BANDPASS MICROWAVE ELECTRON-BOMBARDED SEMICONDUCTOR AMPLIFIERS[1]

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Abstract

This paper introduces a new type of microwave amplifier which employs as its active element electron-bombarded semiconductor diodes. This amplifier is capable of achieving both high peak and high average powers. Useful characteristics include its broad bandwidth (several GHz are possible), high efficiency (in the 50 to 60 percent range), and very low harmonic distortion. These characteristics make this amplifier extremely attractive for use in a variety of communications, radar, and laboratory test applications.

General Background

The basic elements of Class A and Class B EBS amplifiers have been developed by Roberts, et al[2], and are schematically illustrated in Fig. 1. A meander line structure is used to deflection modulate a beam of high energy, e.g., 10 to 20 keV, electrons, so that they impinge on the semiconductor diode target. The hole-electron pairs created by the high energy electrons in the target diode cause a current to flow through the reverse biased diode and an external load.

For each electron entering the target a current multiplication takes place, about 1400:1 at 10 keV and 4100:1 at 20 keV. The current flow in the targets is thus proportional to the electron beam current illuminating the target.

The Class A device shown in Fig. 1(a) is a simple series connection of a dc voltage source, an EBS diode and a resistive load. The maximum theoretical efficiency of this device is low (25% max.) partly because the dc current and harmonics of the fundamental flow through the load. The Class B device shown here in Fig. 1(b) has the advantage that dc and harmonic components do not flow through the load, making possible a maximum theoretical sine-wave efficiency of 78.5%. The sine-wave efficiency of the single diode device can be made to equal Class-B efficiency by filtering out the dc and harmonic components so that they do not pass through the resistive load, and changing the beam position so that it does not illuminate the diode when there is no signal.

Narrow-Band Microwave Amplifier

A narrow-band microwave amplifier operating at 1.277 GHz was constructed to demonstrate the high peak power capability of the diode amplifier at microwave frequencies. A single-diode configuration was used in this device which employs a one-quarter wavelength long coaxial resonator to tune the diode capacitance. An approximate equivalent circuit of the output of this amplifier is illustrated in Fig. 2. An adjustable coupling capacitor C_c was used to match the resonator circuit to the 50 ohm load.

Other important design parameters of this amplifier were:

- Diode area: 1 mm x 2.5 mm
- Diode depletion layer thickness: 17 μm
- Diode capacitance, C_d, when fully reverse biased: 30 pF
- Resonator unloaded Q including coax vacuum window losses: 150

The performance of the amplifier was measured under varying conditions of beam current and beam voltage. The saturated output power was measured by varying the coupling capacitance, C_c, and the input signal level. The results of these measurements are shown in Fig. 3. A maximum of 90 watts was achieved at a beam current of 6 mA and a beam voltage of 14.5 keV.

Maximum power was obtained with the coupling capacitor C_c adjusted for critical coupling, i.e., 50 ohms output impedance, at 1.277 GHz. This was confirmed by means of an impedance measurement at the tube output. This result indicates that the tube was operating at a power level below voltage-swing saturation.

Substantially higher peak powers could be obtained by using higher beam currents and voltages. (Recently 270 W peak power at 1.5 GHz was achieved at Watkins-Johnson on a device, employing two diodes and a radial line resonator inside the vacuum envelope. The resonator unloaded Q was about 800). As an example consider the following case:

- V_{beam} = 15.8 kV
- $I_{beam\ max.}$ = Max. beam current density x diode area = 3 mA/mm^2 x 2.5 mm^2 = 7.5 mA
- V_{bias} = 100 volts
- Current gain = N = 3000

Assuming that the peak output voltage swing can be equal to the bias voltage, the maximum fundamental power P_{max} deliverable to a pure resistance is then,

$$P_{max} = 1/2\, I_{peak} \times V_{peak}$$
$$= 1/2\, I_{beam} \times N \times V_{bias} = 1,125\ \text{W}$$

As a CW amplifier the maximum output of the device depends mainly on the amount of power that the diode can dissipate. For current EBS technology this is about 30 W/mm^2 or about 75 W for this diode which has a 2.5 mm^2 area. Assuming 50% target efficiency we would get about 75 watts CW output power.

Wideband EBS Amplifier

The problem of obtaining power from a capacitive source, over a wide frequency range, has been discussed by Bode[3] and others, and power-bandwidth limitations on this type of amplifier circuit are well known. Analysis based on Bode's theory leads to the conclusion that several GHz of useful bandwidth are possible using diodes working into practical impedance levels. The results of this analysis are illustrated in Fig. 4 in which the impedance level R_{opt} of an ideal coupling network is plotted as a function of bandwidth for diodes of capacitances C_d = 15, 30, and 60 pF. The power generated by the diode is also shown (assuming a 1 Amp rms current in the diode circuit). Analysis has shown that practical coupling circuits containing 2 to 4 reactive elements can yield power outputs that are within 1 to 2 dB of this optimum value.

