LOSSY-LINE STABILIZATION OF NEGATIVE-RESISTANCE DIODES FOR INTEGRATED-CIRCUIT OSCILLATORS

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ABSTRACT: Diodes that show negative differential resistance from DC up to 700 GHz are now available. To exploit these devices, a submillimeter-wave oscillator circuit must encourage oscillation near the upper frequency limit while discouraging oscillation at all lower frequencies. This is not easy. In this paper we describe a tool in the circuit designer's kit which may prove useful in the development of integrated-circuit submillimeter-wave oscillators using resonant-tunneling diodes or other negative-resistance devices. A lossy transmission line of sufficient length presents a nearly constant impedance to its load while furnishing a convenient pathway for DC bias. Following a Smith-chart presentation of the stabilization problem, we describe two microwave oscillator circuits that use lossy transmission lines for diode stabilization. One used a conventional tunnel diode in a quasioptical 2-GHz oscillator, and the other employed a resonant tunneling diode in a quasioptical-cavity-stabilized circuit at 9 GHz.

The Stabilization Problem

The designer of a submillimeter-wave oscillator using a negative-resistance device such as a resonant tunneling diode (RTD) faces a formidable engineering challenge. The need to increase the device's peak current for higher output power leads to difficulties in biasing and bypassing the device so that it will not oscillate at frequencies below the desired output frequency. This problem has been discussed extensively in a paper by Kidner et al. [1], who use a lumped-element circuit analysis to conclude that these stability problems pose a grave difficulty in obtaining useful levels of output power from RTDs. While these cautions should be taken seriously, in this paper we will describe an idea that may alleviate some of the stability problems that circuit designers face in constructing RTD oscillators.

In Fig. 1 we show the equivalent circuit of a submillimeter-wave RTD whose maximum frequency of oscillation, given by

$$f_r = \frac{1}{2\pi R_d C_d}\sqrt{\frac{R_d}{R_S} - 1} \tag{1}$$

is 689 GHz. The differential negative resistance $-R_d = -20$ ohms is obtained by biasing the device in its negative-resistance region, typically 0.2–0.3 V at a few mA. The device capacitance $C_d = 20$ fF and series resistance $R_S = 5$ ohms are similar to devices reported by Brown et al. [2].

The oscillation design problem can be described by means of an oscillation criterion due to Esdale and Howes [3]. If Γ_d is the reflection coefficient of the one-port active device and Γ_ℓ is that of its load, then Esdale and Howes showed that steady-state oscillation is possible only if

$$\Gamma_\ell = \frac{1}{\Gamma_d}. \tag{2}$$

This implies the two conditions

$$|\Gamma_\ell| = \left|\frac{1}{\Gamma_d}\right|$$

and

$$\angle(\Gamma_\ell) = \angle\left(\frac{1}{\Gamma_d}\right).$$

The normalizing impedance used to define the reflection coefficients is completely arbitrary, and we have found it convenient to plot Γ_ℓ and $1/\Gamma_d$ on a Smith chart whose normalizing impedance Z_o is equal to the absolute value of the device's net negative resistance at DC:

$$Z_o = R_d - R_S = 20 - 5 = 15 \text{ ohms} \tag{3}$$

The advantage of this normalization is that the locus of the device's $1/\Gamma_d$ line as a function of frequency always starts at the center of the Smith chart and crosses the unit circle at the cutoff frequency f_r, as Fig. 2 shows.

Although Esdale and Howes do not address the issue of non-steady-state oscillation, it seems reasonable to assume that exponentially growing oscillations will occur at a given frequency if the following two conditions are satisfied:

$$|\Gamma_\ell| > |\frac{1}{\Gamma_d}| \tag{4}$$

$$\angle(\Gamma_\ell) = \angle\left(\frac{1}{\Gamma_d}\right) \tag{5}$$

The region of the Smith chart which satisfies these conditions is shaded in Fig. 2. If the load's reflection-coefficient locus $\Gamma_\ell(f)$ strays into this area, growing sinusoidal oscillations are possible. This portrayal shows why even extremely small values of inductance in series with the load can cause stability difficulties. For example, an inductance of only 25 picohenries has a reactance of 15 ohms at 100 GHz, which would place Γ_ℓ near the top of the Smith chart in Fig. 2, leading to possible problems with spurious "low-frequency" millimeter-wave oscillation in a submillimeter-wave circuit. Such parasitic inductance is difficult to avoid in lumped-element or waveguide circuits. However, integrated-circuit techniques may furnish a way around this problem.

