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Large Amplitude Regime of Two Electron Stream Magnetron Frequency Multiplier

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Introduction

Nonlinear theory of two-cascade two electron stream magnetron frequency multiplier with stepped interaction space in an output cascade was represented in a paper [1]. This theory includes integro-differential equations of motion of both electron streams in an input and output cascades as well as equations of excitation of slow-wave systems (SWS) in the cascades by prebunched electron streams on a frequency of input signal ω and on a frequency of n-th temporal working harmonic $n\omega$. These equations are:

$$\begin{cases} \dfrac{dX_1}{d\xi} = -A_1(\xi)\dfrac{\operatorname{ch} Y_1}{\operatorname{sh} Y_{in1}}\sin X_1; \\ \dfrac{dY_1}{d\xi} = A_1(\xi)\dfrac{\operatorname{sh} Y_1}{\operatorname{sh} Y_{in1}}\cos X_1 \end{cases} \qquad (1)$$

(equations of motion of the first stream in the first cascade);

$$\frac{dA_1(\xi)}{d\xi} = \frac{1}{2\pi}\int_{X_1'}^{X_1''}\frac{\operatorname{sh} Y_1}{\operatorname{sh} Y_{in1}}\cos X_1 dX_0 \qquad (2)$$

(equation of excitation of the first SWS);

$$\begin{cases} \dfrac{dX_1}{d\xi} = -A_{n1}(\xi)\dfrac{\operatorname{ch} n(Y_1+n\beta_e a)}{\operatorname{sh} n(Y_{in1}+n\beta_e a)}\sin nX_1 - S_2 I_1^{12}; \\ \dfrac{dY_1}{d\xi} = A_{n1}(\xi)\dfrac{\operatorname{sh} n(Y_1+n\beta_e a)}{\operatorname{sh} n(Y_{in1}+n\beta_e a)}\cos nX_1 + S_2 I_2^{12} \end{cases} \qquad (3)$$

(equations of motion of the first stream in the second cascade);

$$\begin{cases} \dfrac{dX_2}{d\xi} = -A_{n2}(\xi)\dfrac{\operatorname{ch} n(Y_2+n\beta_e a)}{\operatorname{sh} n(Y_{in1}+n\beta_e a)}\sin nX_2 - S_2 I_1^{22}; \\ \dfrac{dY_2}{d\xi} = A_{n2}(\xi)\dfrac{\operatorname{sh} n(Y_2+n\beta_e a)}{\operatorname{sh} n(Y_{in1}+n\beta_e a)}\cos nX_2 + S_2 I_2^{22} \end{cases} \qquad (4)$$

(equations of motion of the second stream in the second cascade);

$$\frac{A_{n2}(\xi)}{d\xi} = \frac{R_2}{R_1}\left[\frac{1}{2\pi}\int_{X_{11}}^{X_{21}}\frac{\operatorname{sh} n(Y_1+n\beta_e a)}{\operatorname{sh} n(Y_{in1}+n\beta_e a)}\cos nX_1 dX_0 + \right.$$
$$\left. + \frac{I_{02}}{2\pi I_{01}}\int_{X_{11}}^{X_{21}}\frac{\operatorname{sh} n(Y_2+n\beta_e a)}{\operatorname{sh} n(Y_{in1}+n\beta_e a)}\cos nX_2 dX_0\right]. \qquad (5)$$

(equation of excitation of the second SWS by the second electron stream).

All designations we shall use there coincide with ones in the paper [1]. The two main parameters of the frequency multiplier – gain and electronic efficiency – may be written as follows:

$$K = 10\lg\frac{(P_{out})_{n\omega}}{(P_{in})_{\omega}} = 10\lg\frac{R_1}{R_2}\frac{A_{n2}^2(\xi)}{A_1^2(0)}; \qquad (6)$$

$$\eta_e = \frac{(P_{out})_{n\omega} - (P_{in})_{\omega}}{P_0} = \frac{A_{n2}^2(\xi)R_1/R_2 - A_1^2(0)}{2\beta_e d_1\left(1 + \dfrac{I_{02}}{I_{01}}\cdot\dfrac{d_1+a}{d_1}\right)}. \qquad (7)$$

Here $(P_{out})_{n\omega}$ and $(P_{in})_{\omega}$ - output and input signal powers; P_0 – power of feedstock; $A_{n2}(\xi)$ and $A_1(0)$ – amplitudes of output and input signals on frequencies of n-th and fundamental harmonics; R_2 and R_1 – interactions impedances of the second and first SWSs at a level of injection of the first stream into interaction space; $\beta_e = \dfrac{\omega}{v_e}$ – phase constant of electron stream; v_e – velocity of the stream; d_1 – distance between negative electrode and SWS in the input cascade; a – distance between surfaces of negative electrodes in the first and second cascades; I_{02} and I_{01} – permanent components of electron currents in cascades.

