V-3. INTEGRATED MICROWAVE TUNNEL DIODE DEVICE

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Introduction. A microwave tunnel diode amplifier usually requires both a stabilizing network and one or more reactive tuning elements associated with the tunnel diode. The stabilizing network insures satisfaction of the appropriate stability criteria[1,2] governing the given amplifier configuration at all frequencies within the active frequency range of the tunnel diode (dc to resistive cutoff frequency) and, in particular, those outside the operating band. Such networks generally take the form of band rejection filters[1,3] which resistively terminate the diode outside the operating band and appear essentially reactive within it. The tuning element usually consists of a shunt inductor to resonate the generally capacitive parasitic reactance of the diode at the center frequency of the amplifier.

In order to provide effective tuning and stabilization at microwave frequencies, the appropriate circuitry must be physically located as close to the tunnel diode junction as possible, avoiding the decoupling effects of excessive transmission line length and diode parasitic reactance. In addition, it is preferable that the various circuit elements appear essentially "lumped" over the active frequency range of the tunnel diode, avoiding possible spurious higher order resonances. These objectives are often difficult to accomplish using conventional microwave circuitry and encapsulated tunnel diodes.

Therefore, it has been proposed that an unencapsulated tunnel diode, a reactive tuning element, and a stabilizing network be integrated, using thin film technology, into a single stabilized and tuned, active bandwidth-limited negative resistance device of size comparable to most existing encapsulated tunnel diodes. The designation "device" rather than "amplifier", typical of the expanded concept of "device" in integrated circuits, is employed, since the given thin film circuit is, in itself, not an amplifier but can be used in many amplifier configurations.

The advantages of the integrated circuit approach, as compared with more conventional TDA construction, may be enumerated as follows; from the standpoint of the device:

1) The necessity for encapsulating the tunnel diode and the resulting encapsulation parasitics are eliminated and the potential lower bound on diode series inductance is considerably reduced.
2) The tuning and stabilizing circuit elements are drastically reduced in size and are connected almost directly at the tunnel diode junction thus satisfying the "lumped element" and "close connection" objectives expressed above.

From a systems standpoint, the small size and weight of these circuits are of significant advantage, particularly if coupling networks such as circulators can be correspondingly reduced in size. Finally, the potential mass reproducibility of these integrated devices is a distinct advantage.

Integrated Device Configurations. A series of shunt-tuned integrated microwave tunnel diode devices has been fabricated for use in circulator-coupled reflection amplifiers. The exact small signal equivalent circuit of a representative device is shown in Fig. 1, along with a simplified equivalent circuit which is valid in the vicinity of device center frequency ω_o. In the exact circuit, shunt tuning inductor L_t resonates the diode capacity at ω_o, and blocking capacitor C_b, essentially zero reactance at ω_o, prevents short-circuiting of the diode bias voltage.

The bandwidth capabilities of this device are summarized in Table I, assuming that the device is losslessly coupled to a "perfect", frequency-independent circulator. Practical band-limited circulators usually reduce the realizable amplifier bandwidth below these limits.[1,3] Table I also contains a formulation of the degradation[4] in the familiar TDA noise figure[1,3] due to losses in the thin film circuit elements.

Physically, the integrated tunnel diode device consists of a beam-lead germanium tunnel diode bonded to the thin film circuit across a thin film stabilizing network and a fixed shunt thin film tuning inductor, as shown in Fig. 2. Each bond is formed by a split tip or ultrasonic welded joint or a drop of conducting epoxy. The entire thin film circuit is deposited on a .162" long, .188" wide and .031" thick sapphire substrate.

The beam-lead diode used in this device consists of a 4 x 4 x 2 mil p-type germanium wafer (doped with about 10^{20} concentration of gallium) to an edge of which a pointed lead-antimony ribbon is pulse bonded, thereby forming the junction. The junction is strengthened mechanically by the addition of a drop of epoxy. The other contact consists of a 4 mil wide gold plated kovar ribbon bonded to the bottom of the wafer.

The thin film stabilizing network consists of a .005" x .005" tantalum thin film resistor R_N in series with a parallel L_N - C_N circuit, resonant at center frequency ω_o. The L_N - C_N circuit is composed of a .005" x .005" overlap capacitor utilizing a silicon monoxide dielectric, shunted by a coupled strip line inductive loop. The tuning inductor L_t is an inductive loop which is grounded through a .012" x .035" overlap blocking capacitor C_b.

The entire integrated device may be mounted in a conventional transmission line fixture for characterization or use in an amplifier, or it may be formed on a larger substrate containing the remaining components required to realize a complete integrated thin film amplifier. A typical fixture for mounting the device coaxially is shown in Fig. 3.

