EFFECT OF THE INCREASED NUMBER OF DIODES ON THE PERFORMANCE OF OSCILLATORS WITH SERIES-CONNECTED TUNNEL DIODES

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ABSTRACT

Connecting several tunneling devices in series was proven to be an effective method to increase the oscillator output power. However, there are several difficulties associated with the series connection. The phase shift between the devices and the length of the series connection may be quite considerable. Therefore, connecting diode in series is not strictly the device level power combining, but the circuit level power combining as well. The design procedure, as well as the experimental results for the oscillators with two, three, and four series connected tunnel diodes at 2 GHz will be presented here. A multimode operation, characteristic for the circuit level power combining, was observed for the four diode oscillator.

INTRODUCTION

The resonant tunneling diode (RTD) is currently the fastest solid state source, but with a very low output power [1]. An RTD and a tunnel diode, even though physically quite different, are electrically almost identical. They share the same equivalent circuit, and except for the high frequency cutoff, there is no difference in behavior of oscillators with either tunneling device. Series connection of tunnel diodes was proposed by Vorontsov and Polyakov in 1965 to increase the oscillator output power at low frequencies [2]. Series integration of RTD's was proposed by Yang and Pan in 1992 in order to increase the output power at millimeter wave frequencies [3]. Because of DC instability of the series connection, design and excitation of an oscillator with series connected tunneling diodes is much more complex than for a single diode oscillator. A simple DC battery alone is not sufficient for successful biasing, and there is an oscillation amplitude cutoff and a low frequency cutoff [2,3]. The oscillation amplitude cutoff and the low frequency cutoff make the occurrence of low frequency spurious oscillations associated with the bias circuitry highly unlikely. This is an important advantage over a single diode oscillator. A series connection of tunneling diodes is not expected to solve all power problems, however it may be used as a unit device in a power combining grid, which would greatly reduce probability of subharmonic oscillations and chaotic behavior such as reported in [4]. Oscillators with two tunnel diodes in series have been successfully designed and tested so far [7,8]. Connecting several tunneling devices in series was proven to be an effective method to increase the oscillator output power, and both fundamental and subharmonic RF excitation were demonstrated [7,8].

If packaged diodes are used, a distance between the diodes is limited by the package dimensions. The diode separation must be taken into account for the impedance calculation. Due to the diode package, impedance of the series connection is not simply the sum of impedances of the individual diodes. Therefore connecting diodes in series is not strictly the device level power combining, but the circuit level power combining as well. For more diodes connected in series, the circuit level power combining effect is more pronounced. A series integrated device, such as proposed in [3], should not be affected by this problem, since diodes can be placed very close to each other. The design procedure as well as the experimental results for oscillators with series connected, packaged tunnel diodes at 2 GHz will be presented here. Multimode operation, characteristic for circuit level power combining [5], was observed for one four-diode oscillator.

SINGLE DIODE IMPEDANCE

Low peak current (back) tunnel diodes, manufactured by Metelics Co., were used for the experiment. Fig. 1. shows the diode equivalent circuit model. Values of the series resistance R_S (6.5 Ω), junction capacitance C_j (0.32 pF), bonding wire inductance L_S (0.1 nH), and package capacitance C_p (0.23 pF) are provided by the manufacturer, and are considered constant. Negative differential conductance G is a strong function of both the DC bias voltage and the oscillation amplitude, and can be calculated from the DC I-V curve using the procedure described in [6]. The diode DC I-V curve and the negative differential conductance and output power as a function of the oscillation amplitude are shown in [7]. Fig. 2. shows the diode impedance plot for the negative differential conductance of -0.5 mS and -1.7 mS, in the frequency range from 1 GHz to 8 GHz.

