formulas also permitted corrections to be made for the finite thickness of each post. Tuning screws were omitted from the design. In this manner the conditions necessary in the computation were simulated as far as possible in the actual design. Thus any differences between computed and experimental results would be due to manufacturing tolerances or errors involved in the susceptance structures. These latter errors are caused by the approximate relationship assumed for the frequency variation of the susceptance and errors inherent in Lewin's formulas, which were expected to have an accuracy of a few per cent.

The filter was designed for a nominal pass band VSWR ripple of 1.05 over a bandwidth of approximately 7 per cent, centered at 8.5 kMc. In Fig. 4 the experimental results are compared with the theoretical and computed responses. Manufacturing tolerances of ± 0.001 inch were placed upon the position and diameter of each post. The overall effect of extreme tolerance error upon the susceptance values and cavity lengths was estimated and the resulting response computed in each case. The shaded area indicates the variation in response expected as a result of manufacturing tolerances. The experimental curve follows the computed curves fairly closely, except near the limits of the pass band. Thus the deviations at the pass band extremes, between the computed and experimental curves, result mainly from the approximate relationship assumed for the frequency variation of the coupling susceptances in the computation.

Conclusions

Although computations have been made for the special case of a 7-cavity filter the results are a good indication of the effects arising from increase in design bandwidth for all filters. In general it is to be expected that the deterioration in performance will be more severe with increase in number of cavities for a given filter. The results show that it is not advisable to design for a very low pass band VSWR when the bandwidth exceeds about 5 per cent as excessive peaks will be obtained in the pass band. For the particular case of the 7-cavity filter a design VSWR ripple of about 1.25 was found to be free from undesired peaks for bandwidths up to 20 per cent. Another factor which must be taken into account is the reduction in pass band width resulting mainly from a shift in the upper attenuation slope.

The computations have been carried out using a simple proportionality relationship for the variation of susceptance with guide wavelength. An experiment has indicated that a more accurate expression for susceptance may lead to the spurious pass band peaks becoming accentuated. A further reduction in pass band width will also occur, mainly as a result of a shift in the lower frequency skirt.

The process of repeated analysis can be applied to the problem of synthesizing filters with improved performances.[3] At the present time a technique is being developed which involves the progressive perturbation of the filter parameters starting with the approximate Cohn values. The technique has produced responses approaching the design specification for a 9-cavity filter, and it is hoped that results will be published in the near future.

Acknowledgment

The author is indebted to the Chief Scientist, Research and Development Branch, Australian Department of Supply, for permission to publish these results.

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[3] L. Young, "Microwave filter design using an electronic digital computer," IRE Trans. on Microwave Theory and Techniques, vol. MTT-7, pp. 99–101; January, 1959.

Tunnel Diodes as Millimeter Wave Detectors and Mixers*

Backward diodes and tunnel diodes have been successfully operated as detectors and mixers at microwave frequencies [1]–[5]. The extension of their usage from microwave frequencies to millimeter wave frequencies is a natural outgrowth of earlier work.

Tunnel diodes usually have less series resistance than ordinary crystal diodes or backward diodes and thus can be expected to give higher sensitivity and a lower noise factor. The frequency response of the negative resistance of tunnel diodes is good at microwave frequencies. However, at millimeter wave frequencies the usefulness of the negative resistance is curtailed by the junction capacitance. Reduction of this capacitance is difficult, but can be accomplished within the limits of practical design.

This correspondence reports the results obtained with a tunnel diode as a 55-Gc detector and as a mixer. Alloying techniques were used to fabricate the tunnel diodes which were then integrated into a tapered section of RG-98/U waveguide. Fig. 1 shows the arrangement of the diode in the waveguide. The first mount is made with an epoxied contact while in the second the contact is made by means of a wire passing through an opening in the top of the waveguide. No difference in sensitivity of diodes made by the two methods has been noticed; however, the epoxy method gives more mechanical stability.

