Production and Operation of a High-Efficiency DBS-Band Klystron Utilizing a Multistage Depressed Collector

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***Abstract* — The satellite communications market has previously been served by klystrons with grounded collector. Now, CPI has developed a new generation of air-cooled, permanent-magnet (PM) focused, high-efficiency klystrons utilizing a multistage depressed collector (MSDC). We describe the development and production of the VKU-8891M series, pioneering MSDC technology in the direct broadcasting satellite (DBS) market. With a saturated efficiency of 40 percent this klystron far surpasses the performance of a conventional klystron. As a result, this technology saves more than 50 percent of the power required by existing products in this market in average field-operating conditions.**

I. Introduction

MSDC technology for klystrons was first utilized in amplifiers for the UHF-TV broadcast market.[1] This development effort began in 1984 and resulted in the successful introduction of the VKP-7990. For medium-power klystrons used in satellite communications, there was no alternative to the standard grounded-collector klystron until CPI introduced several new lines of high-efficiency klystrons utilizing MSDC technology in various frequency bands.[2] While the first of these new products, the DBS-MSDC klystron, was still in its prototype phase, the scalability of this concept was demonstrated with the development of the VKS-7964M starting in July 1999. This compact, air-cooled, PM-focused S-band klystron amplifier provides 3 kW CW linear rf power and 10 kW peak power at 2.339 GHz. Utilizing MSDC technology yielded a saturated efficiency of typically 47 percent. Due to its excellent performance, it was the microwave power source of choice for the terrestrial transmitters of a major key player in the satellite digital audio radio market. CPI also covers the C- and Ku-band market with MSDC-equipped medium-power klystrons produced by CPI's Canadian division.

Among the obvious advantages of the more energy-efficient MSDC klystrons are the reduced operating costs. In new installation sites, the lower power requirement results in significantly reduced system costs. Furthermore, the lower power dissipation in the collector reduces waste-heat and air-flow requirements, whereas a reduced collector temperature increases the life span of the vacuum electron device (VED).

This paper describes the development, production, and performance of CPI's first air-cooled, PM-focused MSDC klystron, introduced to the DBS market as the VKU-8891M series.

II. Development and Production

A. MSDC Technology

In a linear-beam VED, the electron gun generates an electron beam accelerated by the beam voltage V_0. After interaction with the rf circuit of the device, the kinetic energy of the electrons is dissipated in the collector. In the case of a standard grounded collector, the klystron requires a supply power

$$P_S = V_0 I_0, \quad (1)$$

where I_0 is the beam current. The klystron efficiency is the fraction of the supply power converted to rf output power. Supply power and beam power of a klystron with a grounded collector are the same; that is, klystron efficiency and interaction efficiency are identical.

If no rf input power is applied to the klystron, all electrons leave the rf circuit with a kinetic energy $-eV_0$. This situation is shown in Fig. 1, curve I. Each point $I/I_0(E_{kin}/-eV_0)$ of a curve in the diagram corresponds to the fraction of electrons with a kinetic energy $\geq E_{kin}$. Depending on the rf drive level (curves I to IV), electrons are accelerated or decelerated by the rf electric field, resulting in different kinetic-energy distributions.

A MSDC consists of several collector stages with different electrical potentials designed for energy-selective collection of the spent-beam electrons. Ideally the electrons are decelerated to almost 0 eV by the retarding potential of the appropriate collector stage before being absorbed by the metal. Due to the continuous energy spectrum of the electrons and the finite number of collector stages, most of the electrons reach the collector surface with a finite kinetic energy. The resulting supply power of a MSDC klystron is

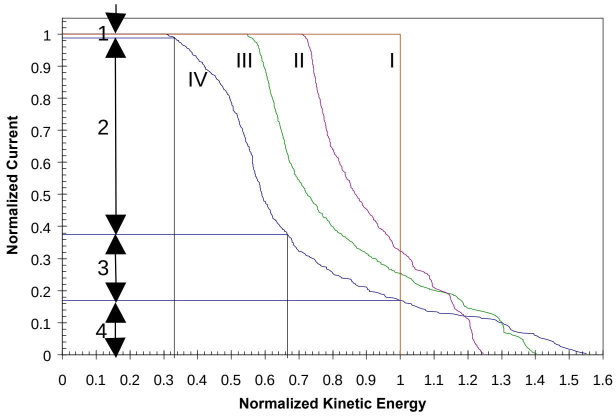

Fig. 1. Spent-beam analysis without rf drive (I) and at output power levels 475 W (II), 1258 W (III) and 2424 W (IV).

$$P_S = V_0\, I_{By} + \Sigma_i\, V_{Ci}\, I_{Ci} \qquad (2)$$

where I_{Ci} and V_{Ci} are current and voltage with respect to cathode, respectively, of the i^{th} collector stage. I_{By} is the body current (the current due to interception by the rf circuit).