There we are going to investigate the most important dependencies such as output signal amplitude $A_{n2}(\xi)$, electronic efficiency η_e and gain K as well as increase in a gain (gain increase) ΔK, due to step in a negative electrode on standardized interaction space length ξ and standardized height of the input cascade $\beta_e d_1$ at different values of the ratios I_{02}/I_{01} and R_2/R_1, space charge density of the second stream S_2, levels of injection of both streams $\beta_e y_{in1}$ and $\beta_e y_{in2}$ and standardized height of the output cascade $\beta_e d_2$.

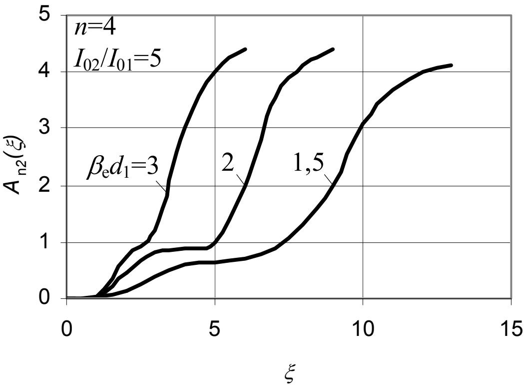

Fig. 1. Distribution of dimensionless amplitude of HFF on the 4-th harmonic along interaction space at different standardized height of the first cascade. $\beta_e y_{in1}=\beta_e y_{in2}=0{,}5$; $\beta_{ea}=2$; $\beta_e d_2=3{,}5$

Amplitudinal characteristics

In an output cascade of the magnetron frequency multiplier with stepped negative electrode in an output cascade as well as in identical device with smooth one takes place an interaction between high frequency fields (HFF) of SWSs and both electron streams. Consider an influence of the height of the step made on a negative electrode in the output cascade on the main output parameters of the multiplier. It is most convenient to do this by comparison two constructions of mentioned above devices. We shall assume that second cascades of the multipliers have the same parameters (geometric dimensions, currents of the streams and interaction impedances on surfaces of SWSs) and that height of the step on a negative electrode in the second cascade can be created by change in a standardized height of the interaction space of the first cascade $\beta_e d_1$. At a maintenance constant distance between static trajectory of the first electron stream (level of injection) and first negative electrode ($\beta_e y_{\text{in}1}$=const)as well as strength of a HFF at the input of the first SWS on the level of injection we can change relatively a magnitude of dimensionless amplitude of input signal $A_1(0, \beta_e, y_{\text{n}1})$.

Fig. 1 represents distribution of HFF amplitude $A_{n2}(\xi)$, at a frequency of 4-th working harmonic (n=4), along the interaction space of the second cascade at different standardized height of the input cascade $\beta_e d_1$ and constant ratio of currents I_{02}/I_{01}=5 with respect to standardized length of interaction space $\xi=2\pi D_1 N$. Here D_1 – parameter of amplification of the first cascade; N – electrical length of the device. Indeed, contribution of the input cascade into electronic efficiency of the multiplier depends, at a first approach, on a ratio $(d_1 - y_{in1})/d_1$. Moreover, the bigger this ratio, the higher electronic efficiency.

It is interesting to remark that according to equations presented in a paper [1] distributions of the HFFs strengths along d_1 in both devices are different. In a multiplier without step longitudinal component of the field at a level of second electron stream is about twice bigger than in a stepped one. (gain of a stepped multiplier is about 3 dB less than in a smooth one). This fact might be explained by quicker exponent abatement of the longitudinal field in d_1-dirrection in the stepped device.

