Stabilization of Active Antenna Arrays Incorporating Heterostructure Interband Tunnel Diodes

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ABSTRACT

In this paper, the stable DC bias condition for a single tunnel diode is examined in experiments and simulations toward array applications. To overcome the malfunction of the diodes connected in series, DC blocking capacitors are used in the antenna array to enforce individual bias conditions. Beam steering is achieved by changing the phase between the two signals injected to the two end-elements of the array. Simulated and experimental results for the diode instability and active antenna array are presented.

INTRODUCTION

The Heterostructure *Interband* Tunnel Diode (HITD) is receiving increased research interests for its enhanced functionality and low supply voltage compared to other diodes. The device, similar to the *intraband* based Resonant Tunnel Diode (RTD), when appropriately biased, exhibits RF negative resistance. It has been used in VCOs, mixers and active antenna circuits. Tunnel diodes can be represented in an equivalent circuit as shown in the insert of Fig. 1, where the voltage-controlled current source (VCCS) provides a source for oscillations. The VCCS is curve fit from the measured I-V characteristic data. On the other hand, the VCCS introduces a possibility that the diode could oscillate on its own (the instability phenomenon), which one cannot control from RF design aspects. Although tunnel diodes have a potential of working at frequencies up to 200.0 GHz, the inherent tendency for bias instabilities has, so far, severely limited the system applications of tunnel diodes [1][2] [3].

In order to achieve controllable active antenna array using the HITDs, we first investigate the DC instability phenomena for the single diode and multiple ones, toward array application of the diodes. A reactance approach is then used to design the active antenna array. DC blocking capacitors are incorporated in the design to overcome the DC instability. The beam steering of the completed active antenna array is achieved by an injection scheme along with RF phase shift, which provides necessary phase difference between the two injection signals. All the investigations of the tunnel diodes in this work are based on single well HITDs in the InGaAs/InAlAs material system lattice matched to InP.

THE ORIGIN OF THE DC INSTABILITY

A. Stability Criteria

The HITD can be represented in an equivalent circuit as shown in the insert of Fig. 1. From the small signal model, where the VCCS is treated as a constant negative differential resistance (NDR) –Rd, two frequencies are defined. First, the cutoff frequency at which the real part of the impedance of the diode becomes zero, is given as

$$\omega_c = \frac{1}{R_d C}\sqrt{\frac{R_d}{R_S} - 1} \tag{1}$$

Second, the resonant frequency at which the imaginary part of the impedance of the diode reaches zero, is given as

$$\omega_r = \frac{1}{R_d C}\sqrt{\frac{R_d{}^2 C_d}{L_S} - 1} \tag{2}$$

To avoid tunnel diode itself oscillate under a DC bias in its NDR region, its resonant frequency must be larger than its cutoff frequency ($\omega_r > \omega_c$). Then, it is straightforward that we have the stability condition

$$R_S C_d R_d > L_s \tag{3}$$

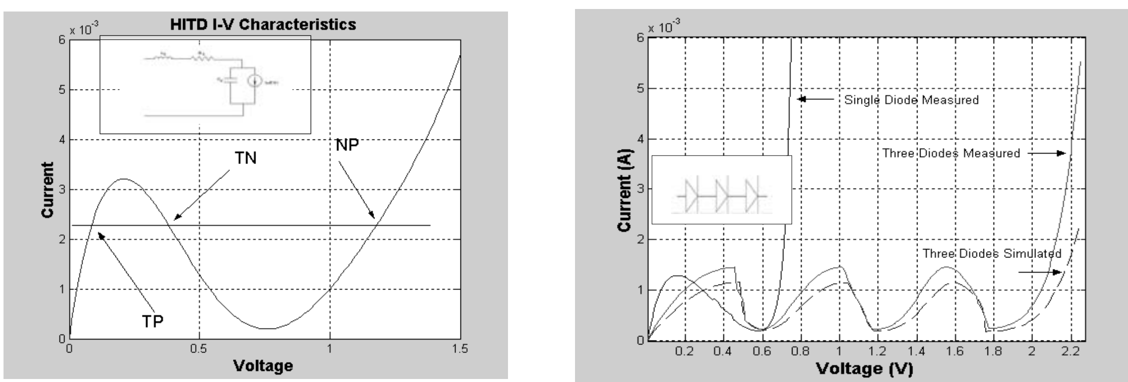

Fig. 1. (a) For a current in circuit, diodes biased in series have three possible statuses. (b) Simulated and measured I-V characteristics of the array of three tunnel diodes connected in series. Diode parameters are L_S=0.12 nH, C_d=0.13 pF, R_S =6.0 ohm.

