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Frequency Modulation of Avalanche Transit Time Oscillators

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***Abstract*—This paper presents experimental data taken to determine the frequency modulation characteristics of avalanche transit time oscillators.**

The active element is a diffused mesa diode with a shallow junction in epitaxial n-$n+$ silicon; the details of the construction of the diode are presented and its typical characteristics are discussed.

The basic oscillator consists of the diode mounted in the capacitive portion of a radial mode cavity machined of copper with the outlines of a DO-5 diode header. The frequency of oscillation is dependent upon the diode junction capacitance and is varied between 5 and 8 GHz for the diodes tested. Microwave power levels up to 100 mW have been observed with an efficiency exceeding 3 percent. The frequency drift over the temperature range from -70 to $+100$°C is 2.5×10^{-5} parts/°C.

The frequency modulation characteristics of these oscillators indicate their potential applications in miniature solid-state low-power communications systems.

ELECTRONIC tuning of avalanche transit time oscillators has been treated explicitly by Gilden and Hines.[1] This electronic tuning effect, which is attributed to the variability of avalanche susceptance with current, is evident also in theoretical and experimental investigations of others for both Read and p-n type devices.[2],[3]

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Read[4] has discussed electronic tuning briefly but was uncertain as to whether the variation of frequency of oscillation with the diode current could be made large enough for a practical frequency-modulation device, particularly when the diode was operating at optimum frequency and bias. For transit angles substantially less than the optimum value, however, Gilden and Hines showed that strong negative resistance effects still occurred and that electronic tuning effects were significant. Recently, Rulison *et al.*[6] reported a germanium p-n diode which exhibited a susceptance variation with current between a half and one order of magnitude larger than that of a Read diode under similar operating conditions.

Since moderate CW output power from these devices is now being realized, the ease of electronic tuning suggests their potential usefulness in many practical applications. This paper presents experimental data which were taken to determine the frequency modulation characteristics of avalanche transit time oscillators made at Sperry Microwave Electronics Company in terms of modulation linearity and inherent amplitude modulation.

The active element is a diffused silicon mesa diode, similar to the one described by Misawa.[5] The junction is formed by diffusing boron 2.4 microns deep in epitaxial silicon. The substrate is arsenic doped to a resistivity of 0.008 ohm/cm and the epitaxial layer has a thickness of 7 microns with a nominal resistivity of 1 ohm/cm. It is known that a high boron concentration in silicon leads to an excessive number of lattice defects resulting in a high density of microplasmas. Therefore, a surface concentration lower than customary for the fabrication of varactor diodes was chosen. The uniformity of the junction was further improved by applying a multiple predeposition post-diffusion technique. The resulting impurity profile is represented in Fig. 1. The junctions are of a nearly abrupt type with a sharp breakdown of 80 to 85 volts. Using conventional contacting and masking techniques, mesa diodes with a junction diameter of approximately 100 microns are formed, and after dicing individual diodes are mounted in a microwave pill package with a case capacitance of 0.25 pF and a lead inductance of $\sim$0.3 nH. The diodes exhibit typically a junction capacitance of 0.4$\sim$0.5 pF at breakdown. This fabrication technique led to diodes which gave higher efficiencies for CW operation with no evidence of microplasma breakdown.

The frequency modulation experiments were carried out with the encapsulated diodes mounted in a radial cavity operating in the fundamental mode. A photograph of an oscillator with external dimensions of a DO-5 power diode header is shown in Fig. 2. The basic oscillator consists of the diode mounted in the capacitive portion of the cavity and employs loop coupling with an OSSM output connector. The top cap and base portion of the cavity are separated by a 1 mil mylar spacer and connected together with nylon screws. Direct current bias and the low-frequency modulating signal are applied between top cap and base (Fig. 3). This biasing arrangement provided an effective short at microwave frequencies, yet offered negligible shunting effects at the modulating frequency. Since the cavity is fixed tuned, the oscillating frequency depends somewhat upon the junction capacitance of the diode at breakdown. The frequency of oscillation for typical diodes was between 6.5 and 7.5 GHz. Maximum CW output power for selected diodes was 100 mW at current levels of 40 mA operating at room temperature. In one typical run, 75 percent of the diodes gave between 40 and 60 mW of microwave power at current levels of 30 mA. Other runs consistently produced diodes which gave better than 20 mW at 30 mA.

