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A CLASS OF DEFLECTION-MODULATED, HIGH-POWER MICROWAVE AMPLIFIERS*

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ABSTRACT

An unusual deflection-modulated, fast-wave electron device is analyzed. It has several unique properties; the electron beam is unbunched and is perpendicular to the direction of power flow in the circuit, and the circuit could be a simple fundamental-mode rectangular waveguide. The amplifier consists of an electron gun, a deflection cavity, an optional beam-bending system, and an output interaction region. An idealized theory showing that 100% electronic efficiency may be achieved, and several large-signal calculations with over 90% electronic and circuit efficiencies, are presented. The power, gain, and frequency limits to this type of amplifier or frequency multiplier are discussed. The beam power must be greater than 100 kW for efficient operation because the output circuit losses and deflection power depend on beam voltage, not on beam power. The devices operate best at frequencies below a few gigahertz because of limitations on the ratio of beam size to circuit size. The power gains vary between 10 and 25 dB.

INTRODUCTION

The deflection-modulated rf amplifier discussed in this paper, Fig. 1, is comprised of an electron gun, a deflection cavity, a beam-bender system, the output interaction region, and a collector. The gun produces a solid beam, and the deflection cavity supports two TM_{120} modes which are excited in phase quadrature to produce a rotating magnetic field at the center of the cavity. This magnetic field causes the beam to travel in an expanding helical path with a conical envelope. A bending-magnet system is located within the cone and is designed to deflect the beam perpendicular to the axis. The beam now will be rotating at the drive frequency of the deflection cavity, but the particle motion is radial. The radial motion carries the beam into an output region, which is a resonant ring of waveguide. The phase velocity of the waveguide field is greater than the speed of light, but the deflection velocity of the electrons is also a phase velocity, and these two velocities can be made equal by a suitable choice of geometry. The electrons can give up most of their kinetic energy to the waveguide field, which is the TE_{01} mode. The electrons may be almost stopped by these fields, and the beam is not bunched in the usual sense. Thus, the dc-to-rf conversion efficiency may be quite high.

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Fig. 1. The deflection-modulated amplifier.

The basic device (without the bending system) was invented in 1941 by McRae, who was granted a patent in 1946 (1). McRae also originated the idea of making the output resonator n wavelengths long and driving the cavity at the n^{th} subharmonic of the output frequency. This idea was pursued by several other workers, and Kaufman and Oltman (2) built a low-power, four-times-frequency multiplier at 34 GHz in 1965. They obtained a few watts of output power with 3 kW of beam power. This paper contains a good small-signal analysis of the device, and several references to unpublished work on similar devices in the 1950s. This device and many other deflection-modulated amplifiers were theoretically investigated in 1958 by Wilson (3), but no devices were built. In 1975 Budker added the bending system to the device (4) and he recently reported (5) a 5-MW cw design called a gyrocon, which is to operate at 181 MHz. Budker's gyrocon has not achieved its design parameters of 5 MW with a dc beam voltage of 500 kV, but the Russian workers have produced 1 MW at an overall efficiency of 80% and a 200-kV beam voltage (6). A pulsed gyrocon operating at 430 MHz was also built at Novosibirsk, and 40 MW of peak power has been produced with 1.3 MV on the gun (6). This device was designed to produce 100 MW at a duty factor of 0.001%. This writer has recently written a report (7) which explores the theory of

the gyrocon. This report is reviewed and expanded upon in this paper.

FIRST-ORDER ANALYSIS OF THE OUTPUT INTERACTION

The possibility of a very efficient interaction of the electrons with the rf field may be demonstrated by considering the ideal case in which the output circuit is a resonant section of TE_{01} rectangular waveguide. For simplicity, consider only the electric field, E_y , parallel to the beam direction, and assume that a very small beam enters the guide at $x = a/2$, $y = b$ with velocity, u_0 , in the $-y$ direction (see Fig. 2). Relativity, the effects of space charge, all higher order modes, and any curvature effects in the output guide are neglected. Under these conditions, the one-dimensional force equation may be integrated twice to obtain expressions for the electron velocity and position as functions of time and of the initial location of the waveguide field relative to the electron. The equation of motion is the multipactor equation. The minimum field solution (7) has the properties that the peak rf field is $E_0 = \omega \mu_0 / 2\eta$ and the waveguide height is $b = \pi u_0 / 2\eta$, where ω is the radian frequency. The rf voltage in the guide is $\pi/2$ times the dc beam voltage, and the electrons are stopped in a 180° transit angle across the waveguide. Thus, the electronic efficiency is 100%.