The horizontal lines in Fig. 1 indicate the relative current values for each stage of a four-stage MSDC with equal voltage splits at 2424 W of rf output. The difference between the lines corresponds to the ideal fraction of current collected by each stage (numbers 1 to 4). Electric and magnetic field profile as well as secondary and back-scatter electrons change the actual current splits to some extent.

B. The VKU-8891M Series

Based on the existing product, the DBS-MSDC klystron was designed to be air-cooled and PM-focused. The development of such a medium-power klystron presented a financial challenge (funding the development costs) and some technical hurdles relating to high voltage, secondary and back-scatter electron emission, and the performance of the VED.

At CPI, an internally funded development effort began in August 1998 and resulted in the first successful test of the prototype in May 1999. A design study on klystrons with several collector stages showed that a four-stage depressed collector could easily meet one of the internal design goals, a supply power not higher than 7 kW at rated power. In the case of a four-stage MSDC klystron with equal voltage splits, equation (2) results in a supply power

$$P_S = |V_0|\,(I_{C1} + |I_{By}|) + 2/3\,|V_0|\,I_{C2} + 1/3\,|V_0|\,I_{C3}. \qquad (3)$$

The use of equal voltage splits allows the integrator a more simplified design of the power supply.

Fig. 2. Photograph of a VKU-8891M1 klystron.

Some general properties of the VKU-8891M series klystron are listed in Table I. With its integrated plenum, the VED exhibits a very compact construction (Fig. 2). The klystron is available with a standard 12-channel preset tuner (channel-changing time = 15 seconds) or with a Digital Fast Tuning System (DFTS) for up to 50 channels, allowing channel changes within one second.

TABLE I
GENERAL DESIGN PROPERTIES OF THE VKU-8891M SERIES

Collector Stages	4
Focusing	PM
Cooling Method	Air
Weight	105 lbs (48 kg)

The regular production of the VKU-8891M series started in spring of 2000. As of December 2001, a quantity of 110 klystrons has been produced and shipped. After more than one year of field experience, this VED proves to be a reliable product with unparalleled performance in its market segment.

III. KLYSTRON PERFORMANCE

The VKU-8891M series klystron is providing a minimum rf output power of 2.4 kW over an instantaneous –1 dB bandwidth of 50 MHz. Here, the center frequencies range from 17.3 GHz to 18.1 GHz. At reduced rf output power, higher bandwidth or higher frequency options are available. The most important operating parameters are summarized in Table II.

The diagram in Fig. 3 shows a comparison between theoretically expected and actual current splits vs. rf output power, measured on three klystrons. Due to reasons

TABLE II
TYPICAL OPERATING PARAMETERS OF THE VKU-8891M SERIES

Parameter	Value	Units
Output Power	2.4	kW
Saturated Gain	50	dB
Beam Voltage	9.5	kV
Beam Current	1.05	A
Perveance	1.13	$\mu A/V^{3/2}$
Supply Power at Saturation	6.0	kW
Saturated Efficiency	40	%
Collector Stage 1, 2, 3, 4 Voltages	0, 1/3, 2/3, 1/1	Beam Voltage
Center Frequency Range	17.3 – 18.4	GHz
-1 dB Bandwidth	50 – 85	MHz
Collector Coolant Flow Rate	800 (360)	lbs/hr (kg/hr)
Collector Pressure Drop	1.5 (0.37)	in/H_2O (kPa)

mentioned in Section II.A, the actual currents on collector stages 1 and 3 are somewhat higher than expected and lower on collector stages 2 and 4. From this data, the supply power can be calculated using equation (3). The supply power vs. rf output power of S/N 100 is shown in Fig. 4.

Generally, the supply power of a klystron can be expressed by

$$P_S = P_{rf} + P_{coll} + P_{By}, \quad (4)$$

where P_{rf} is the rf output power, P_{coll} is the collector dissipation, and P_{By} is the body dissipation. While the supply power for a klystron with a grounded collector is constant and equals the beam power as given in equation

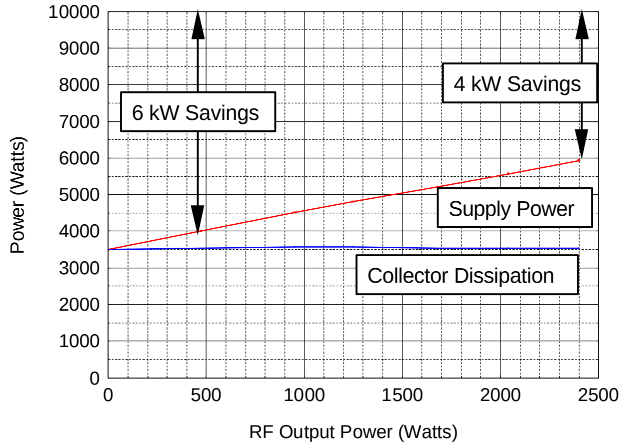

Fig. 4. Required supply power and dissipated power vs. rf output power measured for serial number 100 at a frequency of 17.5 GHz. The arrows indicate the energy savings in comparison to a grounded collector.

