Active Antennas Incorporating Tunnel Diodes—Large Signal Model Approach

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***Abstract*—In this letter, a comprehensive dc and RF model of heterostructure interband tunnel diodes (HITDs) is extracted. Active antennas incorporating tunnel diodes are analyzed in time domain using this tunnel diode model. The simulated and measured results are in good agreement in terms of oscillation frequencies of the active antennas. Phase noise of −114.67 dBc/Hz @ 1.0 MHz offset is achieved for injection-locked active antennas. The simulated injection locking range of a Ka band active antenna array is investigated.**

***Index Terms*—Active antenna, injection locking, RF large signal model, semiconductor heterostructure, tunnel diode.**

I. Introduction

RECENT research has demonstrated several potential applications of tunnel diodes in many semiconductor circuits [1], [2]. The negative differential resistance (NDR) of a tunneling diode allows the design of novel devices and circuits with reduced complexity and size. Although the tunnel diode oscillator as a RF source has been overshadowed by the higher power output available from avalanche (IMPATT) or Gunn-effect transit-time oscillators, the tunnel diode oscillator exhibits lower noise and is therefore useful in applications where short range detection is called for.

To exploit the potential of the tunnel diodes, accurate models are required. These models can be developed based on theoretical, experimental, or combined studies. For tunnel diodes, it is very difficult to derive an ac model from device physics. The circuit model developed in this letter is extracted from on-wafer dc and S-parameter measurements. The model is incorporated in the finite difference time domain (FDTD) scheme for active antenna design.

For active antenna simulation, lumped elements can be incorporated in the FDTD through several methods. These methods include the use of deducted formulas for a simple circuit of resistors, capacitors, inductors, or a parallel combination of these passive devices [4], and the use of SPICE by linking it to the FDTD for the relationship of device voltage and current [5]. Toland, *et al.* [6] derived an update scheme for a large signal model of a resonant tunneling diode (RTD), to simulate a distributed cavity. In [7], the device voltage is evaluated from the state equation of the circuit, and subsequently the voltage is used to update the electromagnetic fields. In this letter we adopt a general method, the Runge–Kutta approach, combined with the FDTD method, to obtain simulation results for active antennas.

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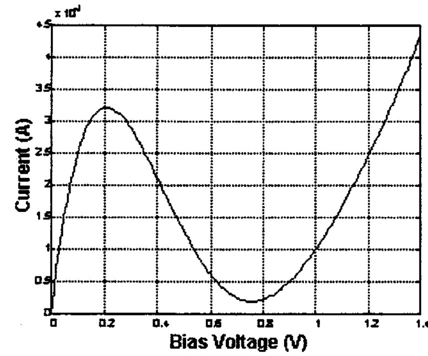
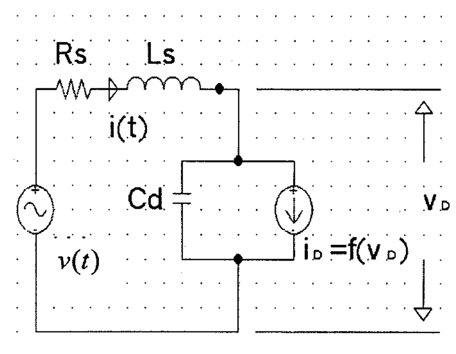


(a)



(b)

Fig. 1. (a) Nonlinear dc characteristics of a typical tunnel diode; (b) RF large signal model for the tunnel diode. The voltage controlled current source (VCCS) is determined from (a).

II. High Frequency Characteristics and Time Domain Analysis of HITD Devices

Fig. 1 shows the dc and RF characteristics of a typical tunnel diode. The nonlinear tunnel diode I–V characteristic represents a variable negative resistor. A fifth-order polynomial is fit to the measured nonlinear I–V characteristics as shown in Fig. 1(a). For biases less than 0.25 V, the current of tunnel diode is determined by majority tunneling mechanism. It reaches a peak and then the diode enters the so-called NDR region. Beyond 0.75 V, the diode behaves like a conventional PN diode, dominated by minority diffusion. The high frequency behavior of the tunnel diode is modeled as a large signal model circuit as shown in Fig. 1(b). The circuit has been simplified by assuming a fixed junction capacitance C_d instead of one that is voltage-dependent, while the diode series resistance and inductance have been included in R_s and L_s, respectively. R_s and C_d are determined from a small signal S-parameter measurement at one bias point in the NDR region of the tunnel diode.

The model provides insight into the device operation and represents both dc and RF properties of tunnel diodes with a high degree of accuracy. Our model for the tunnel diode is developed for analog RF and microwave applications. All investigations of tunnel diodes in this work are based on single well heterostructure interband tunnel diodes (HITD) in the In(0.53)Ga(0.47)As/In(0.52)Al(0.48)As/InP material system [10].

