HIGH-EFFICIENCY AVALANCHE RESONANCE PUMPED AMPLIFICATION*

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0. Summary

Microwave amplification has been obtained from silicon diodes operated in avalanche resonance pumped modes. DC to RF conversion efficiency was 25% at 1.3 GHz for a saturation gain of 12 dB and a bandwidth of 3%. A nonlinear theory predicts a large dynamic range and efficiencies up to 70%.

1. Introduction

High-efficiency modes of operation of microwave avalanche diodes have been found to be dependent on characteristic multi-frequency excitations. These excitations so far have led exclusively to oscillations. However, from an analysis as well as an applications point of view, it is of considerable interest whether diodes to be operated in these modes can be stabilized and driven by variable input signals.

In this paper, it will be reported that stable amplification has been obtained. Under conditions of self-generated "pump" signals at transit-time frequencies of 10 GHz, gains of 9 to 21 dB were measured at subharmonics. High output power levels corresponding to DC to RF conversion efficiencies of up to 25% and bandwidths in excess of 3% were obtained.

2. Modes of Operation

The silicon diodes were P^+-N-N^+ epitaxial-diffused diodes with breakdown voltages of 100 V. A zero differential DC resistance was reached at current densities of 1000 to 2000 $A \cdot cm^{-2}$ [1]. These diodes have previously generated microwaves in the frequency range 1.3 to 4.5 GHz with 10 to 45% efficiency [2]. Some of the oscillator results are displayed in Fig. 1, which also serves as an introduction to the particular modes of operation utilized in the amplification experiments. This figure shows several significant quantities as a function of frequency normalized to the avalanche resonance frequency. Normalized large-signal diode voltage and current amplitudes are shown as well as the phase angle between diode voltage and current and the DC to RF conversion efficiency. The avalanche transit-time (ATT) mode curves indicate the avalanche antiresonance by a broad maximum of the AC voltage V_{ATT}, a narrow minimum of the AC current I_{ATT}, and a phase angle of 180°. Above the resonance, the phase angle increases rapidly, as does the current amplitude, resulting in a smooth efficiency variation between 8% and 10%.

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NOTES

Below the resonance, the phase angle approaches 90° with decreasing frequency. Together with a strongly decreasing voltage amplitude V_{ATT}, the efficiency drops so that at frequencies equal or less than one half the resonance frequency the transit-time modes exhibit no negative resistance.

However, with strongly non-sinusoidal voltage waveforms, negative resistances and efficient power generation are again possible due to the extreme nonlinearity of the ionization processes. Waveforms with narrow spikes of excess voltages are optimum. Thus strong harmonic voltage components are necessary, which can best be produced at the avalanche resonance frequency. In order to avoid power losses, this signal (the avalanche resonance pump ARP) is now reactively terminated or "trapped in the microwave cavity", as indicated by a phase angle ϕ_{ARP} of 270°. Oscillations with large voltage and current amplitudes, V_{ARP} and I_{ARP}, and phase angles close to 180° are then possible at subharmonic frequencies resulting in high DC to RF conversion efficiencies η_{ARP}.

3. Measurements

The following experimental set up was chosen (Fig. 2). The microwave cavity was formed by a coaxial line with a characteristic impedance of 50 ohms and various sets of movable noncontacting transformer slugs. The diodes were mounted at the end of the line. Bias pulses from a reed pulser with a pulse length of 400 ns at a rate of 60 Hz were applied to the diodes through suitable bias insertion units. Under proper tuning conditions, a pump signal was generated at a frequency between 8.8 and 10.5 GHz, which was close to the avalanche resonance frequency for current densities of 1000 to 2000 A/cm^2. In order to obtain amplification, the resonator was tuned so that the avalanche resonance pump signal was established and any oscillations at other frequencies were suppressed. The avalanche resonance pump signal was monitored with a loosely coupled movable capacitive probe, inserted into the cavity. Signal frequencies were selected close to subharmonics of the pump frequency. The amplifier output signal was fed through precision attenuators into the 50 ohm input of a sampling oscilloscope.

The amplifier performance at the seventh subharmonic, 1.3 GHz, of a 10.4 GHz avalanche resonance pump is illustrated in the following figures. Fig. 3 shows the output power as a function of the input power at the center frequency 1.30 GHz. An input power range of 20 dB was investigated. The maximum gain was 19 dB. The gain was constant over a 10 dB range, with 1 dB gain compression occurring at an output power of approximately 2.5 W. The gain was 12 dB for a maximum output power of 6.5 W and a DC to RF conversion efficiency of 25%. Fig. 4 shows the variation of the diode operating point with the output power due to large-signal rectification. As the output power increased, the operating point was shifted towards higher currents and lower voltages, following approximately a 100 ohm load line. The load line could be adjusted by adding a series resistor in the bias insertion line. This self-adjusting bias had the effect that the necessary DC input power increased or decreased with increasing or decreasing RF output power. Therefore the output efficiency varied only slowly with varying output power. The gain as a function of frequency is illustrated in Fig. 5. The 3 dB bandwidth was 40 MHz or 3%. The gain × bandwidth product normalized to the center frequency was 0.5.