SERIES CONNECTION IMPEDANCE

Fig. 3. shows the series connection schematically. The diode package length l_p is 2.25 mm, and the separation between packages l_s 0.75 mm. At 2 GHz, the length of the package is about one fortieth of the wavelength. Oscillators with two diodes reported in [8] were designed assuming that diodes are lumped elements separated by the distance of 0.75 mm. However, it was found later that increased separation resulted in a more accurate design. Since a single diode impedance is in a region of a Smith chart where a small phase delay causes a large difference in the impedance value (Fig. 2), even a small separation between the diodes greatly affects the total impedance of the series connection. Fig. 4. shows the impedance of two, three and four diode connected in series, for negative conductance of 1.7 mS, at 2 GHz, and for three separation lengths. The separation between diodes is modeled as a piece of a transmission line in microstrip configuration, 0.75 mm wide, on a substrate with a dielectric constant of 2.33. The separation of 0.75 mm, which is a physical distance between two packages, brings about 10 %, 20 % and 30 % reduction in the negative resistance for two, three and four diodes respectively. The separation of 3 mm, which is a distance between centers of two packages brings a much more drastic reduction in the negative resistance, specially for four diodes, where it is over 50 %.

EXPERIMENTAL RESULTS

Several oscillators with two, three and four tunnel diodes in series were designed in a one-port microstrip configuration described in [7,8], for the oscillation amplitude of 0.154 V (slightly above the amplitude cutoff) and 0.176 V (slightly below the amplitude at which negative differential conductance vanishes). Fig. 5. shows oscillators with two, three, and four diodes, designed for the oscillation amplitude of 0.176 V. For three and four-diode oscillators, the length of the series connection is considerable compared to the length of the whole circuit, which is about half-wavelength at 2 GHz. The experimental set-up described in [7,8] was used to test the oscillators, and the fundamental RF excitation to initialize them.

Oscillators with three and four diodes were much more difficult to design and excite than two-diode oscillators. It was found that the separation of 3 mm was optimum for the design of the two-diode oscillators. With this separation included in impedance calculation, two-diode oscillator performance improved significantly from what was reported in [8]. For the oscillation amplitude of 0.154 V, the oscillation frequency was 1.979 GHz, and the output power -18.6 dBm. For the oscillation amplitude of 0.176 GHz, the oscillation frequency was 1.99 GHz, with the output power of -28 dBm, and successive triggering was possible. For three and four diode oscillators, additional impedance compensation was required (inductive stub was assumed to be about 1 mm longer than what it really was), probably due to errors in determining the impedance of the series connection. Switching was occurring, but stable oscillation was not possible for the amplitude of 0.154 V in case of three and four-diode oscillators. For the oscillation amplitude of 0.176 V, signal in three and four-diode oscillators existed only for a very limited bias voltage range, successive triggering was not possible, and the output power was barely increased as compared to the two-diode oscillators. For the best three-diode oscillator, the oscillation frequency was 2.001 GHz, with the output power of -27.5 dBm.

The four-diode oscillator designed for the oscillation amplitude of 0.176 V exhibited multimode operation. The oscillation signal was dependent on the excitation frequency. For the excitation frequency of 1.99 GHz, the excitation was possible with a very low power, of only -37 dBm. In this case, after excitation signal was turned off, the oscillation frequency was 1.976 GHz, with output power of -29 dBm (Fig. 6 (a)). The oscillation was possible for a bias voltage between 0.54 V and 0.60 V, and the excitation in somewhat smaller bias range. The bias voltage of 0.64 V is necessary to bias all four diodes in the middle of the NDR region. For the excitation frequency of 2.05 GHz, much larger excitation power was required, of -7 dBm. In this case, the oscillation frequency was 2.015 GHz, with output power of -27 dBm (Fig. 6 (b)). The oscillation was possible for a bias voltage from 0.56 V to 0.615 V, and the excitation in a somewhat smaller bias range. It is possible that only three diodes oscillated in a four diode oscillator, specially in a lower frequency mode.