Lossy Integrated-Circuit Transmission Lines

The ideal bias circuit for a submillimeter-wave RTD oscillator would be a voltage source with essentially zero internal impedance from DC up to the diode cutoff frequency f_r. No passive or active circuit achieves this ideal, but it is clear that a very broadband bias circuit design is called for, one whose impedance on the Smith chart of Fig. 2 would stay in the low-impedance left-hand side over the entire frequency range. Standard radio-frequency bypassing techniques can deal with this problem from DC up to the low GHz range, but above that it becomes very difficult to devise a low-loss filter structure whose input impedance never strays into the danger zone of Fig. 2 from, say, 10 GHz up to 700 GHz.

Fortunately, there are microelectronic components whose impedance can be made low and fairly constant over a wide frequency range. If a microstrip line is laid out on a highly-doped semiconductor substrate as shown in Fig. 3, it forms a slow-wave transmission line under certain conditions. Such transmission lines have been investigated for possible signal-processing applications, but their very high attenuation values (up to 24 dB at 18 GHz in a 1.6 mm-long line reported by Krowne and Neidert [4]) have discouraged this application. However, one man's poison is another man's meat, and the very high loss factors which are such a disadvantage in signal processing turn out to be ideal for RTD biasing.

If these lines are made sufficiently wide, their characteristic impedance can fall below ten ohms. Moreover, the very high loss factors mean that a line a few millimeters long will present an essentially constant impedance to the oscillator circuit, regardless of how the bias-supply end of the line is terminated. This will not be the case at lower frequencies where the loss is not as great, but fortunately the conventional lumped-element circuit techniques can take over at that point.

Oscillators Using Lossy Lines

In some very preliminary experiments, we have used this biasing approach to stabilize negative-resistance devices in quasioptical oscillator circuits. One circuit is shown in Fig. 4. A thin slot antenna measuring 4.5 cm by 1 mm was fabricated on a single-clad microwave circuit substrate 0.508 mm thick, with a relative dielectric constant of 2.2. The low-impedance lossy transmission line, 2.8 mm wide and approximately 2.5 cm long, was fabricated on a 0.38 mm thick silicon wafer with a 7000 Å layer of silicon dioxide (SiO_2) grown on its top surface. The silicon was highly doped with a resistivity of less than 0.01 ohm-cm.

The microstrip line was mounted perpendicular to the slot. A packaged microstrip type tunnel diode was then mounted across the slot with its anode connected to one end of the microstrip line and its cathode to the ground across the slot. Tuning to the desired oscillation frequency was achieved by moving the location of the diode (and the microstrip line) along the slot. An oscillation frequency of 2.4 GHz was achieved by placing the diode 2-3 mm away from one end.

Another circuit in Fig. 5, described in more detail elsewhere [6], used a packaged RTD in a similar slot-antenna oscillator. In this case, the bias was fed through a 6.3-mm-wide parallel-plate transmission line made from 0.25-mm thick fiberglass circuit board material. Its 27-cm length and the lossy nature of its dielectric meant that, at least at high frequencies, its impedance at the diode end was independent of how the far end was terminated. The oscillator ran at 8.9 GHz, and demonstrated that an RTD oscillator's spectrum can be significantly improved if it is coupled to a high-Q cavity.

