can be visualized theoretically as shown in Fig. 3, where information of interest, such as phase delay and signal amplification, can be observed. Fig. 4 illustrates the calculated and measured output power as V_{ds} is varied from –1.4 to 4.4 V. The discrepancy becomes greater when V_{ds} sweeps away from 3 V. This is understandable since the device model in Fig. 1(a) is optimal at V_{ds} = 3 V.

Fig. 5 shows an oscillating circuit that uses a tuning stub instead of a ring resonator at the input line. Without the presence of a injection signal at the input, the circuit works as a free-running oscillator. The comparison of oscillation frequency and output power in this case is shown in Table II. Since the oscillator is not stabilized by a high-Q resonator, the inaccuracy of the device model can significantly contribute to the discrepancy between calculated and measured frequencies. By injecting a 5.09 GHz signal at -10 dBm, the circuit is injection-locked. Fig. 6 shows the comparison of output power as a function of V_{ds} in this case. Similar to Fig. 4, the greater discrepancy is attributed to the invalidity of the device model when V_{ds} deviated from 3 V specified by the device Model. As the injection signal power is increased gradually to 10 dBm, the variation of output power is illustrated in Fig. 7. Higher injection-locking power can only deteriorate the output power of the oscillator.

The FET oscillator in Fig. 5 can also work as a self-oscillating mixer when the frequency of the injection signal is out of the locking range. Fig. 8 illustrates the power spectral at the output of the mixer calculated by FDTD. With a RF frequency sweep between 5.4 and 6.0 GHz, Fig. 9 shows the calculated and measured conversion gain when the input RF available power level is set to -10 dBm. The agreement is better than 1 dBm over the frequency band. Injecting a 5.4 GHz RF signal with a power level sweep between -10 and 2 dBm, Fig. 10 illustrates comparison of the output IF power level. Good agreement can once again be observed.

CONCLUSION

We have demonstrated that the extended FDTD technique can accurately predict the amplitude and frequency of nonlinear FET oscillators. Moreover, the injection-locking and intermodulation phenomena in FET injection-locked oscillator and self-oscillating mixer respectively have also been investigated in this work. This technique should prove more suitable for strongly nonlinear circuits that have multitone excitation than conventional Harmonic-balance and Volterra-series techniques, especially when the mutual coupling between different part of the circuit becomes a crucial issue.

ACKNOWLEDGMENT

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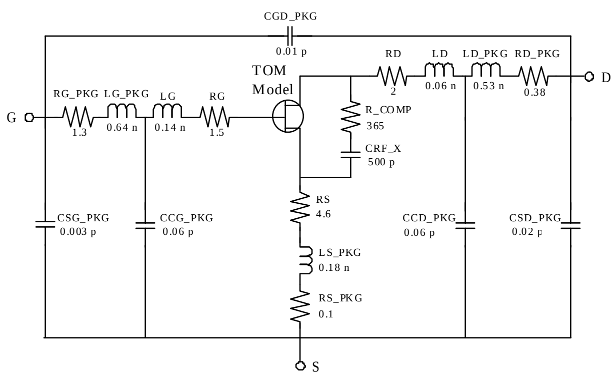
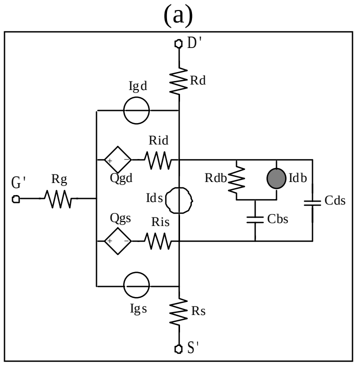


(a)



(b)

Fig. 1 (a) Nonlinear circuit model of NE76038. (b) TOM model schematic.