Active antenna oscillators with three and four diodes were tested as well. The experimental findings for the active antenna configuration will be described elsewhere [9].

CONCLUSIONS

Oscillators with three and four packaged tunnel diodes connected in series were designed and tested. Due to the diode separation, it is difficult to calculate the impedance of the series connection accurately. Because of the considerable length of the series connection, four-diode oscillator exhibits circuit level power combining behavior, such as multimode operation. A series integrated device, such as proposed in [3], should not be affected by these problems, since diodes can be placed very close to each other. Therefore, connecting more than two packaged diodes in series does not provide insight into behavior of a series integrated device.

ACKNOWLEDGMENT

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REFERENCES

[1] E. R. Brown, J. R. Soderstrom, C. D. Parker, L. J. Mahoney, K. M. Molvar, and T. C. McGill, "Oscillations up to 712 GHz in InAs/AlSb resonant-tunneling-diodes," *App. Phys. Lett.*, vol. 58, pp. 2291-2293, May 1991.

[2] Y. I. Vorontsov and I. V. Polyakov, "Study of oscillatory processes in circuits with several series-connected tunnel diodes," *Radio Eng. Electron. Phys.*, vol. 10, pp. 758-763, May 1965.

[3] C. C. Yang and D. S. Pan, "Theoretical investigations of a proposed series integration of resonant tunneling diodes for millimeter-wave power generation", *IEEE Trans. Microwave Theory and Tech.*, vol. 40, pp. 434-441, March 1992.

[4] M. P. DeLisio, J. F. Davis, S. J. Li and D. B. Rutledge, " A 16-element tunnel diode grid oscillator," submitted to the 1995 *AP-S International Symposium.*

[5] S. Nogi, J. Lin and T. Itoh, "Mode analysis and stabilization of a spatial power-combining array with strongly coupled oscillators," *IEEE Trans. Microwave Theory and Tech.*, vol. 41, pp. 1827-1837, October 1993.

[6] O. Boric-Lubecke, D. S. Pan and T. Itoh, "Large signal quantum-well oscillator design", *Proc. of 23rd European Microwave Conf.*, Madrid, Spain, Sept. 1993, pp. 817-818.

[7] O. Boric-Lubecke, D. S. Pan and T. Itoh, "RF Excitation of an oscillator with several tunneling devices in series," *IEEE Microwave and Guided Wave Lett.*, vol. 4, no. 11, pp. 364-366, November 1994.

[8] O. Boric-Lubecke, D. S. Pan and T. Itoh, "Fundamental and subharmonic excitation for an oscillator with several tunneling diodes in series," Special Issue on Space Terahertz Technology of *IEEE Trans. Microwave Theory Techn.*, vol.43, no.4, April 1995.

[9] O. Boric-Lubecke, D. S. Pan and T. Itoh, "Quasi-optical RF excitation of an active antenna with two tunnel diodes in series," submitted to the *25th European Microwave Conference,* 1995.