Use of Device as an Amplifying Element. To demonstrate the use of the integrated microwave tunnel diode device as an amplifying element, two simple circulator-coupled amplifiers were constructed in which 4 GHz and 6 GHz shunt-tuned devices, mounted similarly to that in Fig. 3, were directly connected to relatively wideband, coaxial 4 GHz and 6 GHz circulators, respectively. For preliminary measurements, no attempt was made to broadband the amplifier. The resulting amplifiers were absolutely stable over all

TABLE I

INTEGRATED TUNNEL DIODE DEVICE PERFORMANCE
IN CIRCULATOR COUPLED REFLECTION AMPLIFIER

1) Active bandwidth:

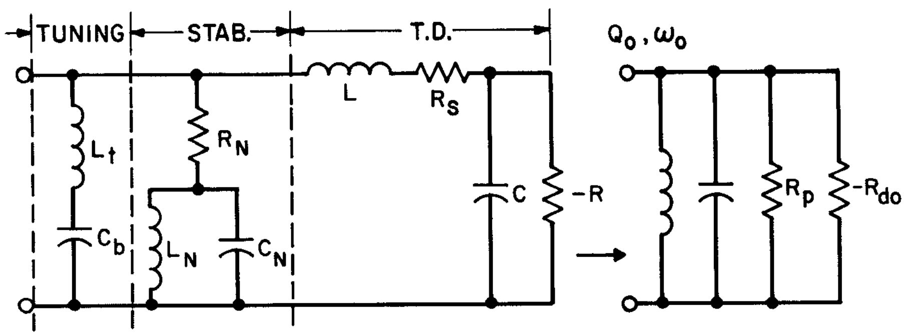
$$\beta_A = \frac{\Delta\omega_A}{\omega_o} = \frac{1}{\omega_o R_N C_N \sqrt{\frac{R_{do}(min)}{R_N} - 1}}$$

2) Maximum amplification bandwidth for flat power gain $\mathcal{G}_o$, assuming a "perfect" circulator:

$$\beta = \frac{\Delta\omega}{\omega_o} = \frac{2\pi}{Q_o \ln \mathcal{G}_o}$$

3) Noise figure degradation due to R_p:

$$\Delta F = \left(1 - \frac{1}{\mathcal{G}_o}\right)\left(\frac{R_{do}}{R_p - R_{do}}\right)\left(\frac{T(^\circ K)}{290^\circ}\right)$$



$$L \lesssim R R_s C, \omega_o = \frac{1}{\sqrt{L_n C_n}} >> \frac{1}{\sqrt{L_t C_b}}$$

$$\omega_o \lesssim 3\omega_R, \omega_R = \frac{1}{RC}\sqrt{\frac{R}{R_s} - 1}$$

$$R_{do} \approx R - R_s$$

$$C_{do} \approx C \frac{R}{R_{do}}$$

$$Q_o = \omega_o R_{do} (C_{do} + C_N)$$

$R_N, R << R_p$ = LOSS RESISTANCE DUE TO R_N, L_N, C_N, L_t, C_b

Fig. 1. Integrated microwave tunnel diode device equivalent circuits.

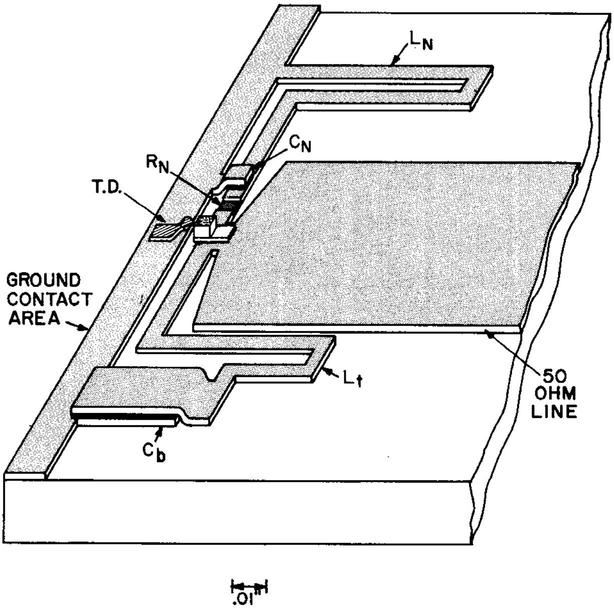


Fig. 2. Physical device configuration.

