compared with those of the individual channels (Fig. 2 and Table II), showing mutual compensations among channel equalizers.

From the designs it is found that in order to obtain a good result, it is important to choose appropriate sample frequencies in (11). The sample frequencies usually include the perfect transmission points, the side-points of channel passbands, and the lowest points at which the return-loss response has minimums. During the optimization process, it is often needed to make adjustment and even add new ones (the lowest points).

V. Conclusion

Formulas were presented for the design of a singly-matched multiplexer with a common junction. A new general design approach was developed by computer optimization using these formulas. A design example of a three-channel S-M multiplexer demonstrated this approach.

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Negative Differential Resistance (NDR) Frequency Conversion with Gain

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***Abstract*—The dependence of the conductance of negative differential resistance (NDR) devices in the presence of an rf signal of varying amplitude has been theoretically analyzed. Variable absolute negative conductance has been observed in both unbiased resonant tunneling devices and biased tunnel diode when the applied pump power is within the correct range. The theoretical observation of the dependence of the dc conductance of the NDR devices on the power level of the applied pump signal is supported by the experimental results. Absolute negative conductance of NDR devices provides the possibility of oscillation and harmonic oscillation up to the cut-off frequency of the device. Biased oscillators and self-oscillating frequency multipliers have been experimentally demonstrated using a tunnel diode. Unbiased oscillators have also been successfully realized with two back-to-back connected tunnel diodes which exhibit an anti-symmetrical I-V characteristic.**

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I. Introduction

There has been increased interest in the study of resonant tunneling devices as the nonlinear characteristics of these devices can be used for frequency conversion applications such as multipliers [1]–[3] and mixers [1], [2]. In addition, their ability to exhibit negative differential resistance (NDR) regions leads to their potential use as gain elements and presents new opportunities for circuit design [1], [2]. This paper will address the pros and cons of using such a potential gain element for frequency conversion applications.

A nonlinear-circuit analysis computer program has been developed to analyze the behavior of negative conductances of NDR devices. The analysis technique was developed by Kerr et al. [4] and the program was implemented for analyzing ideal Schottky barrier diodes by Siegel et al. [5]. The analysis program has been modified to take into account the negative resistance of an NDR device [6]. Since the devices were mounted on a 50 Ω microstrip line for the measurements in this work, an embedding impedance of 50 Ω at every harmonic frequency has been used. A simple experiment was carried out to verify that the embedding impedance at higher harmonic frequencies was indeed 50 Ω [7].

II. Absolute Negative Conductance

1. Nonlinear-Circuit Analysis Results

The I-V characteristics measured from a tunnel diode shown in Fig. 1(a) have been used in the nonlinear-circuit analysis. The expression for the capacitance of a junction diode was used in the analysis. The conductance of the tunnel diode biased at the center of the NDR region was studied. From the results shown in Fig. 1(b), an absolute negative conductance has been observed from the tunnel diode biased in the NDR region when the applied pump amplitude is limited to the appropriate range. The magnitude of the absolute negative conductance changes with the pumping amplitude. The pump amplitude required to achieve absolute negative conductance increases with increasing pump frequency. This can be easily explained using the equivalent circuit model of a NDR device. Since the impedance of the parallel circuit section decreases with increasing frequency, more of the applied voltage is distributed across the series resistance and less appears across the parallel circuit section for higher pump frequencies. The fact that an absolute negative conductance occurs for a tunnel diode biased in the NDR region implies that oscillation can occur at any frequency if the pumping power is within the region that negative conductance occurs.

2. Experimental Results

The measurement of the I-V characteristic was performed using a standard semiconductor analyzer. The rf signal was supplied by a HP signal generator and separated from the dc bias voltage using a standard bias network. During the experiment, it was established that the dc conductance of the NDR device is, indeed, highly dependent on the rf input signal. The I-V characteristics of a tunnel diode measured at different rf input power levels are shown in Fig. 2(a). The dependence of the dc conductance of the NDR device on the frequency of the rf input signal also observed during this measurement can easily be seen from the equivalent circuit model of the NDR device. It was also observed that the frequency dependence of the dc conductances is stronger for larger rf pump level. The I-V curves measured at different pump power levels and frequencies compare favorably to