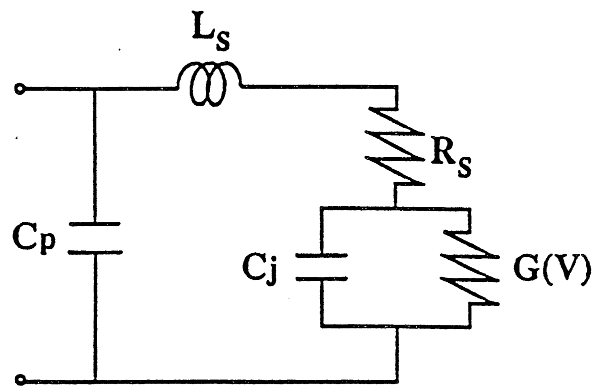


Fig. 1. Packaged tunnel diode equivalent circuit model

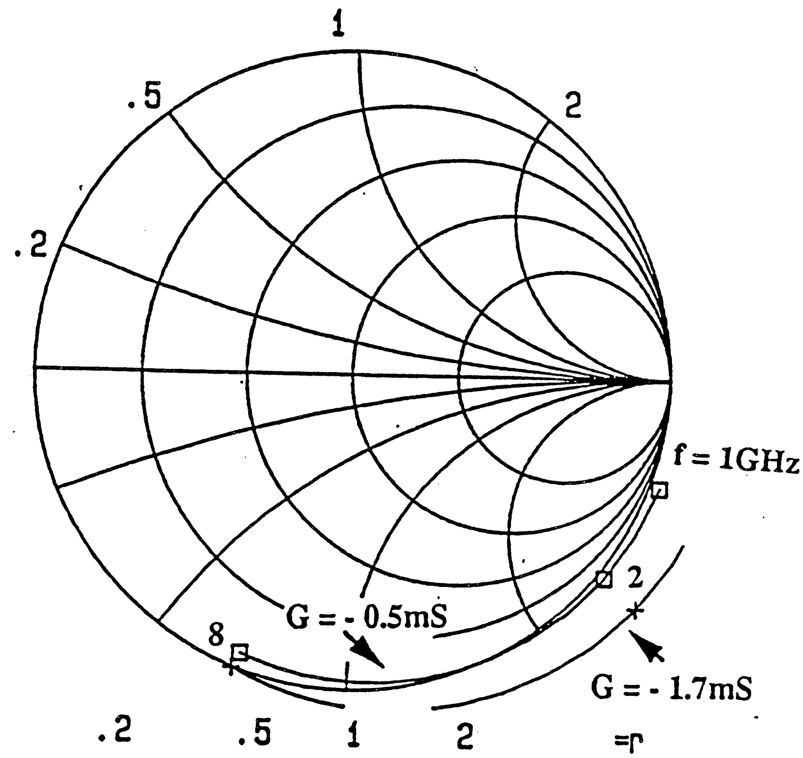


Fig. 2. Tunnel diode impedance for G = -0.5 mS and G = -1.7 mS, from 1 to 8 GHz.

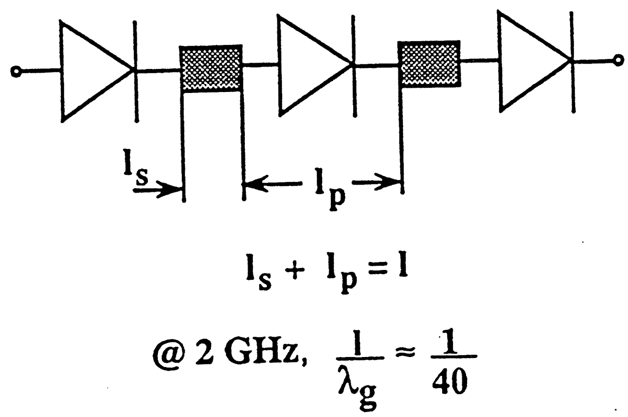


Fig. 3. Series connection; diode package length l_p is 2.25 mm, and separation between packages l_s 0.75 mm.