The impedance is extracted from the equivalent circuit model, using a general approach, the Runge–Kutta method, which may apply to any nonlinear device model. The governing equations for the circuit shown in Fig. 1(b) are given as

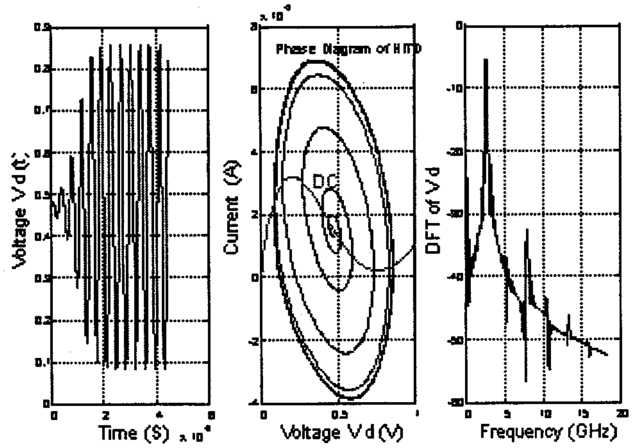
$$\begin{cases} L_S \dfrac{di}{dt} = -v_D - R_S \cdot i(t) + v(t) \\ C_d \dfrac{dv_D}{dt} = i - i_D(v_D). \end{cases} \tag{1}$$

The nonlinear behavior of the tunnel diode is represented in the voltage–current relationship $i_D(v_D)$ in (1). Impedance and self-oscillation of the tunnel diodes simulated through above equation can be found in [8], [10].

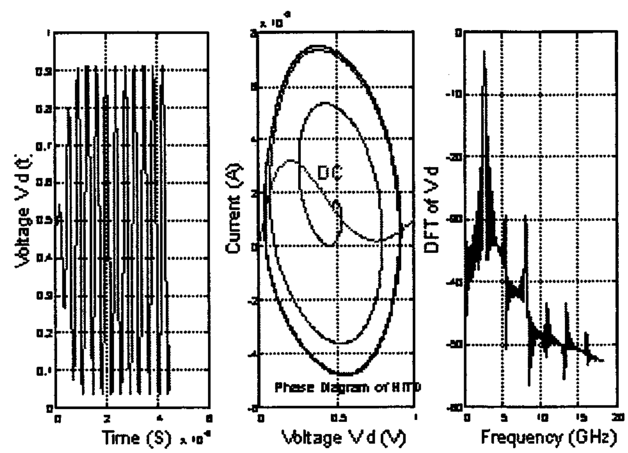
III. Active Antennas and Injection Locking

With the knowledge of the circuit model of the tunnel diode, we designed active antennas incorporating tunnel diodes. Active antennas have the advantage of combining oscillator and radiator together and hence have the potential of being compact in size. On one side, the tunnel diode generates RF power as an oscillator; on the other side, the antenna dissipates or radiates the power. The antenna impedance at the resonant frequency, used in the design of the active antenna, is obtained through Spectral Domain Approach (SDA) [2]. The values of the impedance are chosen from 30$\sim$120 Ω, according to slot antenna geometry. In this paper, we utilize time domain simulation to verify the active antenna design done from the frequency domain approach.

In the time domain simulation, given a voltage $v(t)$, one is able to find the instant current $i(t)$ through the Runge–Kutta method from (1). The R_S in (1) is modified since it now also represents the antenna board impedance. This $v(t)$ and $i(t)$ relationship is then related to electric and magnetic fields in FDTD scheme [8]. For injection locking simulation, injection signal v_{inj} plus dc bias V_d is in place of $v(t)$. During the FDTD run, the voltage v_D across the junction capacitor C_d and the instant current $i(t)$ flowing through the tunnel diode are recorded and plotted as variable and dependent in Fig. 2 in the same figure with dc characteristics of the diode as the phase diagram. It can be seen how the ac components superimposing on the dc components are developed, indicating the oscillation dynamics of the tunnel diode antenna. The time domain data and their frequency counterparts are also plotted in Fig. 2, which show an oscillation frequency of 2.70 GHz. Harmonics due to the nonlinear behavior of the tunnel diode are predicted by our simulation (frequency responses in Fig. 2). The measured oscillation frequency is 2.688 GHz, as shown in the Fig. 3. The phase noise values are measured at the oscillation frequency.



(a)



(b)

Fig. 2. (a) Simulated free oscillation [$v_{inj}(t) = 0.0$] of active antenna with oscillation frequency $f_0 = 2.70$ GHz; (b) injection locking of active antenna. The tunnel diode parameters are $Ls = 4.0$ nH, $Rs = 20.0\Omega$ and $Cd = 0.8$ pF. The amplitude of injection signal $v_{inj}(t)$ is -19.6 dBc lower than that of free oscillation.

