# TWO - CASCADE VOLTAGE TUNABLE MAGNETRON FREQUENCY MULTIPLIER

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***This paper presents the up to date situation on the field of powerful microwave frequency multipliers. It is shown that the most prospective for effective frequency multiplication are the cascade magnetronic multipliers. They not only have high gain and efficiency but also sufficiently broad frequency band. Experimental data submitted in this paper confirm this assertion: the output power of the multiplier, working on the 4-th harmonic in the range of 10 cm wavelength, is 430 W; it has gain 23 dB, electronic efficiency 52 % and frequency band 15 % with linear frequency characteristic. Only relativistic microwave devices working on the principle of the cyclotron resonance maser, such as gyrotron and peniotron, have the similar characteristics. But their structure and feeding are much more complicated.***

## INTRODUCTION

Crossed- field microwave frequency multipliers accumulate all good properties of magnetronic generators and amplifiers and the idea of cascading of the magnetronic oscillation systems tuned to the frequency of the n-th harmonic where electron stream gives their potential energy to the RF field of the slow-wave structure remaining in the synchronizm with the field. This is the main reason of the high efficiency of the M-type devices in comparison with the devices of O-type. But up to now in the powerful crossed-field microwave frequency multipliers the resonant magnetronic oscillation systems were used. Frequency band in such devices usually do not exceed 1%. Therefore practical application of the devices requires to create the multipliers with wider band and better modulation characteristics. For this purpose in the new structure of the multiplier the principles of the voltage tunable magnetron (VTM) [1] were used. They allow to widen frequency band many times and to get linear frequency characteristic.

Voltage tunable magnetrons have several very valuable properties: a wide voltage tunable frequency band; the possibility of linear changing of the frequency of the signal to be generated or amplified by change in the voltage of the slow-wave structure. It also has a high coefficient of efficiency which is a characteristic feature of all crossed-field devices. VTMs are devided into two classes: 1) small and medium power (from 50 mW to several watts) with a very wide voltage tunable frequency range (from 3 octaves in the decimetric range to 0.5 octave in the centimetric range) and small coefficient of efficiency (10 – 30 %) and 2) high power (up to 1 kW) with a rather narrower frequency band (5 – 20 %) and large coefficient of efficiency (70 %).

In VTMs as well as in ordinary magnetrons the frequency of generation is changed by changing the slow-wave structure voltage. The physical reason for this phenomenon is the change in rotational speed of the electron clusters. If there is synchronizm between the electron stream and the wave traveling along the slow-wave structure, the change in voltage results in a new frequency of the generated signal. The faster the electron stream rotates, the bigger the frequency of induced current impulses in delay line. If the device receives an independent input signal then it works as an amplifier and it is necessary to change the input signal frequency synchronically with the voltage change.

Therefore the frequency dependence upon voltage in a magnetron is nonlinear. There are two main reasons for this nonlinearity: the second electron emission from the cathode and the localization of the electron gun in the interaction space of the magnetron. The increasing voltage results in a more intensive bombardment of the cathode surface by striking electrons. This gives rise to an increase in the emission current and space charge density in the interaction space of magnetron. As a result the strong dependence between current and voltage (and also between voltage and frequency) occurs. It is nonlinear and can even become nonmonotonic. But by removing the electron gun from the interaction space and by replacing the cathode in the interaction space with a nonemitting electrode (cold cathode or negative electrode), made from a material with low second electron emission, the frequency voltage characteristic can successfully be linearized.

During the last few decades there has been rising interest in microwave frequency multipliers. A lot of papers and some monographs on this subject have appeared. This could be explained by the growing number of applications for such devices in communication systems (far distance and aerospace), in the observation and shadowing installations and in special equipment for military or security purposes.

## STRUCTURE AND PRINCIPLES

The goal of this work was making the large output power, effectively functioning, wide band microwave frequency multiplier with the linear frequency dependence on voltage. The voltage tunable magnetron cascade design was chosen as suitable for this purpose. This paper deals with the two cascade VTM frequency multiplier principles, structure and characteristics. The first results of investigation of such multipliers were published in an article.

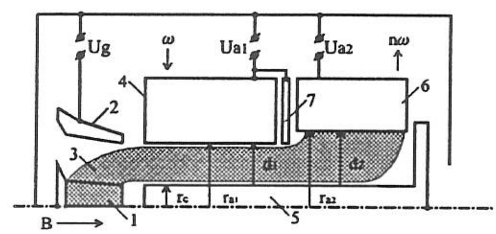


*Fig. 1.*Two cascade VTM frequency multiplier.