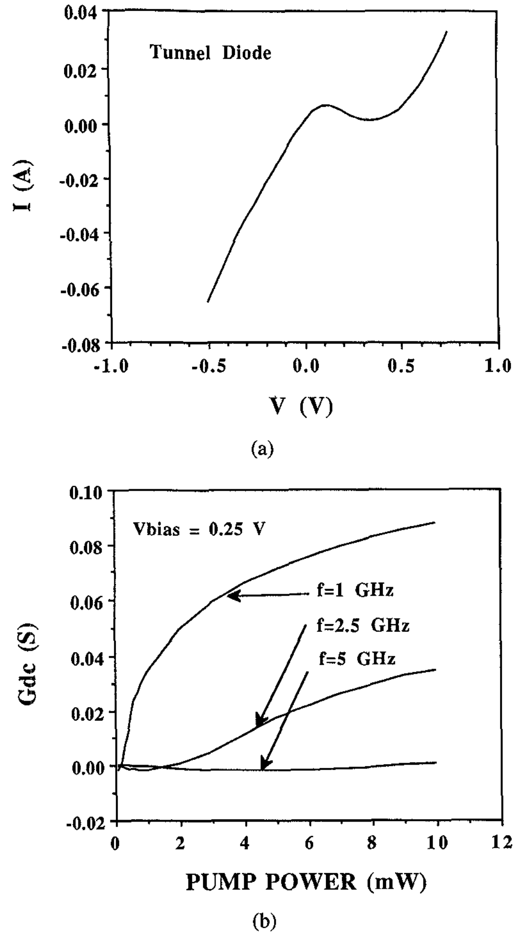


Fig. 1. (a)The I-V characteristic and (b) dc conductances versus pump level at different rf pump frequencies of a tunnel diode.

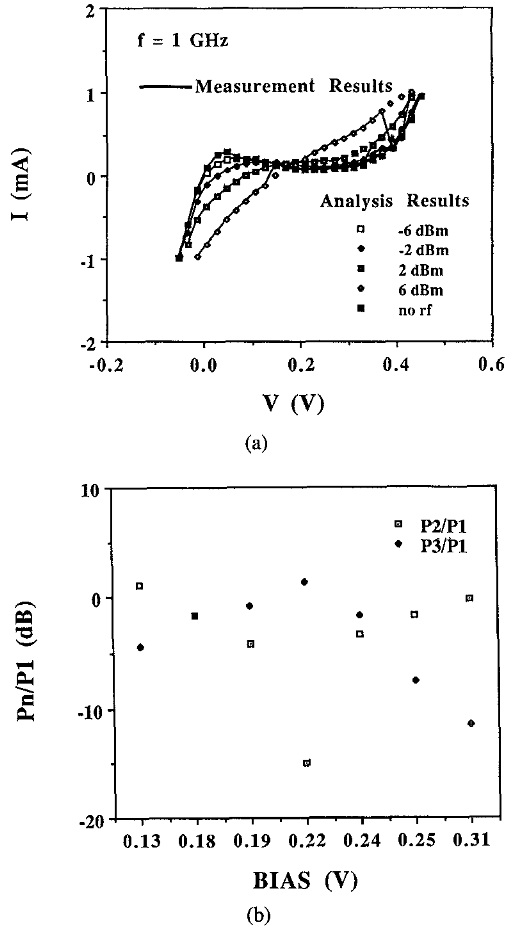


Fig. 2. (a) The I-V characteristics of a tunnel diode at different rf pump levels and (b) the ratio of the output to input power versus bias point of a self-oscillating frequency multiplier employing this tunnel diode.

the simulation results. Variable absolute negative conductance which was observed during this measurement can be used as the basis for oscillators and up to the cutoff frequency of the diode.