A wideband EBS amplifier was designed and constructed. The diode output circuit, illustrated in Fig. 5(a), consisted of a low-pass π network having an image impedance R_π = 10 ohms, followed by a bandpass (1 - 4 GHz) 10 ohm to 50 ohm transformer. The second capacitance, i.e., nearest the transformer, is actually a duplicate of the amplifier diode, but it is not illuminated by the beam.

The transformer was designed using the procedure described by Matthaei, Young and Jones.[4] A 0.015" thick alumina substrate was employed for the two lowest impedance quarter wavelength sections. A 0.040" thick alumina substrate was used for the remaining three sections of the transformer.

Other important design parameters of this amplifier were:

• Diode size:	.36 mm x 1.0 mm
• Diode depletion layer thickness	11 μm
• Diode capacitance, C_d	6.5 pF
• Inductance, L_π	1.5 nH

The cut-off frequency of the π section is 2.5 GHz, determined by the image impedance level R_π, and C_d.

The amplifier consisted of two of the above circuits with the active diodes arranged (see Fig. 1) to intercept the electron beam on alternate half cycles of the input signal. Since the outputs of the two circuits are 180° out of phase they can be added in the Magic-T shown in Fig. 5(b). The fundamental frequency power comes out the difference or "Δ" port of the hybrid. Harmonic power is delivered to the sum or "Σ" port.

Figure 6 shows the essential features of the amplifier output circuit construction in which the four diodes, the inter-diode inductances, L_π, and the two transformers are mounted on a common copper substrate. These components are within the vacuum envelope; the bias assembly and the Magic-T are outside. Fig. 7 shows the performance of the amplifier over the 1 - 2.6 GHz range.

The input signal for this EBS amplifier was applied to a meander line beam deflection structure which has uniform frequency response from DC to 3 GHz.

This development reinforces the initial promise of the feasibility of a broadband EBS microwave amplifier. A bandwidth of about 3.3 GHz is predicted by the resistance-bandwidth equation in Fig. 4. We have achieved over half that optimum bandwidth in the π network. The bandwidth of the transformer can easily be made wider on the low end of the band. Also, the image-designed π network is not the only possibility; higher output power is possible using "insertion-loss" designed output networks. Higher beam current densities are also possible.

Recent calculations indicate that 30 - 40 watts CW can be obtained at microwave frequencies from a pair of diodes operated in a Class-B arrangement. Experiments are under way at Watkins-Johnson to build such a device; also under way is an improved version of the hybrid-combined Class-A diode pair described above.

Summary

Microwave amplifiers using EBS diodes promise to be an important extension of the microwave power generation and amplification art. Narrow-band, 1 to 10 percent bandwidth, amplifiers capable of peak pulse powers as high as 2 kW appear to be feasible and achievable in the very near future. Wide bandwidth amplifiers capable of CW output powers of over 10 watts and 3 GHz bandwidths appear to be feasible based on the results we have already achieved in the laboratory.

Acknowledgments

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References

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2 L. A. Roberts, D. J. Bates, A. Silzars, and J. Long, "Design and Performance of Deflected-Beam Electron-Bombarded Semiconductor Amplifiers" IEEE Trans. E-D Vol. ED-20, No. 4, April 1973.

3 H. W. Bode, "Network Analysis and Feedback Amplifier Design", pp 360-371, D. Van Nostrand Co., New York, 1945.

4 G. L. Matthaei, L. Young and E. M. T. Jones, "Microwave Filters, Impedance Matching Networks and Coupling Structures", Chap. 6, Sections 6.01, 6.02, 6.06, McGraw-Hill Book Co., New York, 1964.

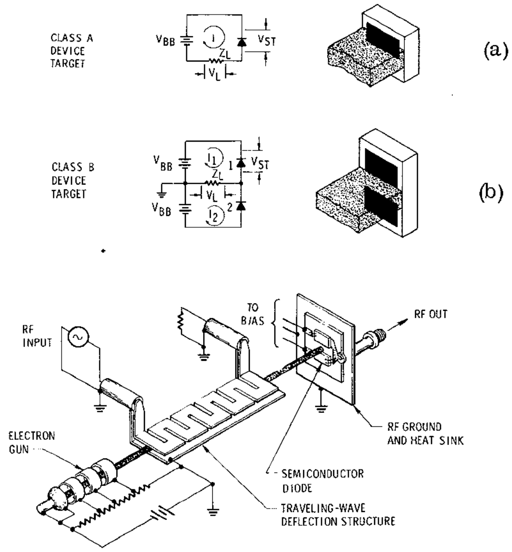

Fig. 1 - Deflected beam EBS using a distributed deflection structure and a semiconductor target in either a class A or class B configuration.