The principle scheme of the microwave cascade VTM frequency multiplier is shown in the fig. 1. The magnetronic electron gun, which consists of the conical cathode 1 and accelerating electrode 2, produces the tube-shaped electron stream 3 and injects it into the interaction space of the input cascade 4. This cascade is made up of the sole (nonemitting cathode) 5 and the slow-wave interdigital line bent into a ring and loaded by quasitoroidal resonator. Usually in the cascade magnetronic frequency multipliers multicavital resonant slow-wave structures are used, but for the purposes of the widening of the frequency band it is more suitable to apply nonresonant or low quality resonant systems with well separated types of oscillations. The input cascade oscillation system consists of vacuum and non-vacuum parts detached by the ceramics rings. In the centre of the quasitoroidal resonator1 the interdigital line 2 is situated (fig. 2).

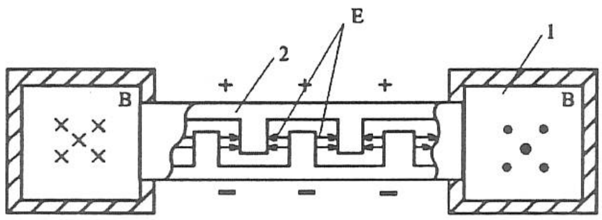


*Fig. 2.* Interdigital delay line loaded by quasitoroidal resonator

This line provides a sufficiently wide frequency band and has no limit from the side of long length waves. This is a very important feature of that line when it is necessary to multiply the quartz-stabilized signal frequency. It is possible to control quite easily the quality of the oscillation system interdigital line - quasitoroidal resonator by changing the electrical characteristics of the line, resonator and energy lead-in.

The destination of the multipliers' input cascade is to form electron clusters rich in the higher harmonics of the convection current. The height and the length of an interaction space in this cascade must be chosen in such a way that it would provide electron clusters of the optimal characteristics. It is proved in the nonlinear theory of the crossed-field devices [3] and in its application to the crossed-field amplifiers [4] that the amplitudes of all higher convection current harmonics at the same time get their maximal values. This occurs when the first electrons reach the surface of the slow-wave structure. Later on the amplitudes of harmonics deteriorate monotonically due to extensive landing of the electrons on the slow-wave structure. Therefore, in our case, the tilting angle of the cathode surface to the axis of the device and the voltage of an accelerating electrode should provide the optimal duration of electron clusters participation in the interaction space of the input cascade. These parameters were calculated on a base of the nonlinear theory of magnetronic cascade frequency multipliers [5]. The efficiency of electron groupping into the clusters depends on the distance between the electron stream and the surface of the slow-wave structure in the input cascade. It usually grows when this distance decreases and at the same level of the input signal it is possible to obtain perfectly groupped electron clusters. But deterioration of the distance has also a drawback because, in this case, the amount of the potential energy to be given to the high frequency electromagnetic field of the slow-wave structure is reduced. The length of the interaction space of the input cascade must also be minimal but it should satisfy the above mentioned criterion of optimal groupping, when the electrons begin to land on the slow-wave structure.

The harmonized electron stream is injected from the input cascade into the output one 6. Its oscillation system should be tuned to the frequency of the working harmonic n. Here the electron clusters must be transformed in accordance with the configuration of the high frequency field in the slow-wave structure of this cascade. In order to avoid the restriction of the frequency band of the device, it is necessary to ensure that the limit frequencies of the output cascade $\omega_{2\ min}$ and $\omega_{2\ max}$ are related to the limit frequencies of the intput cascade as follows: $\omega_{2\ min}=n\omega_{1\ min}$ and $\omega_{2\ max}=n\omega_{1\ max}$. So the oscillation system of this cascade should be also wide-band as the input cascade system is. Therefore the most suitable system for this purpose is one of the same type used in the input cascade: interdigital line loaded by quasitoroidal resonator. As will be shown later, in the case, when slow-wave structures of both cascades work in the regime of the ($\pi$- type oscillations, the coefficient of frequency multiplication n should be equal to the ratio of the numbers of the fingers in the interdigital lines of the output and input cascades. This means that the number of the electron spokes in the output cascade should be n times bigger than that in the input cascade. The speed with which electron clusters move along the axis of the mutiplier is determined by the parameters of the electronic gun. Therefore the height and length of the of the interaction space must be chosen with respect to the time interval necessary to transform the "old" spokes into the "new" ones and to transfer by electrons their whole potential energy to the field of the slow-wave structure of the output cascade. Only in this case it is possible to expect that the device will have the high values of the main parameters.