THE DEFLECTION CAVITY

The TM_{120} mode in a rectangular cavity or the TM_{110} mode in a cylindrical cavity may be used to deflect the beam. Consider a rectangular cavity, shown in Fig. 3. There are magnetic fields in the x and z direction and an electric field in the y direction. At resonance, the other field components vanish. The deflection angle is ψ , where

$$\tan \psi = \frac{4\pi\eta E_d}{\gamma_0 a_1 \omega} \sin D/2 \quad (1)$$

Fig. 2. The output interaction region.

here D is the transit angle of the beam through the deflection cavity, a_1 is the length of a cavity size, and E_d is the electric field strength in the cavity. The power dissipated in the cavity walls is

$$P_d = \frac{R_s (E_d a_1^2 \omega b_0)^2}{10\pi^2} (1 + 2d/a_1) \quad (2)$$

where d is the cavity height and R_s is the skin-effect resistance. The deflection power that goes into beam loading should be considerably less than Eq. (2), and it is neglected here. There is an optimum deflection cavity length for any beam voltage, and an approximate formula for the optimum length is found in (7).

THE OVERALL CONVERSION EFFICIENCY

To obtain a more realistic approximation to $\bar{\eta}$, the overall dc-to-rf conversion efficiency, a large-signal, three-dimensional model of the output interaction was formulated. The output waveguide is assumed to be a rectangular waveguide with a single TE_{01} mode propagating. The model is relativistically correct, but higher order modes, the effects of space charge, the slots, and curvature in the waveguide have been neglected. The initial beam parameters and the electric field amplitude and phase are used as input parameters, and the three equations of motion are numerically integrated with time as the independent variable. The entering beam is divided into a central core and several annular rings. The rings are divided azimuthally into at least four parts. All three field components in the waveguide are considered. The equations and assumptions are fully discussed in (7). The electronic efficiency, η_e , is

Fig. 3. The rectangular deflection cavity.

calculated from the change in kinetic energy of the beamlets as they travel through the interaction region.

The rigorous method of obtaining the beam's entrance parameters is to start with an electron gun program, and follow many electrons through the gun region, any magnetic lenses, the deflection cavity, and the bender magnet, including space charge all along the way. The author is using a more approximate method, in which the laminar flow dc beam equations which are discussed in (8) are used to calculate the beam envelope from the electron gun to the output region. The deflection and beam-bender systems are analyzed by the single-particle technique, so the aberrations produced by these systems are neglected. This abbreviated, single-particle method has been used to obtain the initial conditions for the results which are presented below.

The output resonator is a resonant ring; thus, there is a substantial amount of circulating rf power in it, and the rf losses are not negligible. The power dissipated in the output resonator walls is

$$P_L = \frac{nR_s \left(1 + \frac{b\lambda^2}{2a^3}\right) aE_o^2 \lambda}{2n_o^2 \left[1 - \left(\frac{\lambda}{2a}\right)^2\right]^{\frac{1}{2}}}, \quad (3)$$

where a and b are the width and height of the output waveguide, E_o is the peak electric field in the waveguide, and n is the number of guide wavelengths in the resonator.

NUMERICAL RESULTS

The overall efficiency can be calculated from the individual elements described above,

$$\bar{\eta} = \frac{I_o V_o \eta_e - P_L}{I_o V_o + P_d}. \quad (4)$$

This equation simply states that the dc-to-rf conversion efficiency is the ratio of the rf output power to the sum of the input beam power plus the deflection power. The deflection power is not negligible because the amplifier has much lower gain than O-type devices. A series of calculations in which the

TABLE I
BEAM RADIUS IN CENTIMETERS
AT THE OUTPUT WAVEGUIDE

V_o (kV)	$P_o =$ 100 (kW)	300 (kW)	1000 (kW)	3000 (kW)
50	8.09	16.40	35.10	69.20
100	2.97	5.28	11.10	22.50
200	1.76	2.23	3.68	6.90
500	1.52	1.56	1.69	2.04
1000	1.50	1.51	1.52	1.56
2000	1.50	1.50	1.50	1.51

beam is assumed to be 3.0 cm in diameter at the gun was made for a frequency of 450 MHz. The case with no bending system will be discussed here. For a 10-degree deflection angle, the beam path is about 110 cm from the gun to the output cavity. In Table I the results of the beam-spread calculations are shown for several values of beam voltage and current.

The beam size becomes quite large at low beam voltages; thus, the device must operate at low frequencies, so the beam size is small compared to the output waveguide wavelength. The aberrations in the deflection cavity and the bender system will increase the beam size even further, so the device must operate at high dc beam voltages.

The parameters for a square deflection cavity were then calculated. Each side is 74.5-cm long to resonate at 450 MHz. The optimum cavity length and the deflection power for 10-degree deflection are summarized in Table II.