The equipment which was used to obtain the frequency modulating characteristics of the oscillator is shown in Fig. 4. A low-frequency modulating signal was applied in series with the dc bias voltage using a transformer for isolation. The ac component of diode current was obtained by measuring the voltage across the series resistor. Frequency deviation was measured as a function of applied current either by observing the nulls of the various spectral components or, in the case of high modulation levels at low modulating frequencies, by observing the total deviation directly. A calibrated crystal detector and high-gain oscilloscope were used to measure the amount of inherent amplitude modulation.

In general, the electronic tuning range of an oscillator is inversely proportional to the Q when loaded for optimum output. Thus designing an oscillator cavity to have minimum Q at optimum load has the effect of maximizing the frequency modulating characteristics, i.e. lowering the Q increases the modulation sensitivity and linearity and decreases inherent amplitude modulation. Fig. 5 shows how a change in cavity parameters effects the frequency sensitivity of the oscillator. Frequency deviation is plotted as a function of modulating current for two oscillators which were designed to have significantly different Q values. The internal dimensions of the cavities were proportioned to give different ratios of cavity capacitance to inductance, yet oscillate at essentially the same frequency. A low ratio of cavity capacitance to inductance is conducive to high modulation sensitivity. The data of Fig. 5 were taken by observing the nulls of various frequency components as modulating current was varied. The plots are linear to within measurement accuracy, which is approximately ± 2 percent.

Photographs of the spectrum for various modulation indices for a modulating frequency of 600 kHz is shown in Fig. 6. In the first photograph, the first-order sidebands are zero and in the others the carrier is in its second-, third-, and fifth-order zero. The inherent amplitude modulation deduced from the symmetry and the relative amplitude of the various components agree (within measurement accuracy) with the values obtained with the calibrated detector. The measured amplitude modulation was less than 20 percent for the frequency deviations reported.

Frequency deviation as a function of modulating current and voltage were measured for different modulating frequencies. The modulating current was varied up to 3 mA (rms) yielding a deviation of approximately 35 MHz as shown in Fig. 7. These data, as well as those to follow, were made by observing the deviation directly on the spectrum analyzer display and do not reflect the accuracy of the previous measurements. The plot, however, is essentially linear and independent of modulating frequency. The data plotted as a function of modulating voltage for different modulating frequencies are shown in Fig. 8. For a constant modulating frequency, the deviation is linear with voltage. At a constant modulating voltage, however, the deviation increases with increasing frequency. Thus, for good frequency modulation the oscillator should be modulated with a current source.

The modulating voltage–current relation exhibited an unexpected behavior in the low-frequency impedance of the diode under avalanche conditions, i.e., the ratio of modulating voltage–current decreases with increasing frequency. This implies a circuit time constant three to four orders of magnitude greater than one would expect based on the measured circuit capacitance just prior to avalanche breakdown and the measured dc incremental resistance in breakdown. With the same equipment that was described previously, this behavior was checked for a number of diodes both in and out of the cavity with essentially the same decrease in impedance with frequency. The circuit appears linear at the modulating frequency since no distortion was evident in either the applied voltage or current when observed with the oscilloscope.

A test circuit commonly used to measure the impedance of Zener diodes was constructed (Fig. 9) and confirmed the

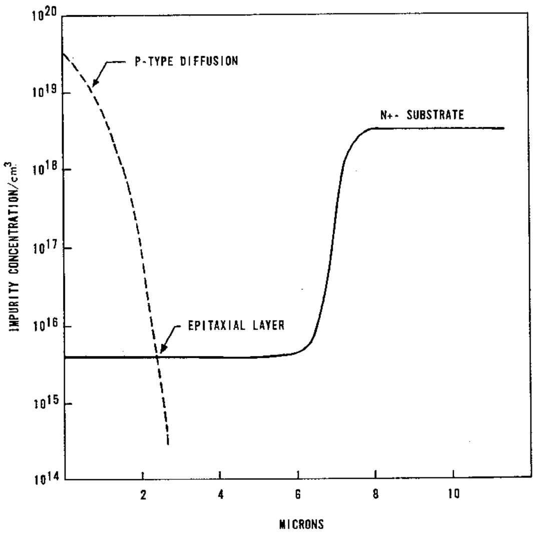


Fig. 1. Impurity profile of oscillator diode.