In the above approach, the NDR ($-R_d$) is taken as constant for simplicity. However, in the following analysis, the tunnel diode I-V is modeled as a VCCS, taking into account the nonlinear characteristics of the diodes. To achieve a controllable oscillation for RF applications of the tunnel diodes, we can use techniques such as, feedback, matching component, and antenna load, to provide the reactance necessary for oscillations.

Table 1. Stability investigation for different HITDs.

Diodes (μm)	I_P (mA)	R_d (ohm)	C_d (pF)	R_S (ohm)	LHS of (3)	Stable?
2.5x2.5	1.37	-217.0	0.12	6.0	0.156	Yes
5.0x5.0	5.50	-54.0	0.48	3.0	0.078	No
10.0x10.0	22.0	-13.5	1.92	1.5	0.037	No

It is observed experimentally that the DC and RF characteristics are unstable for large-size diodes. To investigate the diode stability criteria, DC and S-parameter measurements for small-size diodes (2.5x2.5 μm) are performed and equivalent-circuit parameters are determined. The values of series inductance L_S and resistance R_S for these diodes are in the range of 0.125 to 0.15 nH and 5.0 to 8.0 Ω, respectively. The circuit parameters for large-size diodes are then computed by scaling for the area of the diode. These parameters are shown in Table 1. It is clearly seen from Table 1 that the parameters of the 2.5x2.5 μm diode satisfies the stability criterion, while those from 5.0x5.0 μm and 10.0x10.0 μm diodes do not.

B. Tunnel Diodes in Series

The instability study for diode arrays is also based on the stability condition presented in (3). Note that in the case of a diode array, the circuit parameters are referred for the whole diode array. The DC and RF responses of series-connected diodes differ from those of individually diodes due to the nonlinear I-V characteristics of the devices. Fig. 1 shows the DC characteristics of both a single diode and a three-diode array. Note that there are three distinct NDR regions for the diode array. When a voltage of 1.1 V is supplied, the array is biased in it second NDR region. However, it doesn't mean that all three diodes in the array are in their NDR regions at 0.37 V (1.1/3=0.37 V). Note that 0.37 V is within the NDR region of a single diode from Fig. 1.

Table 2. Tunnel diode operation status in a series-connected diode array. Terminology: TN-Tunneling NDR, TP-Tunneling PDR and NP-Normal PDR. Capacitances: $C_{d1}>C_{d2}>C_{d3}$.

Biases in NDR regions	Status of Diodes
0.51~0.61 V	D1-TP, D2-TP, ***D3-TN***
1.00~1.20 V	D1-TP, ***D2-TN***, D3-NP
1.55~1.80 V	D1-NP, D2-NP, ***D3-TN***

The operation status for each device in the series-connected diodes is summarized in Table 2 based on simulations. The capacitance chosen for the three diodes are in the order of $C_{d1}>C_{d2}>C_{d3}$, and within 5% deviation. When the diode array is biased at 0.51~0.61 V, the diode with smallest capacitance enters its tunneling NDR region, as referred as TN, while other two are driven into their tunneling positive differential resistance (PDR) regions, as referred as TP in Table 2. As the bias voltage increases to 1.0~1.2 V, the diode with the second smallest capacitance sits in its NDR region, while other two are driven to tunneling PDR (TP) and normal diode PDR (NP) regions respectively. The diode with largest capacitance is never biased in its NDR region. The different combinations of operation statuses make the shapes and the spans different in the three NDR regions. The multi-NDR regions give the flexibility for the diodes to be operated in different biases. However, the cutoff frequency ω_c is much lower than that of the single tunnel diode, because of the additional resistance R_S introduced by other diodes biased in their PDR regions.