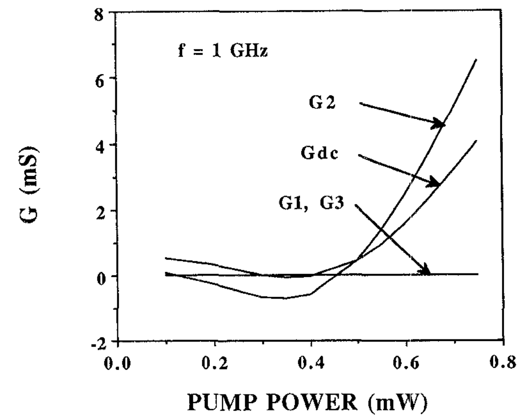
A tunnel diode biased in the NDR region can be used for constructing an oscillator or a self-oscillating frequency multiplier. Both oscillators and self-oscillating frequency multipliers have been realized using the same tunnel diode biased in the NDR region. The output measured from a self-oscillating frequency multiplier is shown in Fig. 2(b). As can be seen from these results, frequency multiplication with gain was realized. The highest tripling efficiency was obtained at the center of the NDR region, while the highest doubling efficiency was obtained at the edges of the NDR region as expected. The I-V characteristic is anti-symmetrical when biased at the center of the NDR region, and is almost symmetrical when biased at the edges of the NDR region (near an inflection point). Noted that the circuit used did not allow for the independent tuning of the harmonics. The self-oscillation at the fundamental generates its own harmonics using the nonlinearity of the NDR device is referred to here as a self-oscillating frequency multiplier, while the term "harmonic oscillator" refers to the case where an NDR device oscillates at a particular harmonic frequency using the negative conductance at that harmonic frequency. One should note that the highest output at the second and third harmonic frequencies will be obtained from a harmonic oscillator at the center and the two edges of the NDR region, respectively, which is very different from the operation as a self-oscillating frequency multiplier. Self-oscillation mixing has also been observed during the measurement (mixing between the self-oscillation and pump signals). Due to the dependence of the dc conductance on the power level of the rf input signal, the performance of this self-oscillating mixer is very sensitive to the rf input power level.

III. Absolute Negative Conductance of an Unbiased Resonant Tunneling Device

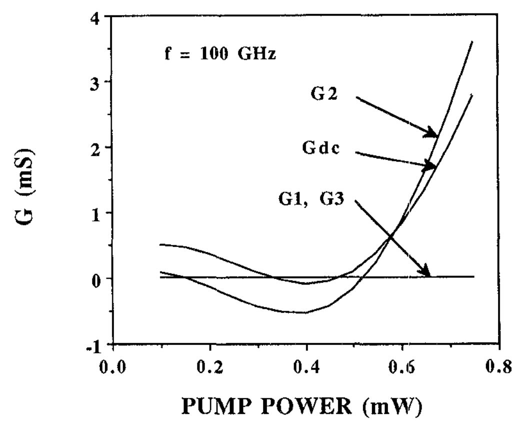
1. Nonlinear Circuit Analysis Results

The previous discussion described a tunnel diode which does not possess an anti-symmetrical I-V characteristic. In this section a resonant tunneling device for which variable absolute negative conductance can be observed, even without dc bias, will be discussed. Variable absolute negative conductance from an unbiased resonant tunneling device was proposed by Sollner *et al.* using a simple mathematical model [2]. The harmonics of the pump generated by the nonlinearity of the I-V curve were neglected in [2], of which some quantitative information was lost. In our work, these harmonics are calculated in a self-consistent manner through the use of the nonlinear-circuit analysis program. The I-V characteristic of [2] and a constant capacitance were used in the nonlinear-circuit analysis for comparison purposes.

From the nonlinear-circuit analysis results, an absolute negative conductance can be found from a resonant tunneling device at zero bias when the applied pump amplitude is, again, limited to the appropriate range (see Fig. 3). The value of the negative conductance is approximately the same as that found in the NDR region. The magnitude of the negative conductance can be adjusted by varying



(a)



(b)

Fig. 3. The conductances at different harmonic frequencies versus pump power of an unbiased resonant tunneling device at the rf pump frequency of (a) 1 GHz and (b) 100 GHz.

the pump amplitude which verifies the work of Sollner *et al.* [2]. The magnitude of absolute negative conductance from our analysis results is similar to that predicted by Sollner *et al.* The pump amplitude required to achieve absolute negative conductance from our analysis is higher than that predicted by Sollner *et al.* This is due to the device parasitics (such as resistance and capacitance) which have been included in our analysis.

