

## Active Coaxial and Active Inverted Coaxial Magnetron Electronic Guns

### J. O. Meilus

*The School of Electronics and Electrical Engineering of Birmingham University  
Great Britain, Edgbaston, Birmingham B152TT, phone: (+370) 68745702, e-mail: j.meilus@takas.lt*

### Z. Petrauskas

*Department of Physics, Kaunas University of Technology  
Studentų str. 50, LT-3031 Kaunas, Lithuania, phone: (+370) 65417018, e-mail: zilva234@one.lt*

### M. J. A. Smith

*Department of Physics, University of Warwick  
Coventry CV4 7AL, Great Britain, phone: 01203 523353, e-mail: phsaz@csv.warwick.ac.uk*

### Introduction

The essential imperfections of the most effective high power microwave electron devices – magnetron oscillators, amplifiers and frequency transformers – are insufficient stability of frequency and duration of operation. Problems of a decrease of the output signal power as well as overall dimensions of the devices at the shortening of working wavelength are also very important. These problems can be partly solved by the use of principles of the coaxial magnetron [1]. The essence of the principles is introduction of the complementary stabilizing high own quality cylindrical resonator covering coaxially the multicavity magnetron slow-wave system (SWS) in which  $\pi$ -mode oscillations take place. This resonator keeps electrical relation with every second individual cavity of the SWS and results in excitation stable oscillations of  $H_{01q}$ -mode in it. Frequency of oscillations is determined by the resonant frequency of the resonator. These circumstances ensure not only sufficiently high extent of separation of adjacent modes of oscillation and stability of the frequency to be generated or amplified but also allow to increase the number of individual cavities in the multicavity magnetron SWS. This causes more efficient use of interaction space (ratio of the surfaces occupied by the high frequency field (HFF) and anode segments) and guarantees enlargement of the emitting surface of a cathode. The increase in the cathode surface ensures facilitation of the working regime of the cathode and makes longer duration of operation of the device. Enlarged emission ability of the cathode and more effective usage of the interaction space guarantees essential rise in a output signal power, gain and efficiency.

At the application of the principles of coaxial magnetron for frequency transformation of microwaves, the magnitudes of coefficients of frequency multiplication and division (numbers of working harmonic or subharmonic) are determined by the ratio of cavity numbers of SWS's in an output and input cascades of frequency transformer. Therefore the increase in a number of individual cavities on the output cascade, at constant

number of cavities in the input one, gets growth of coefficients of frequency multiplication and division.

Much more stronger effect at amplification and frequency transformation with respect to duration of operation, frequency stabilization and level of output signal power could be obtained by the use of principles of the inverted coaxial magnetron [2]. In this magnetron positions of multicavity oscillation system and cathode are exchanged. Cathode here is a cylinder with inner emitting surface, covering, bent into a ring, multicavity SWS. The internal part of this ring makes up the stabilizing cylindrical resonator. This resonator as well as one in the coaxial magnetron is connected electrically with every second individual cavity of multicavity oscillation system. In this case, oscillation frequency of the system in whole is also determined by the resonant frequency of the stabilizing resonator, in which azimuthally symmetrical oscillations  $H_{01q}$  appear. Own frequency of the resonator may be changed by the noncontacting shortening plunger introduced into one of the two open faces of the resonator. Such a construction allows to increase a number of cavities of the SWS as well as emitting surface of the cathode by an order in comparison with to such parameters of ordinary magnetron. This also guarantees the increase in duration of operation for several times. It is quite clear that these factors ensure noticeable growth of the output signal power as well as other main output parameters of the device.

### Active coaxial magnetron electronic gun

One of the most important elements of the high power magnetron amplifiers, frequency multipliers and dividers is active magnetron gun [3]. The main difference between ordinary, for example Kino and Taylor magnetron gun [4] and the active magnetron gun is that this gun in crossed electric and magnetic fields not only forms an electron stream of desired configuration and ensures optimal conditions of injection of the stream into interaction space of the device but also guarantees highly effective bunching of the electron stream by the input signal as well as amplification of the signal.