According to crossed-field amplifier and frequency multiplier theory and practice it is very useful to apply the idea of the stepped interaction space [4, 5]. In this case the slow-wave structure of the input cascade is brought nearer to the electron beam, or the slow-wave structure of the output cascade is drawn away from the electron beam. In order to protect the penetration of the high frequency electromagnetic field from one cascade to another in the gap between two cascades the thin metallic diaphragm 7 is fitted.

## FREQUENCY CHARACTERISTICS

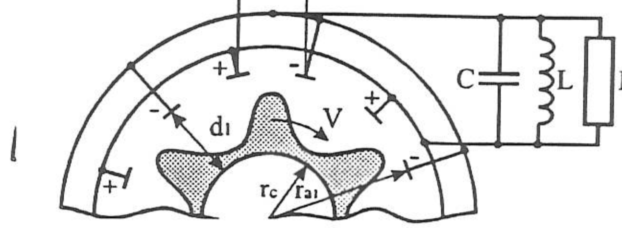


*Fig. 3.* Equivalent circuit of the input cascade oscillation system.

The interdigital line of the first cascade loaded by quasitoroidal resonator is shown in fig. 3. In this figure, C represents the mutual capacitance of the fingers, L - the inductance of quasitoroidal resonator, R - resistance of the external load. If this slow-wave structure works in the regime of ($\pi$- type oscillations, the potentials of its adjacent fingers are of the opposite sign and electron spokes are formed here in the same way as in the ordinary magnetron. The next step is to find the relationship between the frequency of the output signal and the potentials of the slow-wave structures of the both cascades. In order to get the permanent energy interchange between electron stream and high frequency fields of the slow-wave structures in the input and output cascades, it is necessary that electron bunches are able to induce in these structures the traveling waves with velocities approximately equal to that of the electron spokes. If the intensity of the permanent electric field in the interaction space of the input cascade is $E_1$ and magnetic flux density is $B_1$, then electron spokes moving with the velocity $V_1=E_1/B_1$, in the case of synchronic motion the wave and the spoke, will be displaced in the distance $b_1$ (fig. 3) during a half of period $T_1$ of the high frequency oscillations. Only then electron spokes will constantly occur in the stopping phase of the field and will be bunched most effectively. Then

$$T_1 = \frac{2b_1}{V_1} \text{ and } V_1 = 2b_1 v_1 \qquad (1)$$

Here $v_1$ is the frequency generated by the first cascade. If a space charge is left out of account, the intensity of the electric field in the interaction space of the input cascade can be expressed by the slow-wave structure potential $\varphi_1$ of this cascade, at which the synchronism between the wave and electrons exists:

$$\varphi_1 = E_1 d_1 = 2B_1 d_1 b_1 v_1 \qquad (2)$$

One can express parameters $b_1$ and $d_1$ by the radii of the negative electrode rc, slow-wave structure ra1 and a number of fingers in this structure $N_1$:

$$b_1 = \frac{p}{N_1}(r_{a1}+r_c), \qquad d_1 = r_{a1} - r_c, \qquad (3)$$

Then the potential of synchronization in the input cascade will be equal:

$$\varphi_1 = \frac{2\pi}{N_1} B_1 v_1 r_{a1}^2 \left(1 - \frac{r_c^2}{r_{a1}^2}\right), \qquad (4)$$

Thus, when the magnetic flux density in the interaction space of the input cascade $B_1$ is constant, at the given geometric parameters rc, $ra_1$ and $N_1$ between the frequency to be generated and the potential of synchronization, there exists linear dependence.

This potential of synchronization characterizes the energy of the electrons used for making bunches and space charge wheel rotation with the constant velocity around the negative electrode, i.e. for supporting the inextinguishable oscillations. If the slow-wave structure of the input cascade is given an extra potential $\varphi_{1ex}$ which exceeds the potential of synchronization $\varphi_1$, the energy, proportional to this potential can be transferred to the high frequency field of the structure. Therefore the physical reason of the frequency change is the increase of the radial component of the electric field in the interaction space of the input cascade, when the potential increases from $\varphi_1$ to $\varphi_1+\varphi_{1ex}$.Then the intensity of electric field in the first cascade will be:

$$E_1' = \frac{\varphi_1 + \varphi_{1\,ex}}{d_1} \qquad .(5)$$

Since $E_1' > E_1$ the new rotational velocity of

the electrons $V_1' = \frac{E_1'}{B_1} > V_1$ .