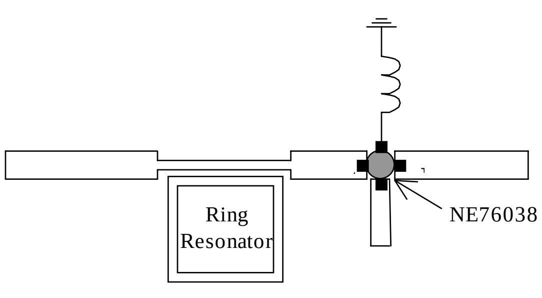


Fig. 2 A frequency-stabilized FET oscillator

Table I

Theoretical and experimental results of the frequency-stabilized oscillator for the bias $V_{gs} = 0$ V and $V_{ds} = 3$ V.

	Calculated	Measured	Deviation
Oscillation Frequency	5.8245GHz	5.8414GHz	-0.289%
Output Power	11.1246 dBm	11.50 dBm	-3.264%

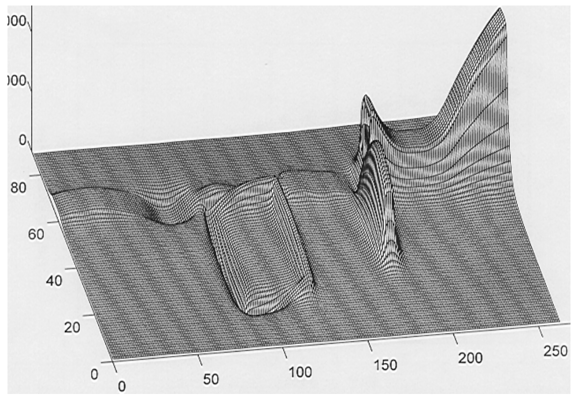


Fig. 3 A snap shot of the wave propagation inside the frequency-stabilized oscillator.

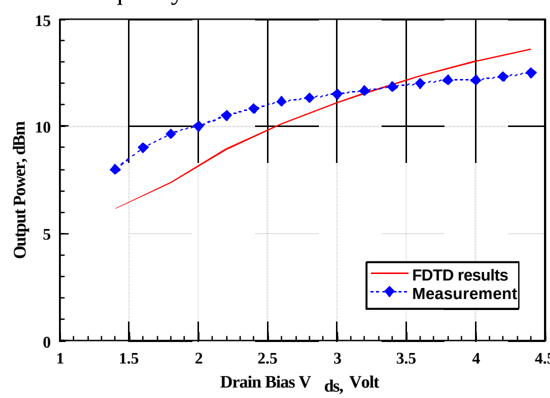


Fig. 4 Calculated and measured output power of the frequency-stabilized oscillator with respect to V_{ds}.

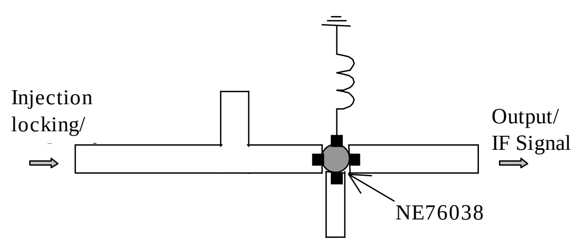


Fig. 5 An FET injection-locked oscillation/self-oscillating mixer.

Table I

Theoretical and experimental results of the Free-Running Oscillator for the Bias $V_{gs} = 0$ V and $V_{ds} = 3$ V.

	Calculated	Measured	Deviation
Oscillation Frequency	5.1519GHz	5.1078GHz	-0.863%
Output Power	9.5108 dBm	10.0 dBm	-4.89%

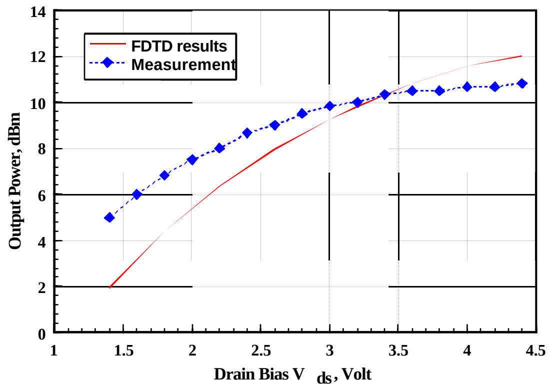


Fig. 6 Calculated and measured output power of the injection-locked oscillator with respect to V_{ds}.