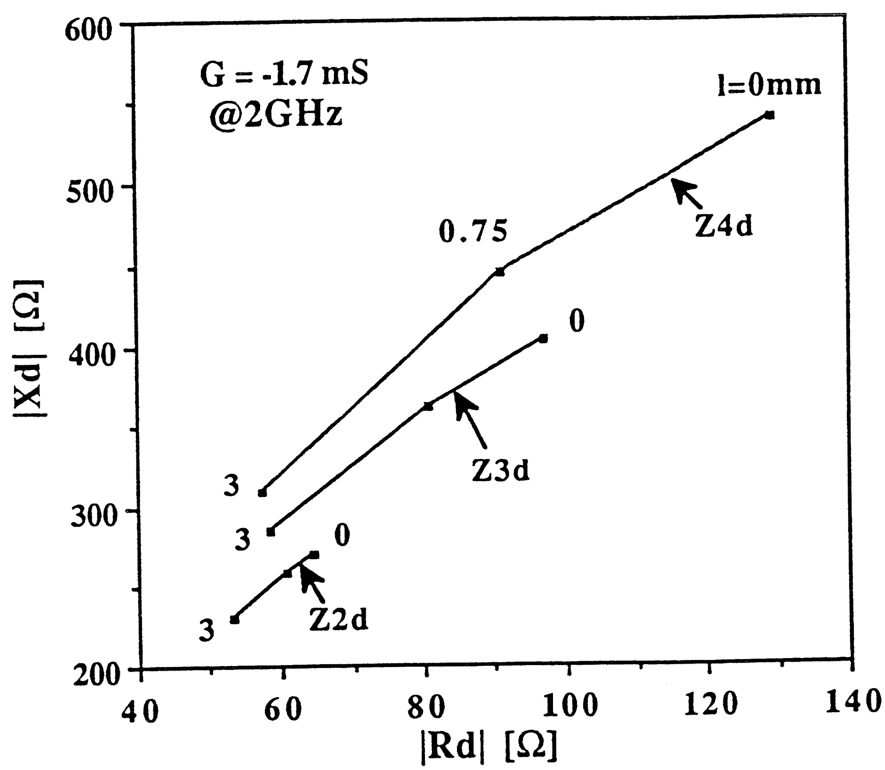
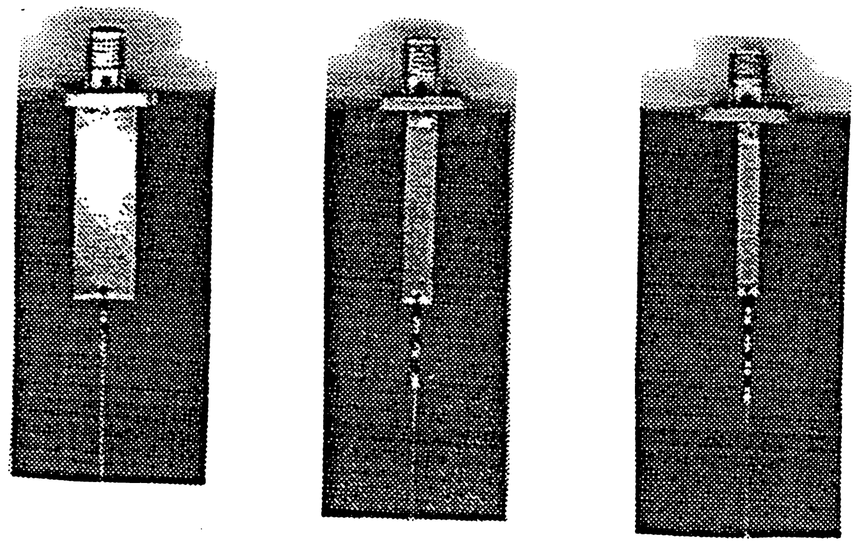


Fig 4. Impedance of the series connection of two, three and four diodes, for separation of 0, 0.75 and 3 mm.



(a) (b) (c)

Fig. 5. One-port oscillators with two (a), three (b) and four (c) tunnel diodes, designed for the oscillation amplitude of 0.176 V.