It was observed that the pump amplitude required to achieve absolute negative conductance increases with increasing pump frequency. The reason for this can, again, be explained by the equivalent circuit model discussed for the tunnel diode in the previous section. We also found that the pump amplitude required to obtain absolute negative conductance varies with the parasitics of the device. This again can be explained from the equivalent circuit model of a NDR diode. When the series resistance and/or capacitance of the device increases, more voltage is dropped across the series resistance and less is developed across the parallel circuit section of the equivalent circuit. The dependence of the pump amplitude required to achieve absolute negative conductance on the device capacitance is stronger for higher rf frequency operation. Fig. 3 also shows the conductance at different harmonic frequencies versus pump power. Because of the symmetrical G-V characteristic of the resonant tunneling device, the magnitude of the second-harmonic component of the negative conductance is larger than other harmonic components.

These studies indicate that one can expect to find absolute negative resistance whenever a device with negative differential conductance and an I-V curve that is anti-symmetrical is driven with a pump having the right amplitude. For unbiased oscillator and harmonic-oscillator operation, one should note that little negative conductance or dynamic range has been sacrificed, and the advantages of operating with zero dc bias have been gained. A resonant tunneling device can also be used in the design of a self-oscillating frequency multiplier if it is biased in the NDR region. The biased self-oscillating frequency multiplier have the intrinsic capability of conversion gain.

2. *Experimental Results*

Two back-to-back connected tunnel diodes were used to achieve an anti-symmetrical I-V characteristic. With an input signal of 1 GHz, self oscillation from this unbiased device was observed. The self-oscillation frequency was determined to be 210 MHz. The output power of the self oscillation changes with the amplitude of the rf pump, indicating the change of the negative conductance with rf input power level. Again, the experimental results agree fairly well with the simulation results. It was also observed that the overall anti-symmetry of the I-V curve about the origin offers highly efficient odd-harmonic generation with this device. The highest tripling efficiency is 59% with an input power level of 10 dBm. The circuits discussed here are not conjugate matched at each port. Unbiased self-oscillating mixing has also been observed from this device. The conversion efficiency of this unbiased self-oscillating mixer changes rapidly with the rf pump level.

IV. Conclusion

Absolute negative conductance can be obtained from either a biased or an unbiased resonant tunneling device when the applied pump power is within a small range. Absolute negative conductance can be used for oscillators and harmonic oscillators up to the cutoff frequency of the device. The advantage of these oscillators comes from the fact that the negative conductance can be adjusted by varying the pump amplitude, which is a very useful circuit property. For an unbiased resonant tunneling device, the negative conductance is larger at even harmonic frequencies, which could simplify the frequency selection of an oscillator design based upon this effect. A resonant tunneling device biased in the NDR region can also be used as a self-oscillating frequency multiplier. Biased self-oscillating frequency multipliers can achieve conversion gain.

Based upon this study, the design and operation of resonant tunneling frequency multipliers could be a complex task. Self oscillation may occur based on the absolute negative conductance induced by the rf pump signal and the frequency and output power of this self oscillation vary with the rf pump level. This will also cause the conversion efficiency of the device to change, since mixing between the self-oscillation and pump signals can occur. The performance of a self-oscillating frequency multiplier is also highly sensitive to the rf pump level. Controlling the self-oscillating frequency and output power requires complete information about the I-V characteristics at different rf power levels. This can be accomplished by extensive simulations of the resonant tunneling device under different pumping conditions using the modified nonlinear circuit analysis program as mentioned in this paper.

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The Introduction of Surface Resistance in the Three-Dimensional Finite-Difference Method in Frequency Domain

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***Abstract*—A full-wave treatment of lossy three-dimensional structures using the finite-difference method in frequency domain is presented. This accounts for both, dielectric and conductor losses. By introduction of a surface resistance the effect of conductor losses and surface roughness can be modeled very efficiently. The modifications of the finite-difference frequency domain (FDFD) algorithm are presented. Comparisons between the conventional approach using elementary cells with finite conductivity and this new discretization method with surface current cells are given, and the advantages and limitations of the surface current model are shown.**

I. Introduction

The FDFD method supports an exact description of the discretized electromagnetic field of three-dimensional structures [1]–[3]. Therefore, the method is capable of modeling all phenomena causing attenuation, if elementary cells with a complex permittivity are used. The validity of this method has been shown for the calculation of the complex propagation constant of transmission lines and three-dimensional discontinuity problems [3]. For good conductors with a small skin depth, however, it is necessary to use a very fine discretization at the conductor surfaces in order to achieve the desired accuracy. This increases the computational effort drastically.