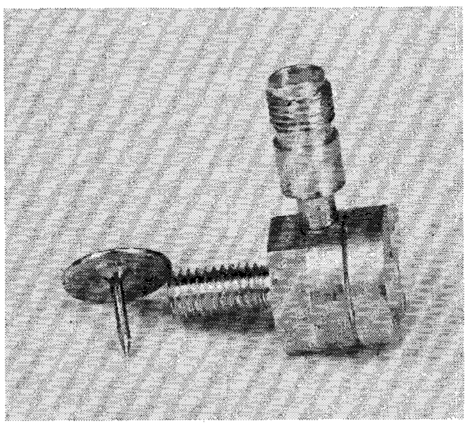


Fig. 2. Microwave oscillator with DO-5 outline.

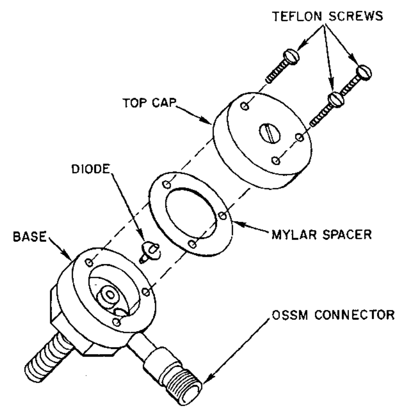


Fig. 3. Sketch of oscillator cavity.

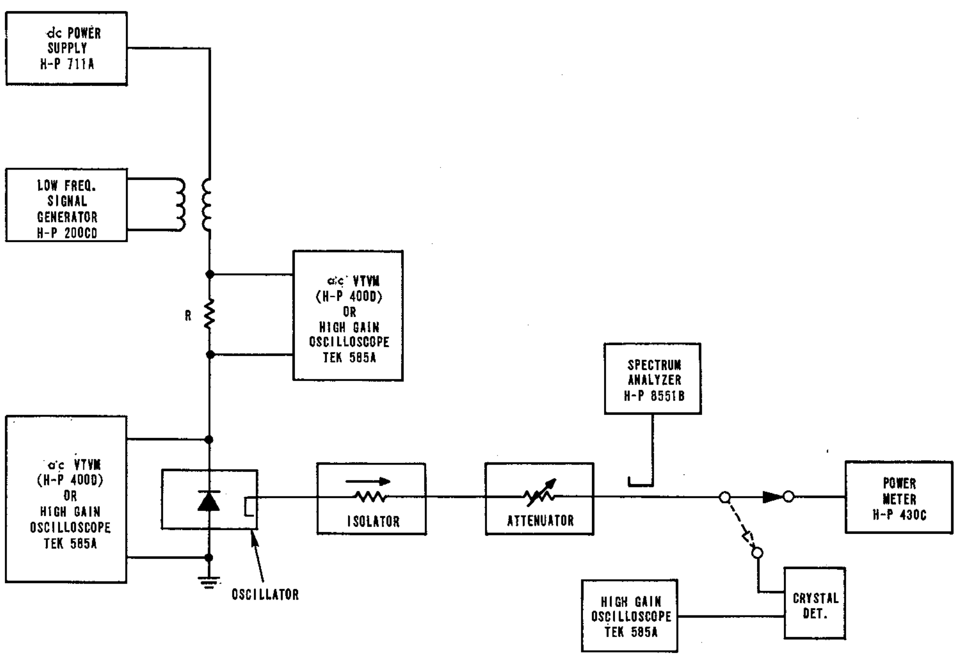


Fig. 4. Equipment used to measure frequency modulation characteristics of oscillator.