One of the issues arising in the application of tunnel diodes is the dc bias stability [9], [10]. The tunnel diode itself tends to oscillate at certain circuit arrangements, which, therefore, makes the dc currents unstable. To overcome the instability of the tunnel diode, injection locking is used in the active antenna. The injection signal level is chosen at a level of $\sim$20 dBc lower than that of the free oscillation of the active antenna. The injection helps to quickly reach the stable oscillation status, which can be seen from the phase diagram depicted in Fig. 2(b). After injection locking, the amplitude of the oscillation voltage for the active antenna increases by about 3$\sim$5 dB [frequency responses in Fig. 2(a) and (b)]. The injection locking results in a very stable oscillation at frequency 2.688 GHz with output power -16.67 dBm, and a smooth phase noise performance as shown in Fig. 3. The peaks in the phase noise in Fig. 3 before injection locking have been suppressed when injection is enforced.

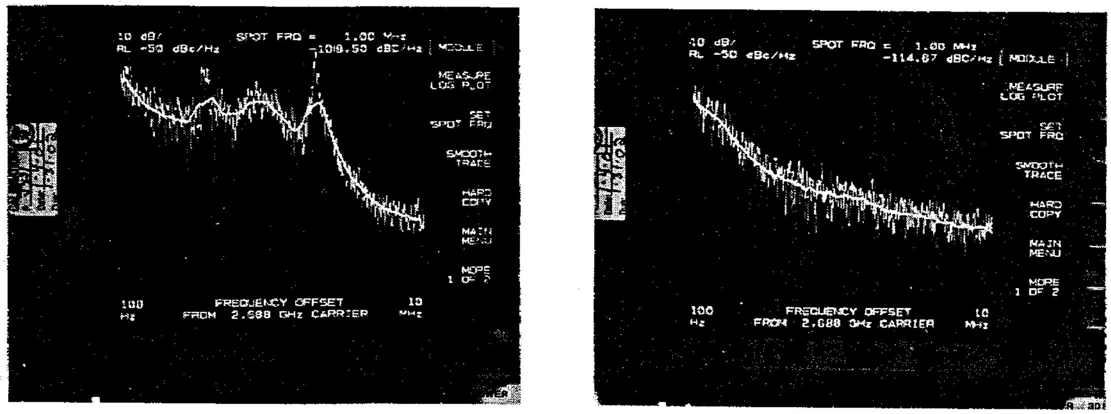


Fig. 3. Improvement of phase noise for $2.5^*2.5$ um HITD by injection locking. dc bias $Vd = 0.314$ V with $Id = 2.34$ mA. Oscillation frequency $f_0 = 2.688$ GHz with output power $P = -16.67$ dBm. Phase noises are -108.50 and -114.67 dBc/Hz @1MHz offset, before and after injection locking respectively.

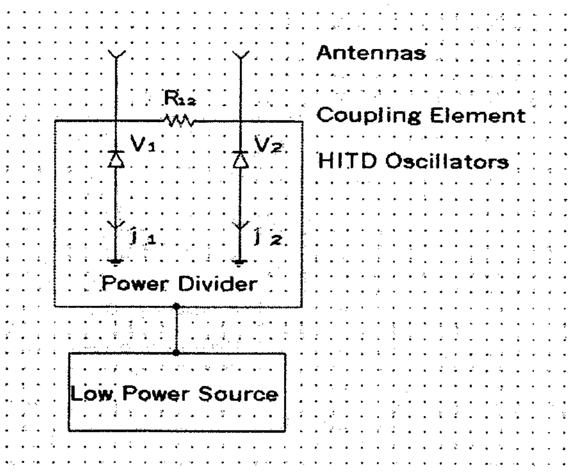


Fig. 4. Injection locking illustration of active antenna array.

The injection range in the Ka band of an active antenna array is investigated through simulation. In Fig. 4, as an illustration, an antenna array with two elements ($N = 2$) is shown, the elements are connected through a resistor ($R_{12} = 100.0\ \Omega$) for simplicity. The analysis can readily be extended to more element cases where inductors, capacitors and transmission lines are chosen. In the simulation, the injection signals (v_{inj}) plus biases (V_d) are placed at the two voltage nodes shown in Fig. 4. The circuit parameters are chosen as $Ls = 0.2$ nH, $Rs = 10.0\ \Omega$, $Cd = 0.15$ pF. We found that, with -20 dBc injection signal, one can achieve a locking range of 5% (1.4 GHz) in the Ka band with the active antenna. It is also seen that when the injection signal level increases three decades from -45.0 dBc to -15.0 dBc, the amplitude of oscillation signal increases from 0.16 V to 0.26 V.

IV. Conclusion

We have characterized the dc and RF properties of the HITDs based on measured data and extraction schemes for wireless applications. The extracted model is used in the circuit design for active antennas with the FDTD. Experimental and simulated results demonstrate that the HITD active antenna, when injection locking is used, can provide comparable phase noise (-114.67 dBc/Hz @ 1.0 MHz offset) at lower power output with very stable oscillations, when compared to Gunn type active antenna.

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