To avoid the fine discretization, the paper proposes an infinitely thin current at the conductor surface, which accounts for the physical field penetration. By the use of this technique, a large reduction of the required number of cells needed to model the conductor is achieved.

II. Conventional Modeling of Lossy Structures

The finite difference algorithm has been described for lossless structures [2] and for lossy structures [1] in detail, so only the new developments are presented in this paper.

Assuming a harmonic time dependence Maxwell's equations in integral form (usual definitions) for source free structures are:

$$\oint_C \frac{1}{\mu}\vec{B}\cdot d\vec{s} = \int_A (j\omega\vec{D} + \kappa\vec{E})\cdot d\vec{A} = \int_A j\omega\varepsilon\vec{E}\cdot d\vec{A} \quad \text{(1a)}$$

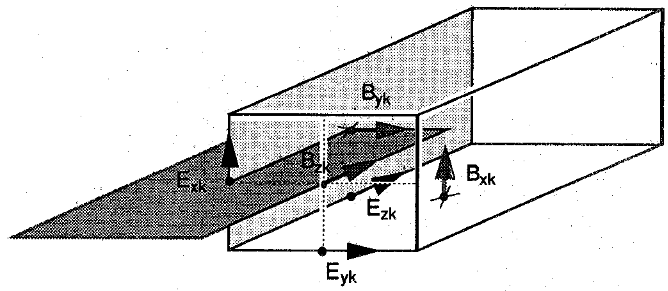

Fig. 1. Elementary cell k and allocation of its associated electric and magnetic field components. The shaded areas indicate integration planes for discretization of Maxwell's equation.

$$\oint_C \vec{E}\cdot d\vec{s} = -\int_A j\omega\vec{B}\cdot d\vec{A} \quad \text{(1b)}$$

Up to now polarization losses ($\tan\delta$) and the finite conductivity κ have been included in the frequency dependent part of the complex permittivity:

$$\varepsilon = \varepsilon_0\varepsilon_k = \varepsilon_0\left[\varepsilon_r - j\left(\varepsilon_r\tan\delta + \frac{\omega\kappa}{\varepsilon_0}\right)\right] \quad (2)$$

Maxwell's equations are discretized on a Yee-grid [4]. Fig. 1 shows the elementary cell k and the allocation of the electric and magnetic field components. The shaded areas denote the integration planes for the E_{xk} component ((1a)) and the B_{yk} component ((1b)).

The discretization is performed by a lowest order integration formula. Setting up the associated equations for all E-field and B-field components of the elementary cells for the whole structure leads to a linear system of equations, which defines a boundary value problem for the unknown electric field.

Conductor losses are treated sufficiently when the conductor is discretized with at least three discretization steps per skin depth. Due to the large number of necessary discretizations required inside the conductor the system matrix gets large, and the great differences in the grid spacing influences the convergency behavior of the equation solver negatively. To overcome these drawbacks elementary cells with a surface resistance are introduced.

III. The Improved Method of Analysis

With the new surface resistance approach a non ideal conductor is modeled by its surface resistance. The interior of the conductor is set free of fields and the actual conduction current is represented by an infinitely thin current on the surface of the cells. For that reason the fine discretization inside the conductor becomes no longer necessary. The losses are introduced by a surface resistance R_S, which is inversely proportional to the skin depth δ of the modeled conductor at the radian frequency ω:

$$\delta = \sqrt{\frac{2}{\omega\kappa\mu_0\mu_r}} \quad (3)$$

Considering the effect of surface roughness σ_{eff} by the correction formula given in [5], [6], leads to an effective surface resistance:

$$R_{S\text{eff}} = R_S\left[1 + \frac{2}{\pi}\arctan\left(1.4\left(\frac{\sigma_{\text{eff}}}{\delta}\right)^2\right)\right] \quad \text{with } R_S = \frac{1}{\kappa\delta} \quad (4)$$