In an active magnetron gun the role of the controlling electrode plays the SWS with, in common with cylindrical or conoidal cathode, gives to electrons transversal and longitudinal velocities. The aim of the gun is to generate the electron bunches (electron spokes) of optimal shape and inject them into interaction space of magnetron amplifier or frequency transformer. Active magnetron gun can be treated as an amplifier of the input signal because electron stream bunched by the input signal induces in it SWS strong enough HFF. This amplified signal may be used to form complementary channel of communication and led out through extra energy outlet or through the energy inlet with the aid of circulator. A very simplified scheme of the active magnetron gun of cylindrical construction, used in magnetron amplifiers and frequency transformers, is shown in a Fig. 1. Electron stream 2 emitted by cathode 1 moves, under influence of permanent electric  $E_0$  and magnetic  $B$  fields, synchronically with the HFF of SWS 3 and interacts with it. The result of this interaction is perfectly grouped electron clusters (spokes) which being injected into next cascade of a device can promote amplification of the input signal (amplifiers of M-type) or change a frequency of the input signal at a simultaneous amplification of the signal on a frequency of working harmonic or subharmonic (frequency transformers of M-type). Over coaxial or waveguide energy inlet 4 input signal is led into SWS of active magnetron gun. The amplified one is led out through outlet 5 and given to external load.

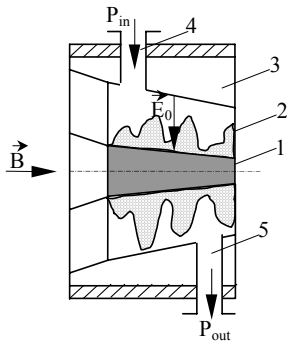


Fig. 1. Active magnetron electronic gun

The active coaxial magnetron gun (Fig. 2) should have been of a very different construction in comparison with one discussed above. Here cylindrical or cone-shaped cathode 1 must be situated in the symmetry axis of the bent into a ring multicavity SWS 2. Its segments make up an angle of about  $1^\circ$  with the symmetry axis of the gun. Due to given configuration of the interaction space and specific structure of the permanent electric and magnetic fields electron stream 3 in the gun moves along symmetry axis and in perpendicular direction.

Coaxial resonator 4 covers multicavity SWS and over the system of longitudinal slots cut out in an outer wall of every second individual cavity is symmetrically bound with it. In this resonator, closed from both sides, symmetrical oscillations of  $H_{01q}$ -mode must be excited. Index  $q$  points out the number of half wavelength's that fit along its symmetry axis. Usually oscillations of  $H_{011}$ -

mode are used. Their structure is represented in Fig.2. In this case along the resonator goes in one half of wavelength. The lines of HF electric field (continuous curves) are circle-shaped and concentrated in a central part of resonator. Magnetic lines (dotted curves) are ellipses-shaped and situated in radial planes.

The resonant frequency of the resonator may be changed by the cut off plunger 5 which is introduced through its face. Waveguide energy inlet 7 is connected with coaxial resonator over the slit 6 cut out in a wall of resonator. Oscillations of  $H_{011}$ -mode of the resonator induce in a rectangular waveguide  $H_{10}$ -wave.

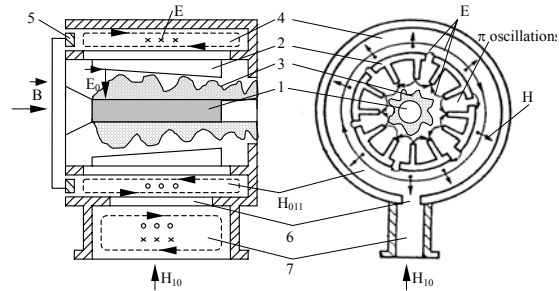


Fig. 2. Active coaxial magnetron electronic gun

Due to mentioned above peculiarity of electromagnetic relation between coaxial resonator and individual cavities of the SWS, in multicavity system of anode block  $\pi$ - or 0-type oscillations may be excited.

These types are separated one from another good enough. Therefore it is quite easy to exclude desired  $\pi$ -type by the mobile plunger. Such a way of separation of oscillations modes is analogous to the use of straps in an ordinary magnetron. The change in plunger position let obtain 10% relative frequency band within the scope of the same type of oscillations.

In the case of  $H_{01q}$  oscillations along the surface of the coaxial resonator flow only circle HF currents. This causes small enough losses in the resonator. The increase in a working frequency at constant dimensions of the resonator decreases these losses. Thus coaxial resonator exhibits a high own quality even in the case when plunger has far bad contact with the walls of resonator.