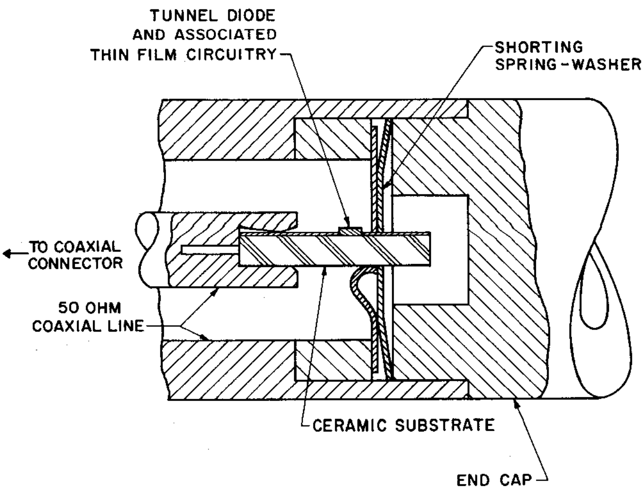


Fig. 3. Coaxial mounting fixture for integrated microwave tunnel diode device.

diode bias voltages, and exhibited the essentially single tuned gain-frequency characteristics (centered at 3.85 and 6.08 GHz, respectively) expected of a single tuned negative resistance device directly connected to a relatively resistive circulator. The measured gain and noise figure as functions of frequency for several values of diode bias are shown for the 3.85 GHz and 6.08 GHz amplifiers in Fig. 4 and 5, respectively. Under typical bias conditions, the 3.85 GHz amplifier exhibits 11.0 dB midband gain, 380 MHz half-power bandwidth, and 5.20 dB midband noise figure, and the 6.08 GHz amplifier, 16.1 dB midband gain, 440 MHz bandwidth, and 5.7 dB noise figure. The measured results agree reasonably well with those predicted on the basis of the given device parameters with about 1.0 to 1.5 dB degradation in measured noise figures[5] attributable to the measured equivalent thin-film loss resistances of the devices ($R_p \simeq 200 - 300$ ohms). This noise figure degradation should be reduced as thin film microwave reactive circuit elements improve in unloaded quality factor.

Conclusions. A series of shunt-tuned integrated microwave tunnel diode devices, including tuning and stabilizing circuitry, has been fabricated using thin film technology. The successful use of shunt-tuned devices in absolutely stable 3.85 GHz and 6.08 GHz circulator coupled reflection amplifiers has been demonstrated.

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2. B. T. Henoch and Y. Kvaerna, "Stability Criteria for Tunnel-Diode Amplifiers", IRE Trans. MTT-10, pp 397-398, September 1962.
3. J. Hamasaki, "A Low Noise and Wide-Band Esaki Diode Amplifier with a Comparatively High Negative Conductance Diode at 1.3 GHz", IEEE Trans. MTT-13, pp 213-223, March 1965.
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5. On the other hand, noise figure degradation introduced by conventional TEM transmission line TDA tuning and stabilizing circuitry is typically about 0.5 dB.

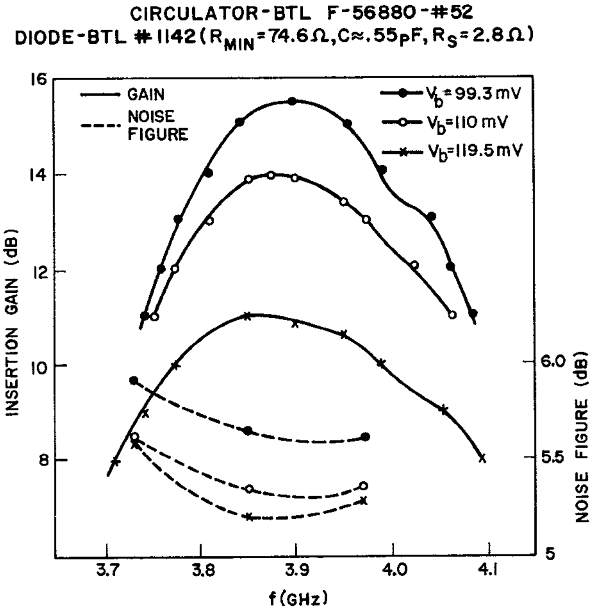

Fig. 4. Measured performance of 3.85 GHz reflection amplifier.

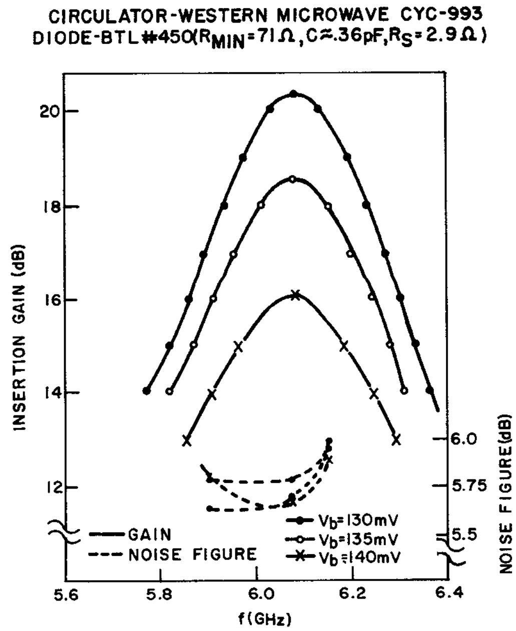

Fig. 5. Measured performance of 6.08 GHz reflection amplifier.