TABLE II
OPTIMUM DEFLECTION CAVITY LENGTH, FIELD
AND POWER VERSUS BEAM VOLTAGE

V_o (kV)	d (cm)	E_d (MV/m)	P_d (kW)
50	13.0	1.71	2.01
100	17.0	1.87	2.58
200	21.0	2.19	3.78
500	27.0	3.11	8.32
1000	27.0	4.67	19.32
2000	30.0	7.76	54.08

The most time-consuming part of the analysis is the calculation of the electronic efficiency in the output region. The beam radius from Table I was used to start the calculation for any particular beam voltage and current. A waveguide width of 40 cm was chosen, and the mean radius of the output waveguide is 19.2 cm. The output waveguide field, E_o , and height, b , were varied, and the phase angle ξ between the peak of the field and the beam center was swept in 5-degree steps. With this procedure, b was optimized to ± 1 cm and E_o to $\pm 5\%$. The optimum values are listed in Table III. Calculations at lower beam voltage were not made because the beam size would be greater than the width of the waveguide. The electrons were found to gain energy rapidly in the z -direction as they were halted in the y -direction. Thus, an optimum energy exchange corresponding to equal amounts of energy in the y - and z -directions exists. Budker *et al.* were aware of this effect (5) and overcame this by injecting the beam at an angle into the output resonator. Even without injection at an angle, electronic efficiencies of greater than 90% appear achievable. The overall efficiencies gradually increase with beam power because the deflection power and waveguide ohmic power depend only upon the beam voltage, and not significantly on beam power. The power gain for the high-efficiency cases is about 20 dB, but it is possible to raise the gain by using a smaller deflection angle and then using a bender-magnet system to obtain the necessary radial motion.

A series of calculations were made for a six-times-frequency multiplier to estimate the performance potential at 2700 MHz. A 30-degree deflection angle, 200-kV beam

TABLE II
TEN DEGREE DEFLECTION ANGLE AMPLIFIER SUMMARY

V_0 (kV)	I_0 (A)	r_0 (cm)	b (cm)	E_0 (MV/m)	ξ (deg)	Electronic Efficiency	P_L (kW)	P_{out} (kW)	Gain (dB)	Overall Efficiency
50	2.00	8.09	5.0	1.20	45	0.9402	15.8	78.18	26.9	0.7664
100	1.00	2.97	7.0	1.65	55	0.9556	31.7	63.84	13.9	0.6223
200	0.50	1.76	11.0	2.30	75	0.9349	68.5	24.99	8.2	0.2408
500	0.20	1.52	16.0	4.00	85	0.8771	233.2	-	-	-
1000	0.10	1.50	14.0	7.00	55	0.8134	682.3	-	-	-
2000	0.05	1.50	10.0	16.00	35	0.7435	3231.9	-	-	-
50	6.00	16.40	4.0	1.50	25	0.7958	24.0	214.70	31.3	0.7110
100	3.00	5.28	6.0	1.85	45	0.9459	38.0	245.00	19.8	0.8097
200	1.50	2.23	9.0	2.50	55	0.9348	76.9	203.60	17.3	0.6702
500	0.60	1.56	16.0	4.00	85	0.8764	233.2	8.91	10.3	0.0286
1000	0.30	1.51	16.0	6.60	70	0.8146	634.8	-	-	-
2000	0.15	1.50	16.0	12.00	70	0.7496	2098.7	-	-	-
100	10.00	11.10	7.0	1.75	45	0.8899	35.7	854.2	25.2	0.8520
200	5.00	3.68	8.0	2.70	45	0.9307	87.3	843.4	23.5	0.8402
500	2.00	1.69	14.0	4.10	70	0.8769	234.1	642.8	18.9	0.6375
1000	1.00	1.52	15.0	6.80	65	0.8148	658.9	155.9	9.1	0.1529
2000	0.50	1.50	16.0	12.00	70	0.7496	2098.7	-	-	-

voltage, and 5-A current were used. The waveguide width is 6.67 cm. A waveguide height of 2.4 cm was found to yield an optimum overall efficiency of 29.1% with a field of 6 MV/m in the output waveguide. The initial beam radius was 1.84 cm. With a smaller beam and operation as an amplifier, the device would be more efficient, but it is doubtful if this type of amplifier could compete with a well-designed klystron at frequencies above 3 GHz.

SUMMARY AND CONCLUSIONS

A class of deflection-modulated, high-power amplifiers has been analyzed in this paper. The large-signal calculations indicate that overall efficiencies approaching 90% with power gains of 10 to 30 dB are achievable in the 450-MHz region. Several design parameters, such as the electron gun and waveguide width, were not varied to achieve the above results, which makes the results even more remarkable. The devices appear to operate best at frequencies below a few gigahertz.

The author has done extensive work on the optimization of klystron and traveling-wave amplifier efficiency. On very rare occasions, if all parameters are carefully optimized, one can calculate an electronic efficiency of over 70% for a klystron. However, for the devices considered here, it is rather easy to find combinations of parameters which predict over 80% overall efficiency. Thus, the author believes that these devices will find many applications where high-power, low-frequency microwave amplifiers with very high efficiency are required. Since the output circuit is a resonant ring, the bandwidth will be narrow, but adequate for accelerator applications.

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