High own quality of the coaxial resonator improves quality of oscillation system of the coaxial magnetron gun in whole and should cause high stability of oscillations at variations of an external load or a regime of power supply. Because own quality of the coaxial resonator exceeds value of this parameter in standart magnetrons about ten times it is possible to decrease outer quality of the resonator without reduction of the efficiency of oscillation system as a whole. This guaranties the 3-5 times lessening in a frequency pull extent. The electronic frequency shift should have been decreased by an order because about 90% of HFF energy is accumulated in the stabilizing coaxial resonator.

The working frequency of the coaxial magnetron gun is determined in essence by the resonant frequency of the coaxial resonator and reactive electronic conductivity of

the interaction space of the gun does not have a large influence on it.

Stabilizing resonator which guaranties fairly good separation of the oscillations types at the same time allows to increase 6-8 times the number of individual cavities in an anode block. This causes enlargement of the surfaces of the anode and cathode. The energetic coefficient  $f_0 P_{out}$  in comparison with standart magnetrons rises 2-3 times. Here  $f_0$  – working frequency;  $P_{out}$  – output signal power.

The rise in a number of individual cavities and a higher extent of homogeneity of HFF results in a growth of electronic efficiency of the gun. By the choise of a bigger ratio of the own and outer qualities it is possible to obtain higher efficiency of the oscillation system. Therefore the product of two these efficiencies – the total efficiency of the active coaxial magnetron gun – should also exceed the values of the total efficiency of standart magnetron.

In order to evaluate the increase in gain and electronic efficiency of the gun, when it operates in a regime of external signal amplification, upon potential energy electron stream possesses, it is useful to analyze the case when electron stream enters the interaction space of the gun at different levels with respect to the surface of a negative electrode.

If  $d$  is a distance between SWS and negative electrode (the height of interaction space) in a planar gun under investigation and  $y$  is a variable distance between thin electron stream and surface of the negative electrode, the amplitude of HF electric field in a direction perpendicular to the surfaces of negative electrode and SWS have to change according to [1]:

$$E = E_{in} sh \beta_0 y / sh \beta_0 y_{in}. \quad (1)$$

Here  $E_{in}$  – amplitude of the input signal;  $\beta_0 = \omega / v_e$  – phase constant of the electron stream;  $y_{in}$  – variable distance of injection of electron stream;  $\omega$  - frequency of the HFF;  $v_e$  – velocity of the electron stream.

Let amplitude of the HFF on the surface of SWS, where  $y = d$ , be  $E_{max}$ , then

$$E = E_{max} sh \beta_0 y / sh \beta_0 d, \quad (2)$$

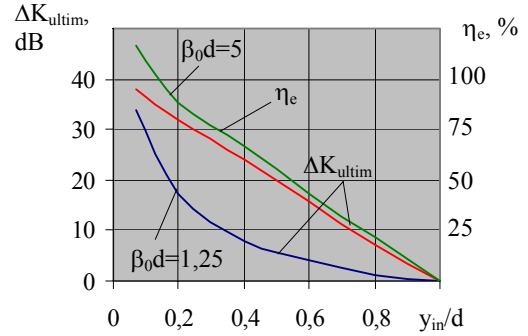
and a gain of the device  $K = 10 \lg P_{out} / P_{in}$ , where  $P_{in}$  and  $P_{out}$  – input and output signal powers, gets an ultimate increase:

$$\Delta K_{ultim} = 20 \lg E_{max} / E_{in} = 20 \lg sh \beta_0 d / sh [\beta_0 d (y_{in} / d)]. \quad (3)$$

We emphasized in this expression the multicand  $y_{in} / d$  because in accordance with [5] electronic efficiency of M-type amplifier is also determined by this cand:

$$\eta_e = 1 - y_{in} / d. \quad (4)$$

Practically values of  $\beta_0 d$  lie in an interval between 1.25 and 5. Dependeces of  $\Delta K_{ultim}$  and  $\eta_e$  on a relative coordinate of the electron stream with respect to negative electrode  $y_{in} / d$  at different  $\beta_0 d$  are given in Fig. 3.