Similar results and maximum output efficiencies of 15% were obtained from the same diode at the second subharmonic, 3.2 GHz, of an avalanche resonance pump at 9.6 GHz.

4. Theory

An approximate large-signal theory [3] in an optimization process has produced efficiencies up to 70% at the first subharmonic of the avalanche resonance frequency. The total dynamic I-V curve as well as the fundamental and pump contributions are shown in Fig. 6. Amplitudes and phases are denoted by subscripts T in Fig. 1, which also shows that there is a significant contribution at the third harmonic of the output frequency. The theoretical pump voltage amplitude is 30 V as compared with measured values V_2, V_3, V_8 of 15 V or less for saturated signal amplitudes. The measured pump amplitudes were found to increase up to 35 V with decreasing signal amplitudes. This is part of the complex power conversion mechanisms and indicates decreasing amounts of down-converted power. It also shows that increased pump voltage amplitudes are necessary for efficiency improvement. The theoretical negative resistance at the signal frequency increases as the signal amplitudes decrease, which is essential for the amplifier stability.

5. Conclusion

In this paper it has been shown that stable power amplification with good dynamic range and bandwidth as well as high output efficiencies is possible by operating avalanche diodes in resonance pumped modes, and that higher efficiencies than the 25% reported here can be expected. Single silicon diodes with circular disk geometries on diamond heat sinks should be capable of CW output powers of 80 W at 10 GHz with 50% efficiency [4].

References

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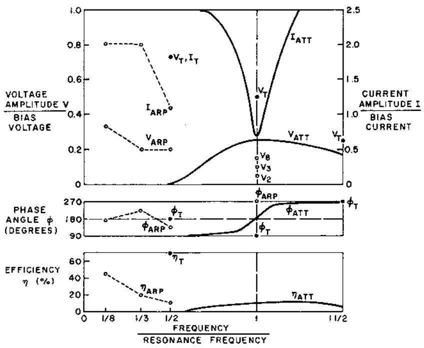

Figure 1. Mode voltages, currents, phase angles and efficiencies as a function of frequency. ATT: avalanche transit-time (experimental). ARP: avalanche resonance pumped (experimental). V_2, V_3, V_8: pump voltage amplitudes for ARP operation at 1st, 2nd and 7th subharmonic (experimental). T: avalanche resonance pumped (theoretical).

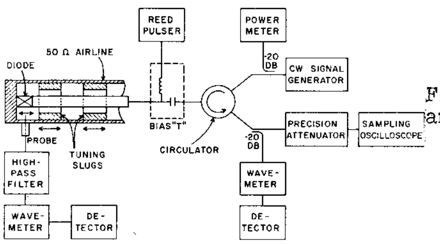

Figure 2. Block diagram of amplifier circuit.

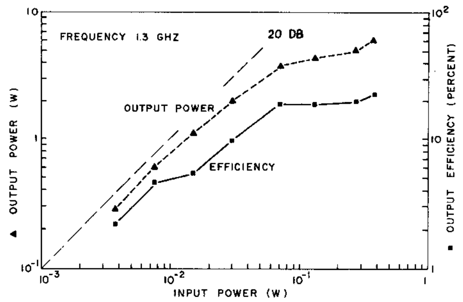

Figure 3. Output power and DC to RF conversion efficiency as a function of input power at 1.3 GHz.

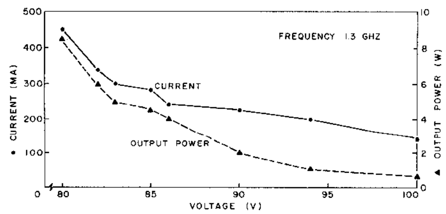

Figure 4. Plot of bias current and amplifier output power at 1.3 GHz versus bias voltage.

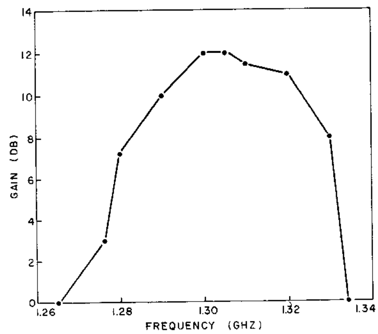

Figure 5. Gain as a function of frequency for maximum output power.

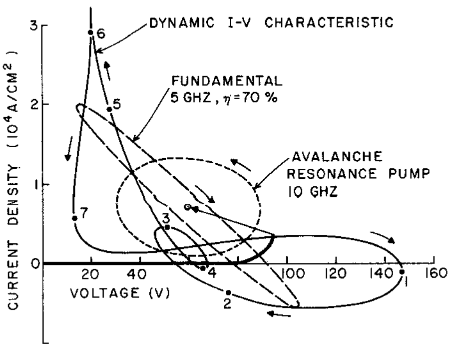

Figure 6. Optimum computed dynamic current-voltage characteristic for saturated avalanche resonance pumped mode.