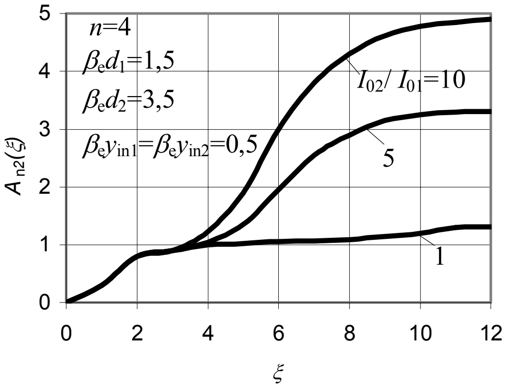

Fig. 2. Distribution of HFF amplitude along the interaction space of multiplier at different values of I_{02}/I_{01}

Now consider influence of the ratios I_{02}/I_{01} on the main parameters of multiplier. Fig. 2 shows distribution of HFF amplitude $A_{n2}(\xi)$ along interaction space for three values of I_{02}/I_{01}. Here current I_{01} is kept up constant and the ratio grows for the sake of increase in I_{02}. Calculations carried out in accordance with (6) and (7) show that at fixed length of interaction space $\xi = 10$ and $I_{02}/I_{01} = 10$, gain K=22,8 dB and electronic efficiency $\eta_e = 74\%$. At $I_{02}/I_{01} = 5$, K=19,5 dB, $\eta_e = 66\%$ and at $I_{02}/I_{01} = 1$, K=11,5 dB and $\eta_e = 37\%$.

Fig. 2 shows that increase in I_{02} gives rise to electronic efficiency as well as to gain. This may be explained by the bigger contribution of more powerful second electron stream into energetic balance of the device. On the other hand, shortening of longitudinal dimension of the multiplier makes worse bunching of the second stream.

Let a length of the first cascade be small enough, so that certain part of electrons do not reach the surface of the first SWS. Moreover, let space charge of the second stream be finite. Fig. 3 represents distribution of HFF amplitude against standardized length of the device at different values of space charge parameter S_2. Another parameters used for calculations are: $\beta_e y_{in1} = \beta_e y_{in2} = 0{,}5$; $\beta_e d_1 = 1{,}5$; $\beta_e d_2 = 3{,}5$. If the space charge of the second stream is vanishingly small (S_2=0), electronic efficiency of the device at saturation conditions does not depend on amount of electrons landing on the first SWS. But at a decrease of this amount length of multiplier can be done less. This possible shortening becomes especially evident at large values of I_{02}/I_{01}.

Composition of the curves at S_2=0 and S_2=0,5 shows that growth of a space charge parameter causes rise of HFF amplitude in an initial part of the first cascade. However, further increase of the amplitude stops at about $\xi \geq 3$ and at S_2=1 becomes equal zero at $\xi = 4{,}5$. When $S_2 \geq 1$ some of assumptions of the nonlinear theory [1] (adiabatic equations of motion, model with infinitely thin electron streams) become partly incorrect.

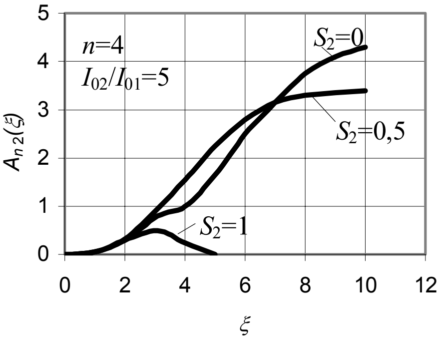

Fig. 3. Distribution of HFF amplitude at different values of space charge parameter of the second electron stream. Another parameters are the same as in Fig. 2

Analysis of HFF amplitude distribution taking into account existence of a space charge should include diocotron effect in second stream leading to a growth of HFF in an initial part of the second SWS (regime of relatively small deflections of second stream electrons) as well as negative influence of the second stream space charge on electrons of the first stream which displays itself at large declinations accomplished by electrons of the second stream. This negative influence is caused by Coulomb's forces of the second stream electrons, situated under electron clusters of the first stream, and results in elongation these clusters in a direction of wave propagation. Therefore, certain part of electrons of the first stream can find themselves in an accelerating phase of HFF and takes energy from the field of a traveling wave.