**Fig. 3.** Increase in ultimate gain and efficiency versus relative coordinate of electron stream in planar active coaxial magnetron gun

It is quite natural that when electron stream goes close to the surface of SWS ( $y_{in} = d$ ), it does not give any potential energy to HFF of SWS and  $\eta_e$  approaches zero.  $\Delta K_{ultim}$  is also small because of intensive landing of electrons on the SWS of the gun. And on the contrary, the energy transmission from electron stream to HFF becomes maximum when electrons begin their performance directly from the surface of negative electrode ( $y_{in} / d \rightarrow 0$ ). But in this case, naturally, it is necessary sufficiently bigger input signal power in order to get good enough bunching of electrons therefore active coaxial magnetron gun may operate with high efficiency (~50-80%) only in the interval where  $y_{in} / d = 0.2-0.5$  and in this interval may be obtained the largest increase in a gain  $\Delta K_{ultim}$  of about 7-35 dB. Thus active coaxial magnetron guns are not free as well from incompatible contradictions between gain and efficiency that is characteristic to all crossed-field amplifiers and frequency transformers [6]. The most effective way for softening these contradictions is sectioning of the device with simultaneous programing of the height of interaction space [3].

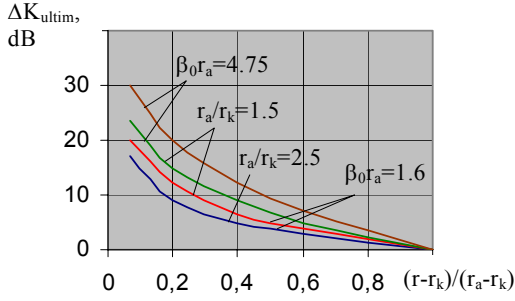
To calculate the gain increase for cilindric construction of an active coaxial magnetron gun, when oscillation system of the gun includes multicavity anode block, we need to have an expression of tangent component of HFF in such a system [1]:

$$E_\varphi = \frac{A}{r} \frac{(r/r_k)^M - (r/r_k)^{-M}}{2} = \frac{A}{r} sir(r/r_k)^M. \quad (5)$$

Here  $A$  – amplitudinal factor;  $r$  – variable radius;  $r_k$  – radius of negative electrode or cathode;  $M$  – number of pairs of individual cavities in a magnetron SWS;  $sir(r/r_k)$  – radial sine of the argument  $r/r_k$ .

In a cilindric magnetron oscillation system slow-wave coefficient is equal to [6]:

$$k_s = c / v_{fnp} = \lambda(n + pN) / 2\pi a, \quad (6)$$



**Fig. 4.** Increase in ultimate gain against relative radius of electron stream in cilindric active coaxial magnetron gun

where  $v_{fp}$  – phase velocity of  $p$  – spatial harmonic of  $n$  – mode oscillation;  $r_a$  – radius of interaction space;  $N=2M$  – number of individual cavities in an anode block. At  $p=0$  slow-wave coefficient equals:

$$k_s = \lambda n / 2\pi r_a \quad (7)$$

and

$$n = 2\pi r_a / (\lambda / k_s) \pi = 2\pi r_a / \lambda_s = \alpha r_a. \quad (8)$$

Here  $\lambda_s = \pi \lambda / k_s$  – slow-wave length. In a case of  $\pi$  – oscillations  $n=M=N/2$  and

$$E_\varphi = \frac{A}{r} \text{sir}\left(r/r_k\right) \alpha r_a. \quad (9)$$

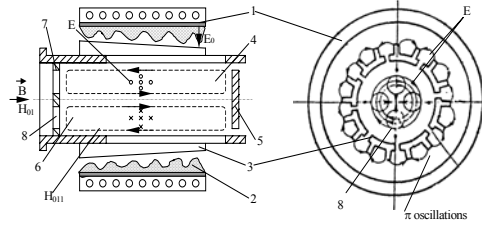
After calculation of amplitudinal factor  $A$  and substitution it's value into (9) we obtain the expression active coaxial magnetron gun in a convenient for consideration shape:

$$\Delta K_{ultim}^{cil} = 20 \lg \left[ \frac{\text{sir}\left(r_a/r_k\right) \alpha r_a}{\text{sir}\left(r/r_k\right) \alpha r_a} \left( \frac{r}{r_k} \frac{r_k}{r_a} \right) \right]. \quad (10)$$

Fig. 4 represents graph  $\Delta K_{ultim}^{cil}$  against  $r-r_k/r_a-r_k$  at different values of  $\alpha r_a$  characterising an extent of slowing down of the wave at various  $r_a/r_k$ . Ratio  $r-r_k/r_a-r_k$  determines the coordinate of electron stream injection with respect to the surface of negative electrode. As one can see from Fig. 4 at  $r-r_k/r_a-r_k=0,1$  the ultimate increase in a gain may achieve rather high value: 12-28 dB. This property of the gun to have a high gain is very valuable when it is used for getting a complementary channel of communication on a frequency of input signal.