Conclusions

Despite the difficulties of designing oscillator circuits with submillimeter-wave negative-resistance devices, their promise as a useful source of power at those wavelengths has created a need for innovative oscillator circuit techniques. We hope that the notion of using integrated lossy transmission lines will encourage more efforts to exploit the great potential of resonant tunneling diodes to serve as a useful source of submillimeter-wave energy.

Acknowledgements

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References

[1] C. Kidner, I. Mehdi, J.R. East, and G.I. Haddad, "Power and stability limitations of resonant tunneling diodes," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 864-872, July 1990.

[2] E.R. Brown, C.D. Parker, L.J. Mahoney, J.R. Söderström, and T. McGill, "Room-temperature oscillations up to 675 GHz in *InAs/AlSb* resonant-tunneling diodes," 1990 Device Research Conference, Santa Barbara, CA.

[3] D.J. Esdale and M.J. Howes, "A reflection-coefficient approach to the design of one-port negative impedance oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 770-776, Aug. 1981.

[4] C.M. Krowne and R.E. Neidert, "Slow wave monolithic variable phase shifter," *Proceedings of Tenth Int'l. Conf. on IR and MM Waves*, pp. 275-276, Orlando, FL, Dec. 9-13, 1985.

[5] H. Hasegawa, M. Furukawa, and H. Yanai, "Properties of microstrip line on Si-SiO_2 system," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 869–881, Nov. 1971.

[6] K.D. Stephan, E.R. Brown, C.D. Parker, W.D. Goodhue, C.L. Chen, and T.C.L.G. Sollner, "Resonant-tunneling diode oscillator using a slot-coupled quasioptical open resonator," submitted to *Electronics Letters*.

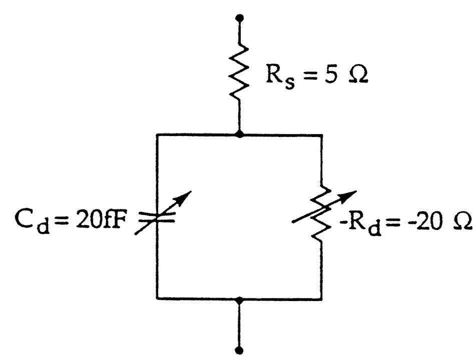

Fig. 1. Equivalent circuit of negative-resistance diode with cutoff frequency $f_r = 689$ GHz.