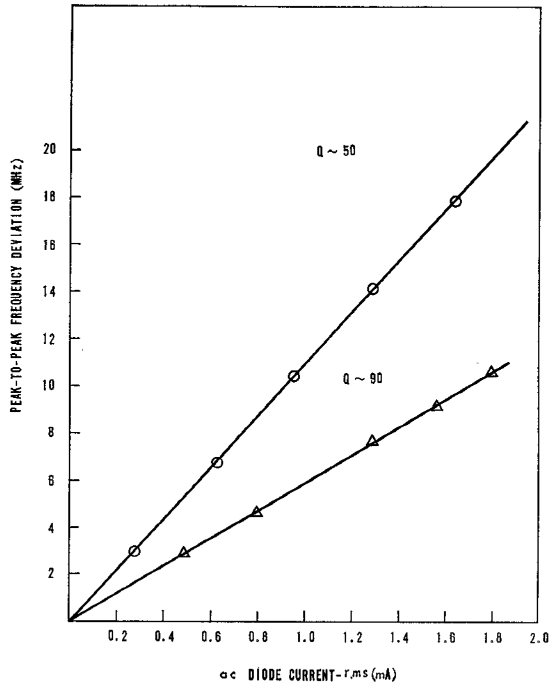
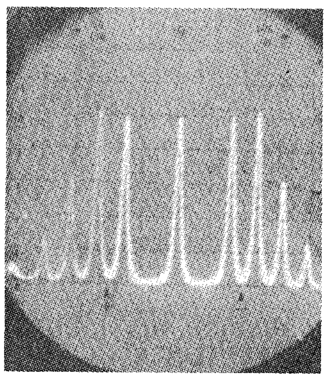
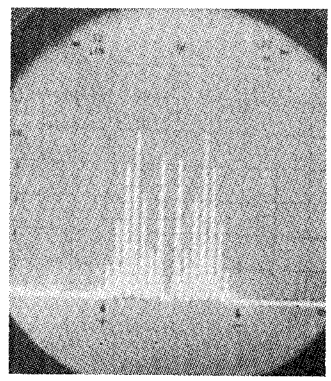


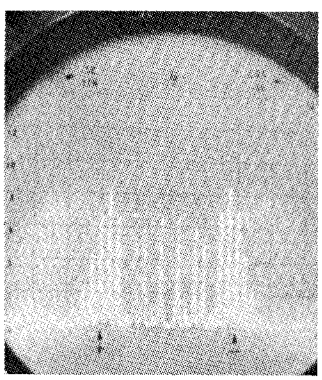
Fig. 5. ΔF versus I_{ac} for two different cavity designs.



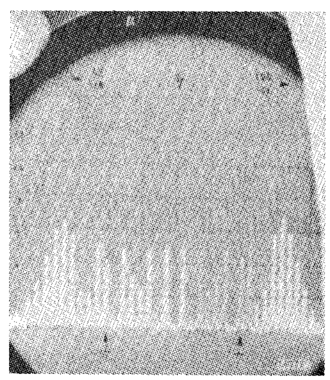
(a) m: 3.8; Horizontal sweep: 1 MHz/div.



(b) m: 5.5; horizontal sweep: 3 MHz/div.



(c) m: 8.7; horizontal sweep = 3 MHz/div.



(d) m: 14.9; horizontal sweep = 3 MHz/div.

Fig. 6. Photographs of spectrum analyzer displays for various modulation indices. $f_m = 600$ kHz, $f_c \sim 7$ GHz.

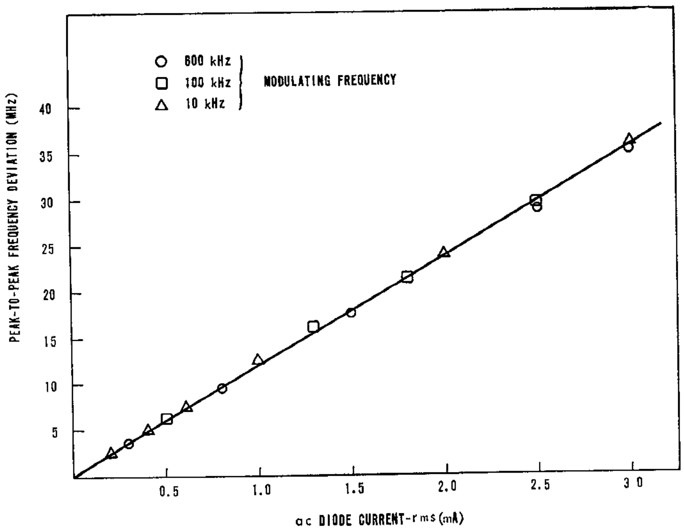


Fig. 7. ΔF versus I_{ac} for different modulating frequencies.

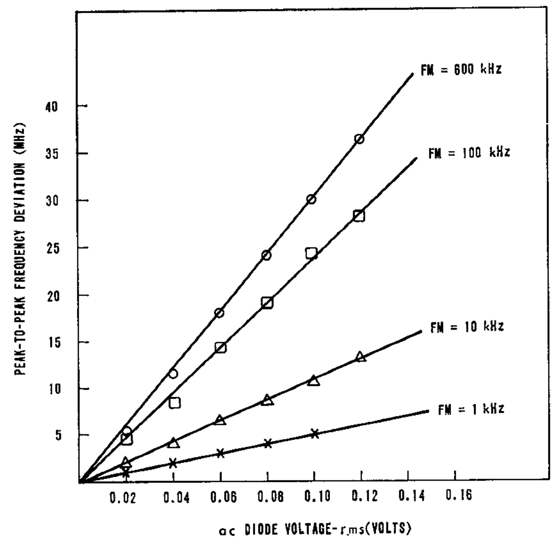


Fig. 8. ΔF versus V_{ac} for different modulating frequencies.