### Active inverted coaxial magnetron electrons gun

More effective in regard to frequency stability, duration of operation, achievement of higher output powers and development of new short-wave ranges of microwaves should be an active inverted coaxial magnetron gun (Fig. 5).



**Fig. 5.** Active inverted coaxial magnetron electronic gun

In this gun of cylindric construction conoidal or cilindric cathode 1 with internal emitting surface creates tube-shaped electron stream 2. The cathode covers multicavity magnetron SWS 3 which anode segments are turned outwards in a direction of emitting surface of the cathode. The symmetry axis of the gun is girded by the stabilizing cylindrical resonator 4 which frequency may be controlled by plunger 5 (or by another installation). The resonator is electrically bound with multicavity magnetron anode block through the slits cut out in every second individual cavity of the block, similarly as in a mentioned above active coaxial magnetron gun. Cilindric resonator goes on continually to the round waveguide 6 in which wave of  $H_{01}$  – mode propagates. Partition 7 with communication apertures 8 separates vacuum and nonvacuum parts of the gun.

If in the multicavity SWS connected with cilindric resonator by  $N/2$  slits  $\pi$ -mode oscillations are excited, in the cilindric resonator azimuth symmetrical oscillations  $H_{011}$  appear. Their structure is shown in Fig. 5. Thus along the axis of cilindric resonator fits one half of a wavelength. Own frequency of the resonator may be changed by the noncontact plunger arranged in one of faces of the resonator. In another face round-shaped cross-section apertures filled with dielectric are made. The centers of these apertures are placed at a level of maximum values of azimuth electric field strength of  $H_{011}$  oscillations. In a case of necessity the round cross-section waveguide may be connected with the rectangular one in which wave  $H_{10}$  propagates.

The main merit of such inverted coaxial magnetron gun is very large duration of operation which is caused by high lasting emission ability of a cathode. For the emitting surface of the cathode is very large, in comparison with the cathode surface of an ordinary magnetron or coaxial magnetron gun, its working regime is much more light.

The own quality of the cilindric resonator of inverted coaxial magnetron gun, when  $H_{011}$ -mode oscillations in it take place, is sufficiently higher than in a coaxial one. This advantage is very striking in a millimetre range of microwaves. High stability of  $\pi$ -mode oscillations allows to enlarge the number of individual cavities in a magnetron anode block as well as diameter of stabilizing resonator and dimensions of anode block cavities. Technology of manufacture such oscillation systems becomes also more simple. There is no problem to produce 120- or 140-cavities magnetron block for 8-mm wavelength range [2].

Comparison of the oscillation systems of 8-mm range ordinary magnetron block having 22 individual cavities and 120-cavities inverted coaxial magnetron block shows that diameter of the last block is 6 times bigger and

emitting surface of the cathode is by an order higher than that of ordinary magnetron. The duration of operation exceeds 3-5 times values of this parameter characteristic to classical magnetron and is more than 5 thousand hours.

Of course similar values of mentioned parameters might be expected in the active inverted coaxial magnetron electronic gun in a regime formation of electron spokes, their injection into next section of the device and simultaneous amplification of the input signal when the gun is used as an input cascade of magnetron amplifier or frequency transformer. Evaluation of electronic efficiency  $\eta_e$  and ultimate increase in a gain of a active inverted coaxial magnetron gun may be carried out in a similar way we had used above for the active coaxial magnetron gun.

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**J. O. Meilus, Ž. Petrauskas, M. J. A. Smith. Aktyvusis bendraašis ir aktyvusis apgražos bendraašis magnetroniniai elektronų prožektoriai // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2004. – Nr. 7(56). – P. 5-9.**