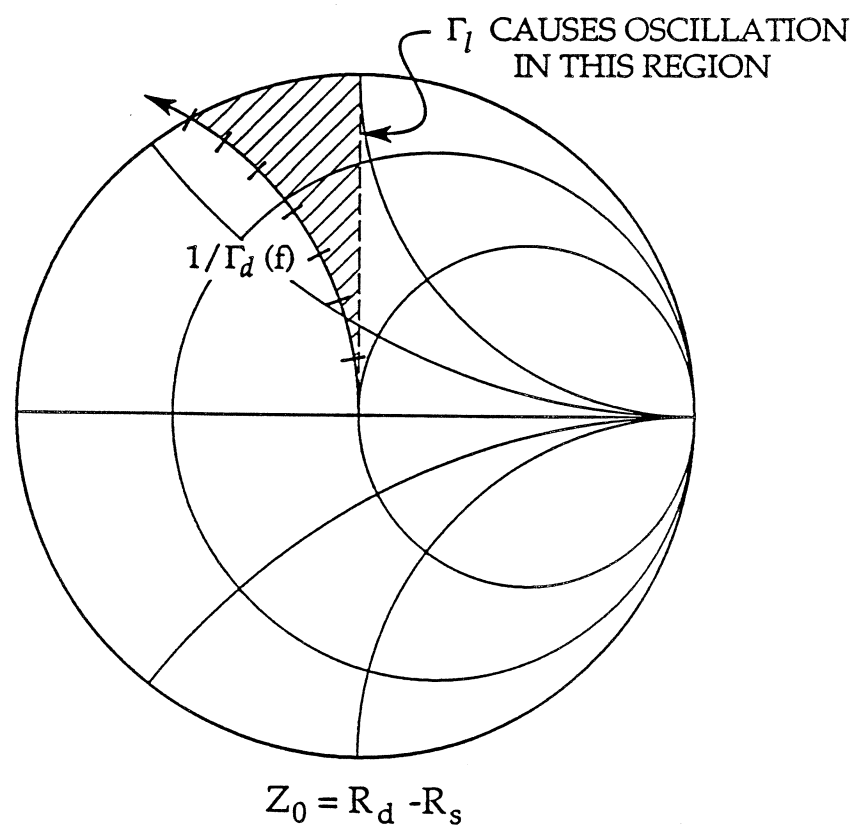

Fig. 2. Smith-chart plot of diode reflection coefficient inverse $1/\Gamma_d(f)$ and shaded area in which load impedance can cause oscillation.

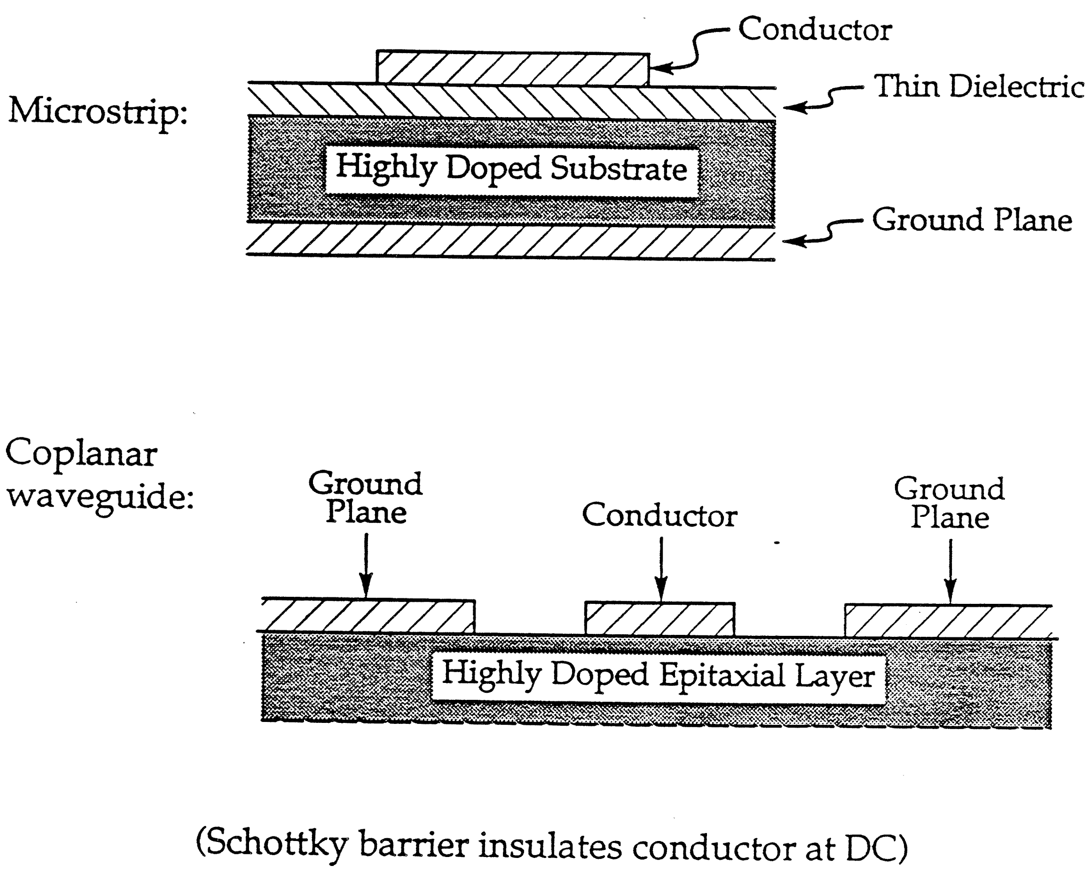

Fig. 3. Microelectronic low-impedance lossy transmission lines suitable for DC biasing negative-resistance devices.