ACTIVE ANTENNA ARRAYS

We use the reactance approach to design the active antenna arrays. To include a large-signal model in the frequency-domain approach, the nonlinear behavior of the HITD is first investigated in time domain. During the time-domain simulation, a device update-equation based on the Runge-Kutta method for larger-signal model is performed. Then, the resulted impedance of the tunnel diode is incorporated in the reactance design scheme.

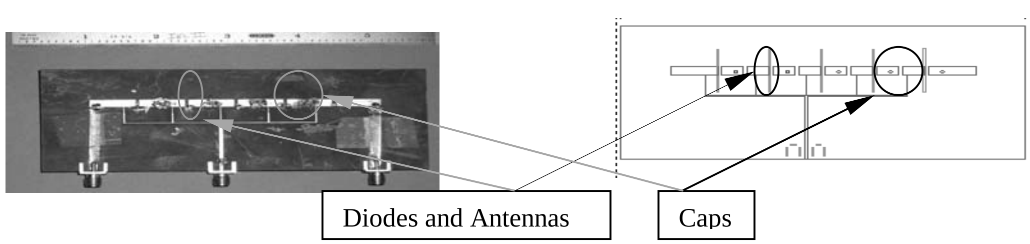

Fig. 2. Fabricated active antenna array with series-implemented diodes (left) and its layout (right). The slot antennas are in the bottom layer. The DC blocking capacitors are used for the purpose of achieving a stable oscillation.

In Fig. 2, an active antenna designed in X-band is demonstrated. The diodes are implemented in series and the slot antennas, fed through via holes, are in bottom layer. The measured oscillation frequency is 11.0575 GHz. A good agreement has been achieved in terms of oscillation frequency. After employing the beam steering scheme with two injection signals of equal phase at the two end-elements (two RF feeding paths are made temporarily in the array as shown in Fig. 2), the maximum radiation direction is squinted from normal direction (90 degree) to 60 degree, as shown in Fig. 3. By changing the phase shift, the pattern steering of the main lobe is seen. For the phase shift value we chosen, a four-degree pattern steering is observed. Although this steering is not that significant by the phase shift value we chosen, in principle, it reveals that the active antenna array can be beam steered electronically.

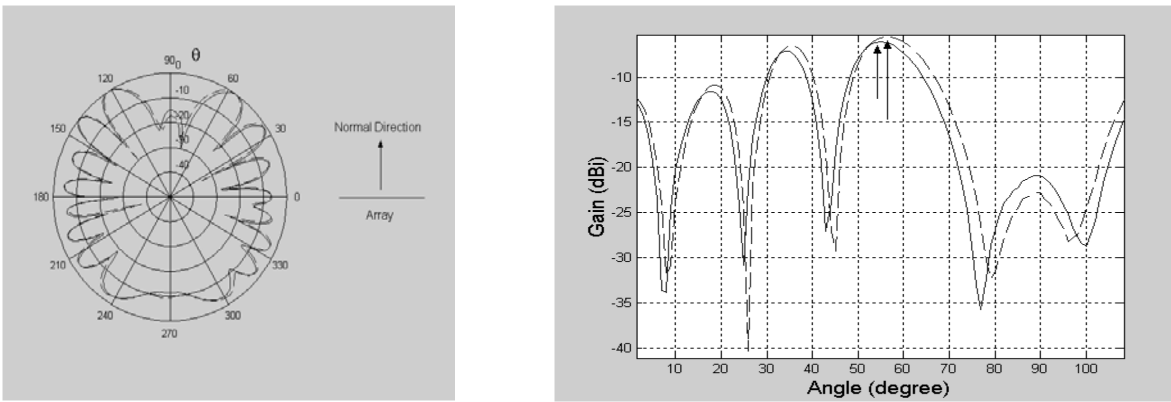

Fig. 3. Measured pattern for the active antenna array (left) and the zoom-in of the pattern around its main lobe (right). The beam steering is achieved by adjusting a RF phase shift.

CONCLUSIONS

Instabilities of the HITD and its array have been investigated toward achieving stable and controllable RF applications for active antenna arrays. The developed stability criteria can be applied to analyze both single diode and multiple ones. Stable active antenna arrays can be achieved by introducing DC blocking capacitors between elements. Good agreement has been obtained in term of the oscillation frequency for the fabricated array. The pattern of the active antenna array can be steered by providing two phase-different RF signals to the two end-elements of the array.

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