Gain. Electronic efficiency. Electrical length

In order to evaluate merits of the stepped device with respect to the identical multiplier with smooth interaction space introduce parameter of an increase in a gain (or gain increase) as a difference between gain of stepped K_s and non-stepped K_{non} devices in a saturation regime, when all electrons land on a surface of the second SWS:

$$\Delta K = K_S - K_{non}. \quad (8)$$

Fig. 4 represents a dependence between gain increase ΔK at saturation conditions and standardized height of the input cascade $\beta_e d_1$ at different ratio of interaction impedances of the second and first SWSs at a level of injection of the first stream. The interval of R_2/R_1 was chosen taking into account real values of this ratio which depends mainly on working frequency (in our case on number of working harmonic) and ratio of areas taken by faces of SWS segments and that occupied by HFF. One can see that step on a negative electrode in an output cascade gives similar effect as it takes place when step is made on SWS of input cascade [2]. Comparison with identical dependencies for magnetron amplifiers [3] confirms our inferences.

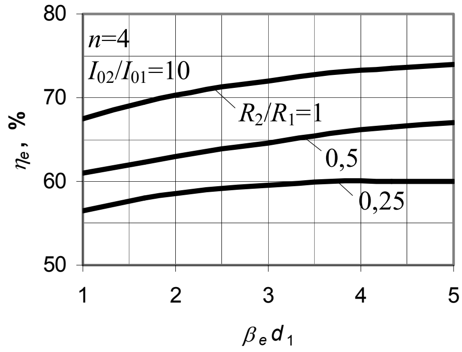

Fig. 5. Electronic efficiency versus height of interaction space of the first cascade

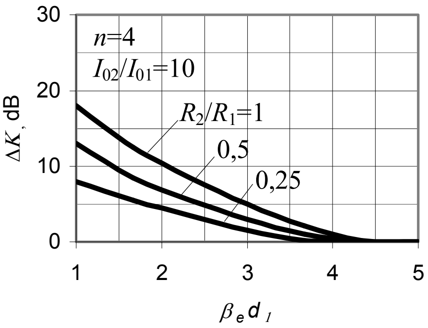

Fig. 4. Gain increase against height of interaction space in the input cascade

In Fig. 5 is shown a family of three curves corresponding to the same values of the ratio R_2/R_1 as in Fig. 4 representing dependence of electronic efficiency of a stepped multiplier. In a saturation regime all electrons reach the SWS of output cascade and maximum potential energy obtained by HFF from electrons is known exactly, therefore limit electronic efficiency at adiabatic approach may be appreciated as follows:

$$\eta_e^{\lim} = \frac{d_1 - y_{in1} + (I_{02}/I_{01})(d_2 - y_{in1})}{d_1 + (I_{02}/I_{01})d_2}. \quad (9)$$

Calculations carried out in accordance with (9) at I_{02}/I_{01}=const show the increase in η_e due to saturation of about (4-8)% with respect to optimal pre-saturation state. The opposite nature of the curves in Fig. 4 and Fig. 5 confirms the fact about existence of incompatible contradictions between gain and electronic efficiency in crossed-field microwave devices [2].

The last Fig. 6 shows how standardized length of the stepped frequency multiplier (normalized electrical length) depends on standardized height of the input cascade at the same interval of the ratio of interaction impedances. It is quite natural that at a higher interaction space in the first cascade bunching extent of the first stream is less and for achievement perfect grouping and effective interaction in the output cascade it is necessary longer second SWS.

Dependence between ξ and R_2/R_1 shows that the smaller interaction impedance in the output cascade with respect to that in the input one, the worse processes of grouping and interaction between electron stream and HFF on a frequency of working harmonic. This deterioration is just reflected in Fig. 6 as a growing length of the device at a decrease of the ratio R_2/R_1.

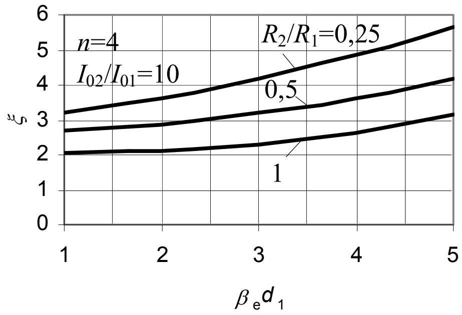

Fig. 6. Standardized length of interaction space against height of input cascade

Thus, analysis of the two-cascade two-electron stream magnetron frequency multiplier with a step on a negative electrode of the output cascade carried out on a base of nonlinear theory [1] shows that the device under investigation may have sufficiently higher gain and smaller electrical length at a big enough electronic efficiency in comparison with identical device with smooth interaction space. Distinguishing feature of represented nonlinear theory is possibility to describe a performance of the device in extreme saturation regime.