Kuriant efektyvius šiuolaikinius kryžmųjų laukų aktyviuosius bendraašius ir aktyviuosius apgražos bendraašius elektronų prožektorius, kurie ne tik generuotų reikiamos konfigūracijos elektronų pluoštą, injektuotų jį į kitą magnetroninio stiprintuvo ar elektroninio dažnio keitiklio pakopą, bet ir garantuotų didelį signalo dažnio stabilumą, didelę sustiprinto įėjimo signalo galią ir užtikrintų prietaiso darbą įėjimo signalo dažnio laiko harmonikų arba subharmonikų išskyrimo ir stiprinimo režimu, siūloma panaudoti bendraašio ir apgražos bendraašio magnetronų veikimo principus. Abiejų rūšių prožektoriuose svarbiausią vaidmenį vaidina aukštos savosios kokybės bendraašis rezonatorius, turintis aukštadažnį elektromagnetinį ryšį su kas antru daugiarezonatorės magnetroninės lėtinimo sistemos, kurioje vyksta  $\pi$  svyravimai, rezonatoriumi. Pirmuoju atveju šis aukštadažnis svyravimus stabilizuojantis rezonatorius gaubia daugiarezonatorę lėtinimo sistemą ir katodą, o antruoju lėtinimo sistema ir stabilizuojantysis rezonatorius yra didelio vidinio emituojančio paviršiaus cilindrinio ar kuginio katodo viduje. Mikrobangų prietaisų, naudojančių tokio tipo elektronų prožektorius, darbo trukmė dėl žymiai lengvesnio nei įprastame magnetrone šiluminio režimo turėtų padidėti 3–5 kartus. Il. 5, bibl. 6 (anglų kalba; santraukos lietuvių, anglų ir rusų k.).

**J. O. Meilus, Z. Petrauskas, M. J. A. Smith. Active Coaxial and Active Inverted Coaxial Magnetron Electronic Guns // Electronic and Electrical Engineering. – Kaunas: Technologija, 2004. – No. 7(56). – P. 5-9.**

It is proposed to use the principles of the coaxial and inverted coaxial magnetrons for creation of highly effective crossed – field active coaxial and active inverted coaxial electron guns that not only produce, bunch and inject electron stream into next cascade of the M-type amplifier or frequency transducer, but also ensure high frequency stability, large output signal power and operation at higher temporal harmonics and subharmonics of the input signal. Both magnetron active coaxial and active coaxial inverted electron guns should include a high quality coaxial resonator connected with the slow – wave system operating at  $\pi$ -oscillations but in a first case this resonator covers the slow –wave system and a cathode and in a second one – a large cathode with inner emitting surface covers slow – wave system and stabilizing resonator. Working duration of the devices using such active coaxial magnetron guns should be 3 – 5 times larger in comparison with ordinary magnetron guns because of released thermal regime of operation. The expressions for evaluation of electronic efficiency and ultimate increase in a gain of the active coaxial magnetron gun are presented. They confirm the high efficiency of the gun. Il. 5, bibl. 6 (in English; summaries in Lithuanian, English and Russian).

**И. О. Мейлус, Ж. Пятраускас, М. Я. А. Смит. Активная коаксиальная и активная обращенная коаксиальная магнетронные электронные пушки // Электроника и электротехника. – Каунас: Технология, 2004. - № 7(56). – С. 5-9.**

Предлагается использовать принципы коаксиального и обращенного коаксиального магнетронов для создания эффективных современных активных коаксиальных и активных обращенных коаксиальных электронных пушек со скрещенными полями, обеспечивающих не только получение электронного потока необходимой конфигурации, инъекцию его в следующую секцию магнетронного усилителя или электронного преобразователя частоты, но и гарантирующих высокую стабильность частоты сигнала, большую мощность усиленного входного сигнала и обеспечивающих работу прибора в режиме выделения и усиления рабочих временных гармоник или субгармоник. В пушках обоих типов главную роль играет коаксиальный резонатор с высокой собственной добротностью, имеющий высокочастотную электромагнитную связь с каждым вторым резонатором многорезонаторной замедляющей системы, в которой имеют место высокочастотные колебания  $\pi$ -типа. Но в первом случае этот стабилизирующий резонатор охватывает многорезонаторную систему и катод, а во втором – замедляющая система и стабилизирующий резонатор находятся внутри цилиндрического или конического катода с большой внутренней эмитирующей поверхностью. Срок службы микроволновых электронных приборов, использующих электронные пушки такого типа, из-за облегчения теплового режима работы катода, должен увеличиться в 3-5 раз по сравнению с обычным магнетроном. В статье приводятся результаты расчетов увеличения предельного коэффициента преобразования мощности и электронного КПД активной коаксиальной магнетронной пушки в режиме усиления входного сигнала, когда усиленный сигнал используется для создания дополнительного канала связи на частоте входного сигнала. Расчеты подтверждают высокую эффективность работы подобных электронных устройств. Ил. 5, библи. 6 (на английском языке; рефераты на литовском, английском и русском яз.).