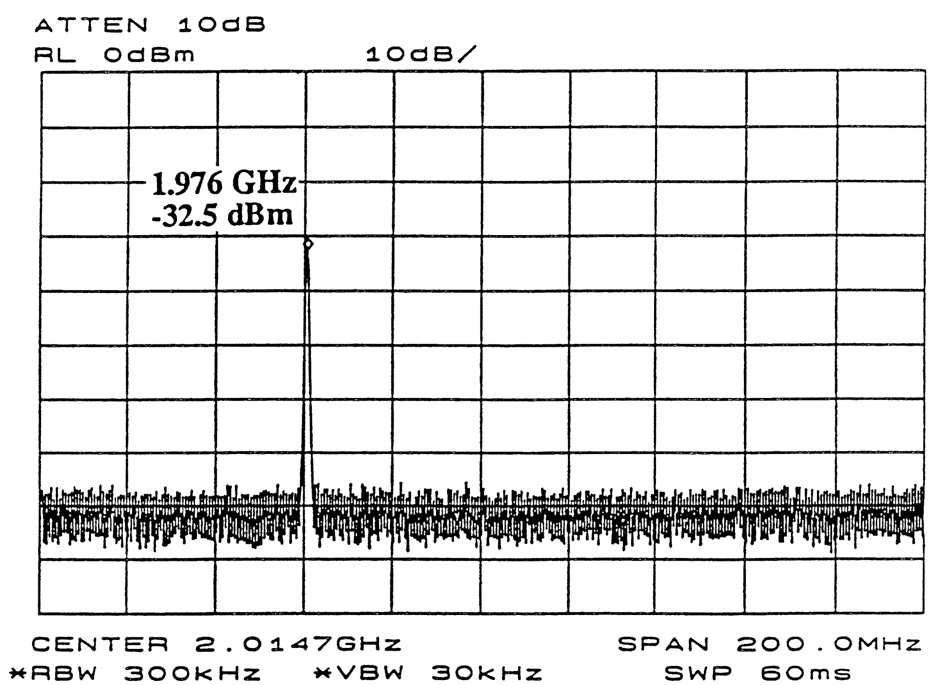
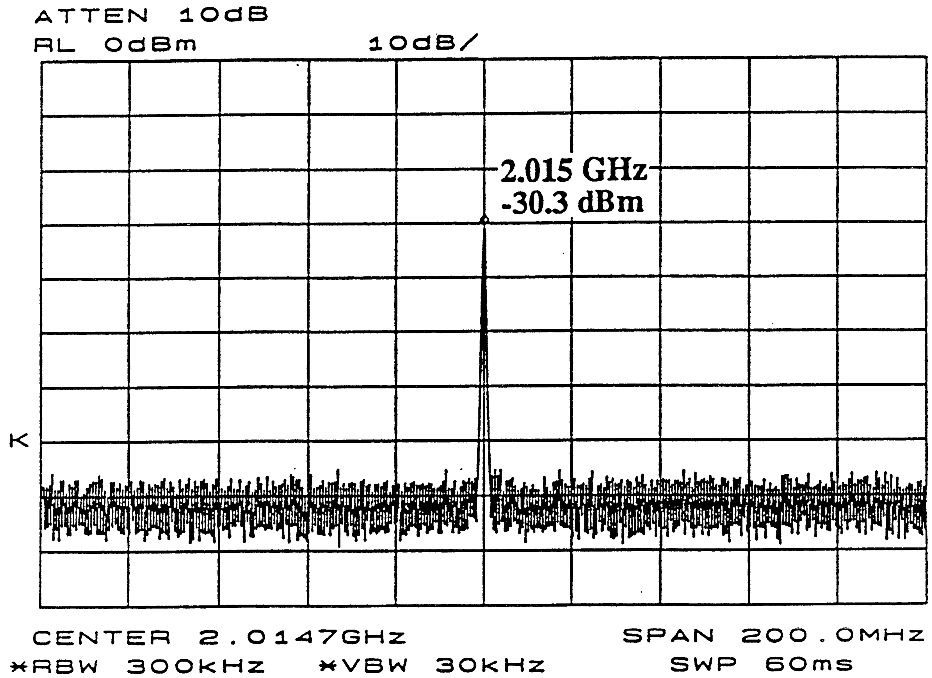


Fig. 6 (a)



(b)

Fig. 6. Output spectrum of four-diode oscillator for excitation frequency of 1.99 GHz (a), and 2.05 GHz (b).