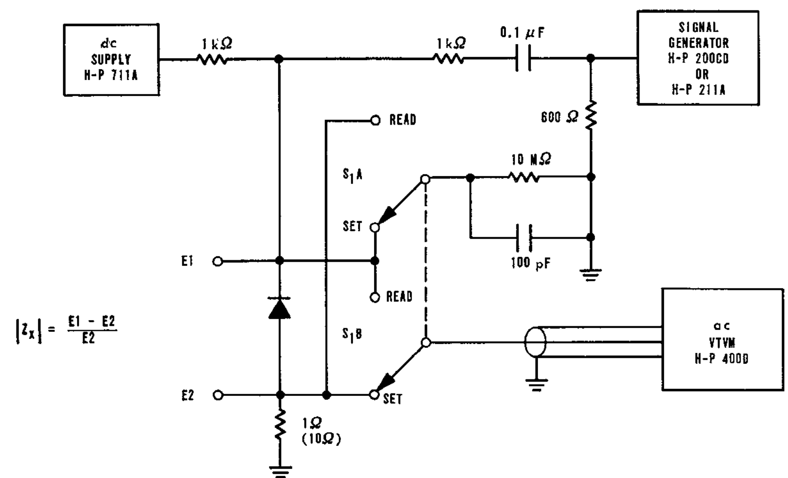


Fig. 9. Low-frequency Zener impedance test circuit.

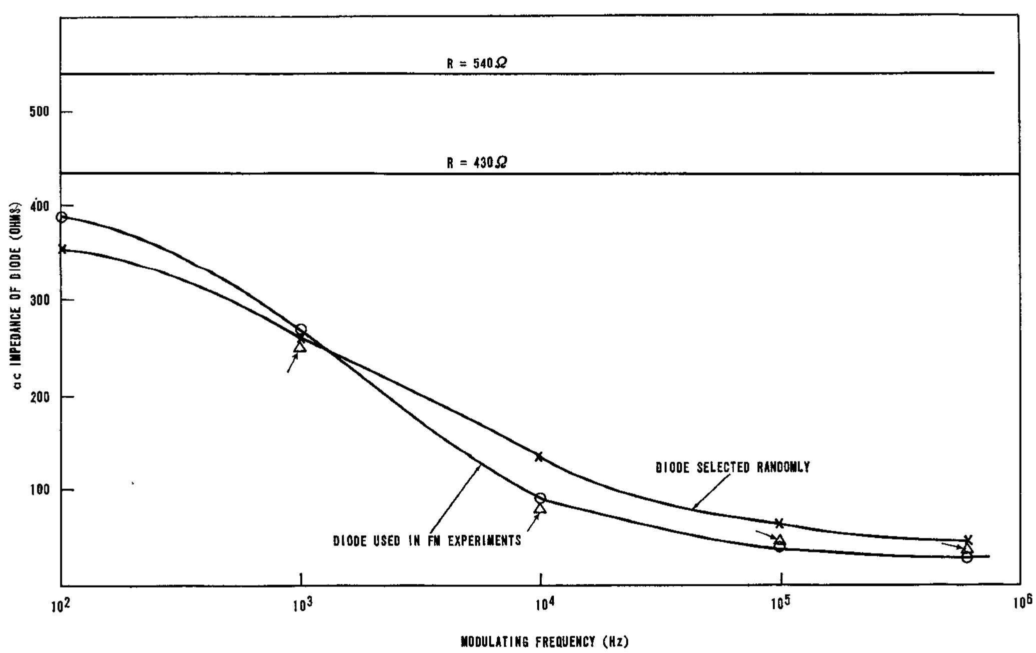
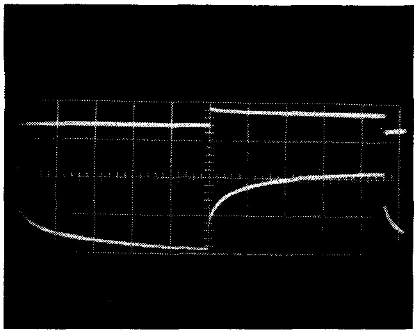
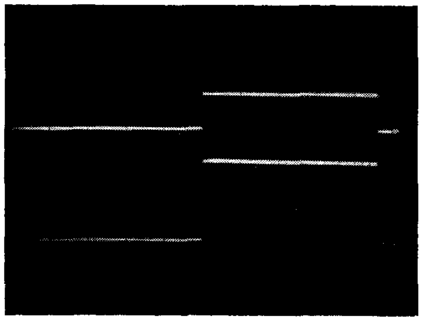