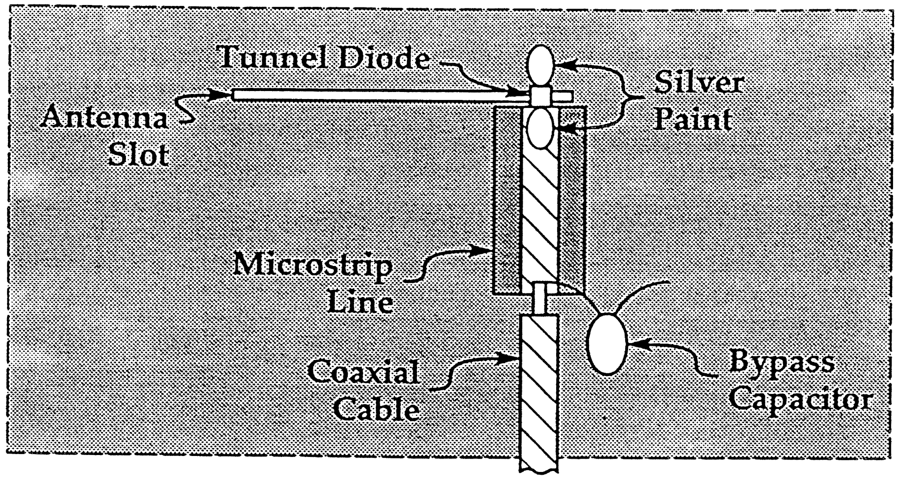

Fig. 4. Quasioptical oscillator using silicon lossy line for bias stabilization: $f_{osc} = 2.3$ GHz.

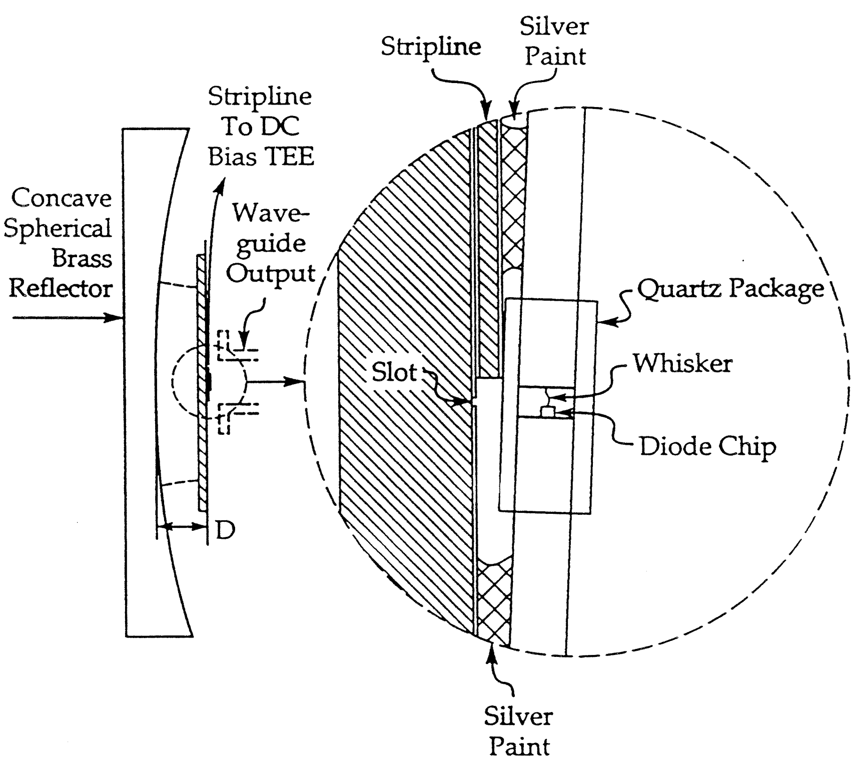

Fig. 5. Quasioptical cavity – stabilized oscillator using lossy-line bias: $f_{osc} = 8.9$ GHz.