The diodes used were of n-type gallium antimonide and tellurium. The impurity concentration of the gallium antimonide was 1 to 2×10^{18} per cc and the resistivity was 0.001 to 0.0025 Ω-cm. Fig. 2 is the I-V characteristic of a typical diode. Units

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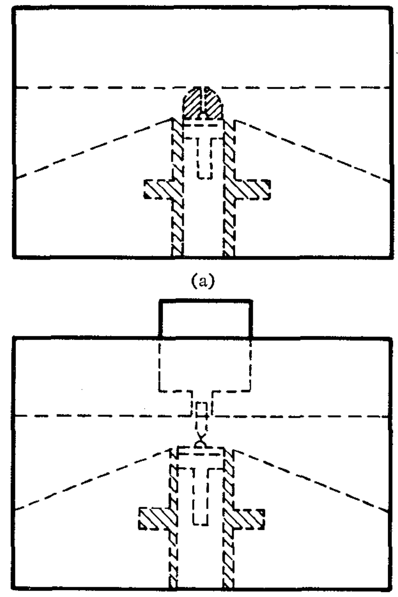

Fig. 1—Tunnel-diode mounts for millimeter wave mixer.

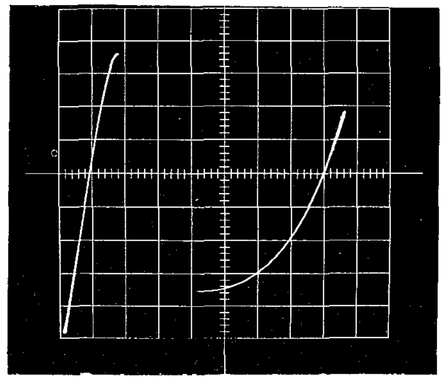

Fig. 2—I-V characteristic of a GaSb tunnel diode (0.1 ma/vertical division and 0.05 v/horizontal division).

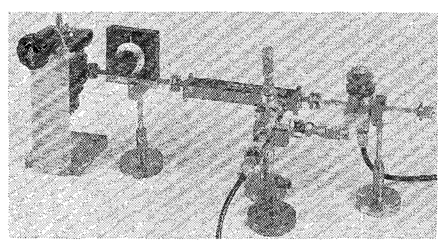

Fig. 3—A millimeter wave tunnel-diode detector.

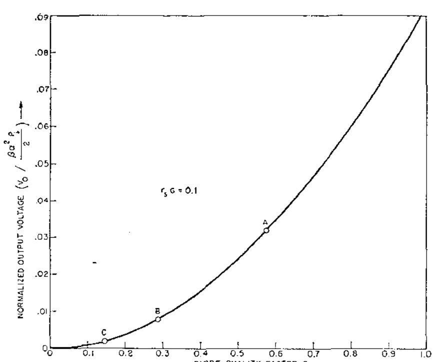

Fig. 4—Normalized output voltage as a function of diode quality factor.

which exhibit peak-to-valley current ratios of 14 to 1 with peak currents of 5 ma have been achieved. Representative measured values of junction capacitance and series resistance are 0.2 pf and 5 Ω, respectively. These parameters correspond to cutoff frequencies in the range of 40 to 50 Gc.

An experimental 55-Gc tunnel-diode detector is shown in Fig. 3. The detector voltage for such a detector can be shown to be

$$V_0 = \frac{P_i \frac{R}{2} \alpha(r_s G)}{r_s G + (r_s G)^2 + \omega^2 C^2 r_s^2}$$

where P_i is the RF input power, ω is the angular frequency, r_s is the diode series resistance and C is the junction capacitance. G ($=1/R$) is the diode conductance and is equal to the slope of the I-V characteristic of the diode. α is a nonlinearity coefficient with the dimensions of $1/V$ and is equal to the ratio of the curvature to the slope of the I-V characteristic.

Fig. 4 shows the detector behavior for the case where $r_s G = 0.1$ ($Q_d = \omega C r_s$, $\beta = \alpha/R$). The curve is marked by three special points: A) a tunnel diode biased near the peak current point, B) a backward diode, and C) an ordinary crystal diode. The circuit parameters of these diodes are

A) $R = 50\ \Omega$
$r_s = 5\ \Omega$
$L_s = 0.5 \times 10^{-12}$ h
$C = 10^{-12}$ f
$\alpha = 200\ 1/V$

B) $R = 100\ \Omega$
$r_s = 10\ \Omega$
$L_s = 10^{-9}$ h
$C = 10^{-12}$ f
$\alpha = 50\ 1/V$

C) $R = 200\ \Omega$
$r_s = 20\ \Omega$
$L_s = 10^{-9}$ h
$C = 10^{-12}$ f
$\alpha = 25\ 1/V$.