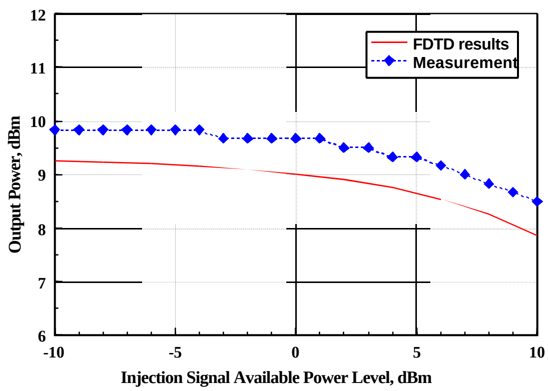


Fig. 7 Calculated and measured output power of the injection-locked oscillator with respect to injection signal available power level.

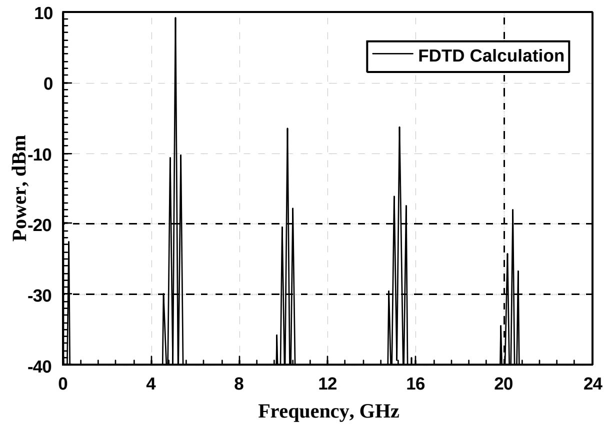


Fig. 8 Calculated power spectra at the output of the self-oscillating mixer.

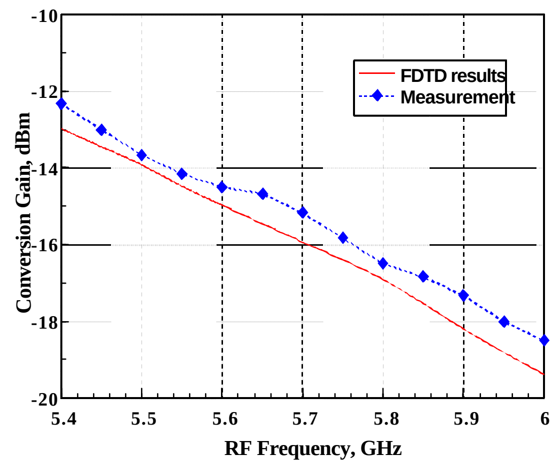


Fig. 9 Calculated and measured conversion gain of the self-oscillating mixer with respect to RF frequency.

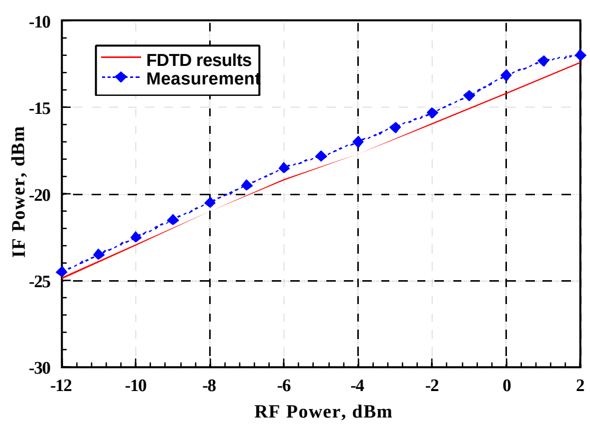


Fig. 10 Calculated and measured output IF power of the self-oscillating mixer with respect to input RF available power level.