(1), the supply power of the DBS-MSDC klystron increases nearly linearly with rf output power. The resulting klystron efficiency vs. rf output power in comparison to the interaction efficiency measured on three klystrons is shown in Fig. 5. As mentioned before, in a klystron with a grounded collector, the interaction efficiency equals the klystron efficiency. The interaction efficiency reaches approximately 24 percent at saturation while typical values for the saturated klystron efficiency of the DBS-MSDC klystron are around 40 percent. On some channels, efficiencies as high as 44 percent have been measured.

With respect to a grounded-collector klystron, the power savings associated with MSDC technology are given by the difference between beam power and supply power. As

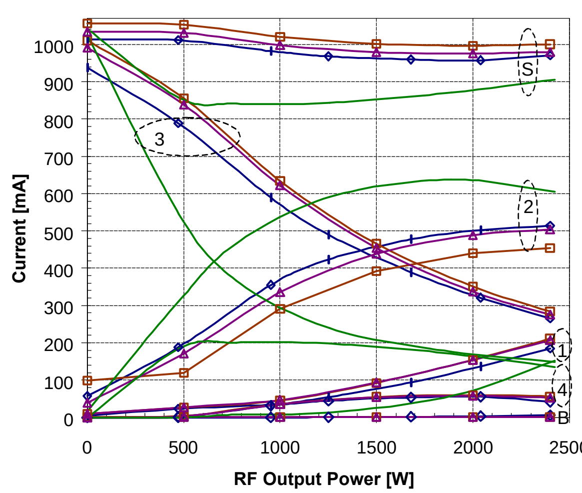

Fig. 3. Power supply current (S), collector current splits (1, 2, 3, 4) and body current (B) of the VKU-8891 vs. rf output power. The diagram shows measured data of serial numbers 100 (◊), 102 (□), 103 (∆) and theoretical values (¾).

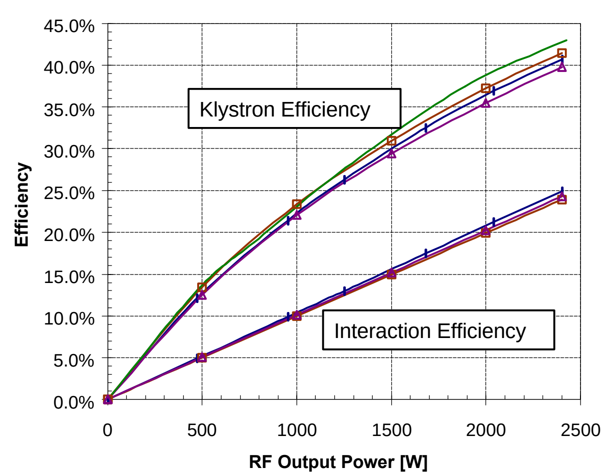

Fig. 5. Measured interaction and klystron efficiency vs. rf output power for serial numbers 100 (◊), 102 (□) and 103 (∆). The theoretically expected klystron efficiency (¾) is shown as well.

shown in Fig. 4, the MSDC saves 4 kW during saturated klystron operation. When operating in the field, the high rf output power is only required in bad weather conditions. Most of the time, these VEDs are operating below 500 W rf output, where the supply power is even further reduced. Fig. 4 illustrates savings of 6 kW when operating the klystron at approximately 450 W rf output power.

IV. Conclusion

CPI successfully utilized the MSDC technology in the development of the VKU-8891M series klystron for the DBS market. The PM-focused, air-cooled VED meets or surpasses all design targets. The use of the MSDC provides considerable economy and performance advantages for the end user. The already available field experience and the ongoing production of significant quantities demonstrates the feasibility and reliability of this klystron. The application of the MSDC technology, not only to the DBS-product family, proves its potential for further markets and a future extension to even higher efficiency klystrons.

Acknowledgement

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References

[1] E. W. McCune, "MSDC Klystron Field Experience – 5-Year report," *NAB Engineering Conference*, Las Vegas, NV, April 1995.

[2] E. L. Wright, R. Batra, R. Begum, E. W. McCune, A. Shabazian and L. Zitelli, "Multistage Depressed Collector Klystron Development and Production," *2nd IEEE International Vacuum Electronics Converence, Abstract Book*, Noordwijk, Netherlands, April 2001.