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J.O. Meilus, S. Gelžinis. Dviejų elektronų pluoštų magnetroninio dažnio daugintuvo didelių amplitudžių režimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2003. – Nr. 7(49). P. 5-8.

Interpretuojama neseniai šio straipsnio autorių paskelbta netiesinė pakopinių dviejų elektronų pluoštų magnetroninių dažnio daugintuvų teorija. Pateiktos prietaiso elektroninio naudingumo koeficiento ir jo elektrinio ilgio priklausomybės nuo įėjimo pakopos sąveikos erdvės aukščio esant skirtingoms išėjimo ir įėjimo pakopų lėtinimo sistemų ryšio varžoms pirmojo elektronų pluošto injekcijos į sąveikos erdvę lygyje. Palyginti laiptuotos ir lygios sąveikos erdvės analogiškos konstrukcijos dažnio daugintuvų galios transformacijos koeficientai, esant fiksuotam nuolatinių srovės dedamųjų santykiui ir skirtingoms ryšio varžoms. Netiesinės teorijos pagrindu atlikta dviejų pakopų dviejų elektronų pluoštų magnetroninio dažnio daugintuvo su programuota išėjimo pakopos sąveikos erdve analizė rodo, kad šio tipo prietaisai pasižymi aukštomis pagrindinių išėjimo parametrų vertėmis: galios transformacijos koeficiento išlošis, palyginti su neprogramuotos sąveikos erdvės prietaisu, gali siekti iki 20 dB, o elektroninis naudingumo koeficientas – 70-80%. Il. 6, bibl. 3 (anglų kalba; santraukos lietuvių, anglų ir rusų k.).

J.O.Meilus, S.Gelžinis. Large Amplitude Regime of Two Electron Stream Magnetron Frequency Multiplier // Electronics and Electrical Engineering. – Kaunas: Technologija, 2003. – No. 7(49).- P. 5-8.

The paper represents an approval of recently published by the authors of this article nonlinear theory of cascade magnetron frequency multipliers with two electron streams. Graphs of dependencies between electronic efficiency and electrical length of the device on a height of interaction space of the first cascade at different values of interaction impedances of the first and second slow-wave systems are given. Comparison of the gains of two frequency multipliers – with stepped interaction space and with smooth one – having identical constructions at fixed ratio of permanent currents and different interaction impedances is carried out. Analysis of two-cascade two electron stream magnetron frequency multiplier with programmed interaction space in the output cascade has shown that devices of that type possess high output characteristics: increase in a gain in comparison with non-programmed identical frequency multiplier reaches up to 20 dB at electronic efficiency adjacent to 70-80%. Ill. 6, bibl. 3 (in English; summaries in Lithuanian, English and Russian).

И.О. Мейлус, С. Гельжинис. Режим больших амплитуд двухлучевого магнетронного умножителя частоты // Электроника и электротехника. – Каунас: Технология, 2003. – № 7(49). – С. 5-8.

Представлена интерпретация недавно опубликованной авторами статьи нелинейной теории секционированных магнетронных умножителей частоты с двумя электронными потоками. Приведены зависимости электронного кпд и электрической длины пробора от высоты пространства взаимодействия входной секции при различных сопротивлениях связи замедляющих систем первой и второй секции на уровне встрела первого потока в пространство взаимодействия. Проведено сравнение коэффициентов трансформации мощности приборов со ступенчатым и гладким пространствами взаимодействия при фиксированном отношении постоянных составляющих токов и различных сопротивлениях связи. Анализ двухсекционного магнетронного умножителя частоты с двумя электронными потоками и с программированным пространством взаимодействия в выходной секции показал, что приборы данного типа обладают высокими выходными характеристиками: выигрыш в коэффициенте трансформации мощности, в сравнении с непрограммированным прибором, достигает 20 дБ, а электронный кпд – 70-80%. Ил. 6, библ. 3 (на английском языке; рефераты на литовском, английском и русском яз.).