The points indicate that the tunnel-diode detector yields the highest output voltage. The experimental tunnel-diode detectors did show an improvement in sensitivity of 15 to 22 db over the sensitivity of an ordinary 1N53 crystal.

With the addition of a pump source, a millimeter wave detector circuit can also be operated as a mixer. If the signal frequency differs from the pump frequency by only 100 Mc, the pump source can be coupled to the same input circuit through a directional coupler.

The noise-factor improvement of a tunnel-diode mixer over a crystal diode mixer has been demonstrated [2] at UHF and microwave frequencies. The diodes described above were operated in a 55 Gc to 100 Mc down converter. An improvement of about 10 db in the system noise figure was observed when the tunnel diode was used as the mixer compared to the same system with a 1N53 crystal as the mixer. A tangential sensitivity of −82 dbm was observed with the tunnel diode as compared to a tangential sensitivity of −71 dbm for a 1N53 crystal.

The crucial problem in the use of tunnel diodes at millimeter wave frequencies is one of technology, the fabrication of diodes with low junction capacitance and low series resistance. The present art seems capable of fabricating these diodes. There is reason to expect that future technology should increase the usefulness of tunnel diodes at millimeter wave frequencies and even allow them to be used at submillimeter wave frequencies.

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References

[1] S. T. Eng, "Low-noise properties of microwave backward diodes," IRE Trans. on Microwave Theory and Techiques, vol. MTT-9, pp. 419–425; September, 1961.
[2] C. T. McCoy, "Present and future capabilities of microwave crystal receivers," Proc. IRE, vol. 46, pp. 61–66; January, 1958.
[3] W. M. Sharpless, "Gallium arsenide point contact diodes," IRE Trans. on Microwave Theory and Techniques, vol. MTT-9, pp. 6–10; January, 1961.
[4] K. Ishii and A. L. Brault, "Noise output and noise figure of biased millimeter wave detector diodes," IRE Trans. on Microwave Theory and Techniques, vol. MTT-10, pp. 258–262; July, 1962.
[5] M. D. Montgomery, "The tunnel diode as a highly sensitive microwave detector," Proc. IRE (*Correspondence*), vol. 49, pp. 826–827; April, 1961.
[6] H. J. Prager and K. K. N. Chang, "The effect of large pump voltage on tunnel diode down converter performance," *RCA Rev.*, pp. 567–581; September, 1961.

Correction to "Group Delay and Dissipation Loss in Transmission-Line Filters"*

In the above Correspondence,[1] on page 216, in (17), the numerical factor should be 27.3, and not 2.73.

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* Received July 5, 1963.

[1] L. Young, "Group delay and dissipation loss in transmission-line filters," IEEE Trans. on Microwave Theory and Techniques (*Correspondence*), vol. MTT-11, pp. 215–217; May, 1963.

Correction to "Direct-Coupled Cavity Filters for Wide and Narrow Bandwidths"*

In the above paper,[1] on page 170, the Δ symbols were omitted in (34) and (35), which should have read

$$\frac{\Delta f'}{\Delta f_1'} = \frac{\Delta f}{\Delta f_1} \quad (34)$$

$$\frac{\Delta f'}{\Delta f_2'} = \frac{\Delta f}{\Delta f_2} \quad (35)$$

On page 176, the caption to Fig. 24 should be: Characteristics in the stop band of the quarter-wave transformer prototype and the two filters (B and C in Fig. 23) derived from it.

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* Received July 5, 1963.

[1] L. Young, "Direct-coupled cavity filters for wide and narrow bandwidths," IEEE Trans. on Microwave Theory and Techniques, vol. MTT-11, pp. 162–178; May, 1963.