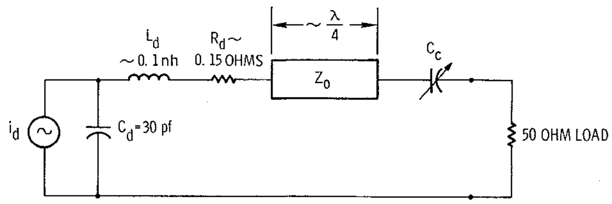

Fig. 2- Equivalent output circuit of narrow-band EBS amplifier using a one-quarter wavelength long TEM resonator.

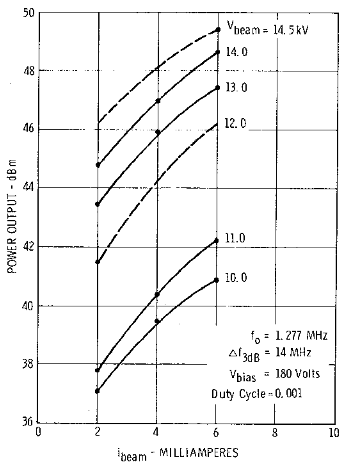

Fig. 3 - Performance of narrow-band amplifier at 1.277 GHz as beam voltage and beam current are varied.

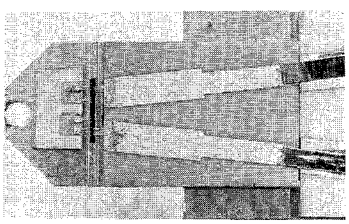

Fig. 6 - Photograph of portion of broadband amplifier circuit showing diodes and first two sections of transformer.

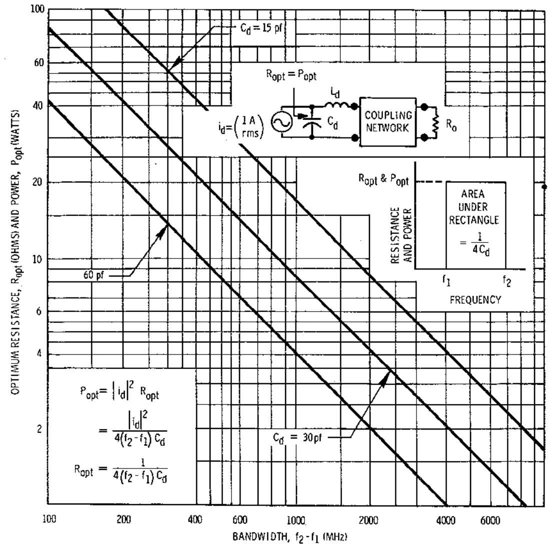

Fig. 4 - EBS optimum output resistance and power vs. operating bandwidth.

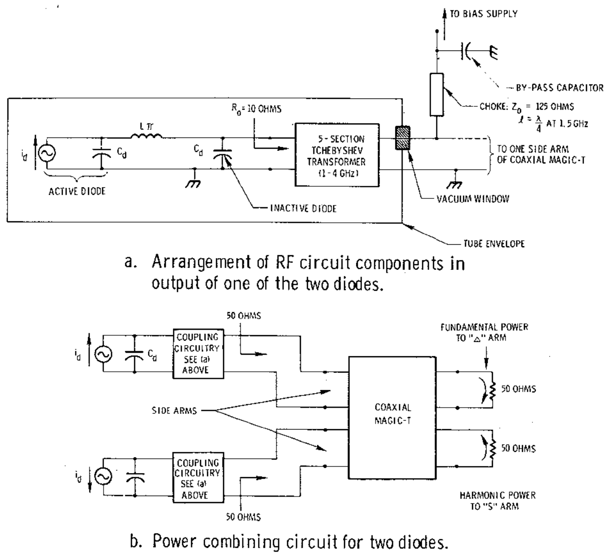

Fig. 5 - Broadband amplifier, 1 - 2.6 GHz.

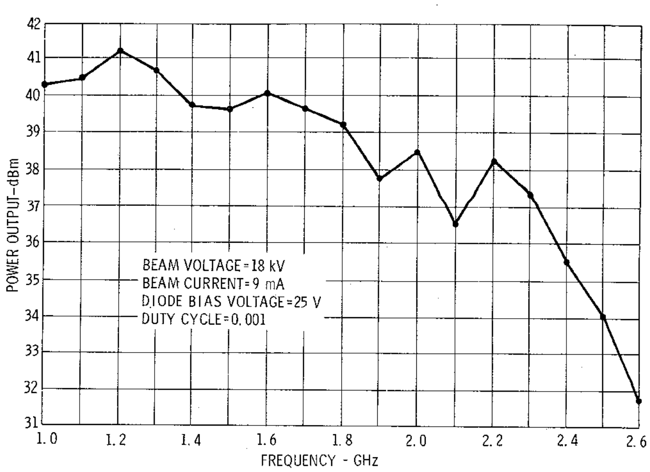

Fig. 7 - Performance of broadband EBS amplifier.