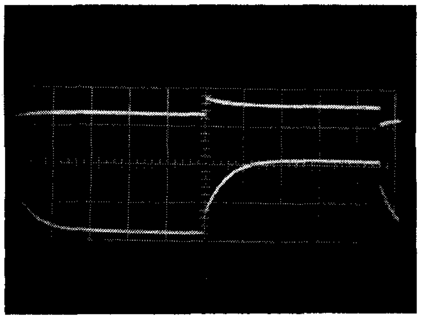
Fig. 10. Small signal ac impedance of diode under avalanche conditions.



(a) Diode dc biased to 20 mA.



(b) 100 ohm resistor.



(c)

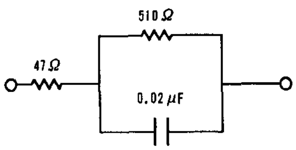


Fig. 11. Current and voltage pulse for 10 kHz square wave using Zener impedance test circuit. The top trace is the voltage across a 10 ohm viewing resistor; vertical scale: 0.05 V/div. The bottom trace is the voltage across the sample; vertical scale: 0.2 V/div. The horizontal scale is 10 μs/div.

previous measurements. With this circuit small signal measurements were made for different dc bias levels between 5 and 20 mA. The ac impedance at a given frequency was slightly dependent upon dc bias level, as would be expected, but retained its characteristic decrease with frequency. Fig. 10 is a plot of the impedance of two typical diodes as a function of frequency. The triangles represent values obtained during the frequency modulation experiments, i.e., the diode was in the cavity and in an oscillating state, and the circles represent values obtained with the diode out of the cavity and were obtained with the Zener impedance test circuit. The impedance curve of another diode selected randomly is also shown. Two resistors of value approximately equal to the incremetal dc resistance of the diodes were measured in the test circuit with no observable decrease in impedance with frequency.

Fig. 11(a) shows the current–voltage waveforms when the square wave current pulse is applied to a typical diode biased at 20 mA in the avalanche region. The top trace is voltage (0.05 V/cm) across the 10 ohm current viewing resistor and the bottom trace is voltage (0.2 V/cm) across the diode sample. The horizontal scale is 10 μs/cm. This characteristic behavior was typical of a large number of diodes, some from two other sources, in which pulse risetimes varied between approximately 5 to 10 μs. For comparison Fig. 11 also shows voltage–current pulses when lumped circuits are substituted into the impedance test circuit. The bottom left trace is for a 100 ohm nonreactive resistor for which the wave shape of the voltage pulse is nearly identical to that of the current pulse. The other trace is for a 47 ohm resistor in series with a 510 ohm resistor and a 0.02 μF capacitor in parallel. Risetime of a 1N978B Zener diode was measured in the same test circuit and was several orders of magnitude less than that for the avalanche transit time diodes.

The phenomena responsible for the long risetime of the avalanche transit time diodes and its effect on their oscillating properties are presently being investigated and will be reported later. C. B. Swan of Bell Telephone Laboratories has suggested that this is a thermal effect, corresponding to a thermal time constant of approximately 5 μs due to an increase in avalanche voltage with junction temperature.[7]

The avalanche transit time oscillator reported in this paper, however, exhibited frequency modulation characteristics comparable to those of a reflex klystron. In the laboratory, these devices have been used to transmit music with good fidelity. Using a battery to supply dc power and a crystal microphone and transformer to achieve current modulation, these devices have been used to transmit voice communication over a distance of $\frac{1}{3}$ mile with approximately 5 mW output power. In both cases, standard waveguide horns with a nominal gain of 17.5 ± 1.5 dB were used as receiving and transmitting antennas. The receiver consisted of a conventional microwave receiver, slightly detuned to provide FM–AM conversion.

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