For this reason, if the magnetic flux density and parameters of the interaction space in the input cascade remain constant, the frequency of the current impulses, induced in the slow-wave structure, must increase. This means that the frequency generated by the first cascade $v_1$ also increases. Finally the relationship between frequency $v_1$ and the potential $\varphi_1+\varphi_{1ex}$ can be submitted in such a form:

$$v_1 = K_1 \frac{\varphi_1 + \varphi_{1\,ex}}{B_1} \qquad .(6)$$

where $K_1$ - coefficient which depends on the parameters of the interaction space of the input cascade.

The rotational velocity of the electron spokes in the output cascade is $V_2 = E_2/B_2$, where $E_2$ and $B_2$ - intensity of permanent electric field and magnetic flux density in the interaction space of this cascade. A magnetic field is created in both cascades by the same source. Thus $B_1=B_2$. When $E_1=E_2$, $V_1=V_2$ and the heights of the interaction space in both cascades are equal to each other ($r_{a1}=r_{a2}$ and $d_1=d_2$), in the case of -type oscillations in both cascades, it is possible to express frequencies $v_1$ and $v_2$ through the number of the fingers in the interdigital lines of the input and output cascades $N_1$ and $N_2$:

$$\frac{v_1}{N_1} = \frac{v_2}{N_2} \qquad .(7)$$

But $v_1=v_{n1}$, therefore

$$n = \frac{N_2}{N_1} \qquad .(8)$$

So the ratio of the finger numbers in the delay lines of the output and the input cascades should be equal to the coefficient of frequency multiplication.

The synchronization potential of the output cascade according to (2) and (4) can be calculated as follows:

$$\varphi_2 = E_2 d_2 = 2B_2 d_2 b_2 v_2, \qquad .(9)$$

or

$$\varphi_2 = \frac{2\pi}{N_2} B_2 v_2 r_{a2}^2 \left(1 - \frac{r_c^2}{r_{a2}^2}\right) \qquad .(10)$$

But as $v_2=nv_1$, $b_2$ must equal $b_1/n$. Then, when $r_{a1}=r_{a2}$ ($d_1=d_2$) and $B_1=B_2$ the synchronization potentials of both cascades coincide ($\varphi_1=\varphi_2$). Therefore the dependence between the signal frequencies $v_1$ and $v_2$ and the potentials in both cascades, in the case when extra potential ex is given to the slow-wave structures, can be expressed by:

$$\varphi_1 = k\frac{\varphi + \varphi_{ex}}{B} \text{ and } v_2 = nk\frac{\varphi + \varphi_{ex}}{B} \quad .(11)$$

Here $\varphi + \varphi_{ex}$, B and k are the same for both cascades. Therefore the electron mechanism of the frequency changing in the cascade voltage tunable magnetron frequency multiplier is similar to that in the ordinary VTM: the slow-wave structures in both cascades must have the same potentials.

But the heights of the interaction spaces in both cascades can differ. Then, as follows from (4) and (10), the potentials of synchronization will also be different. And the voltage between slow-wave structures and negative electrode in the input and output cascades will not be equal to each other. In spite of this difference the change in the frequency can be carried out by synchronic tuning of the two voltages. This makes the control of the device much more simple. As was mentioned above, device of this type can operate in two regimes: 1) as a harmonics generator, when it multiplies the frequency of the signal generated by itself; 2) as an amplifier of the harmonics of the input signal. In the last case the input signal is amplified in the input cascade and its working n-th harmonic - in the output cascade. Therefore such frequency multiplier - amplifiers must have a power transformation coefficient (gain)

$$K = \frac{P_{out}(n\omega)}{P_{in}(\omega)} \quad .(12)$$

much bigger than 1. If the frequency multiplier operates in the regime of multiplication and amplification of the external signal, it is necessary to suppress its own generation. Besides, the change of the frequency of the input signals makes it necessary to change synchronically the potential of the slow-wave structures. This technical problem can be solved easily. Thus both of the above-mentioned working regimes are important and practically used [6]. In addition the signals from both cascades are often applied: generated or amplified in the input cascade external signal of the frequency (and amplified signal of the n-th harmonic.

Another prospective type of microwave frequency multipliers are relativistic microwave devices gyrotron and peniotron [7, 8] using principles of the cyclotron resonance maser. But for their operation it is necessary an extremely powerful electron gun forming relativistic electron beam and very high values of magnetic flux density. In the case of generation of the fundamental harmonic the relationship between frequency to be generated (and magnetic flux density B is (v in GHz)=28 (in T). Therefore the milimetric signal generation requires of applying superconductive magnets. Fortunately, in the regime of generation of the higher harmonics it is possible to reduce some the magnetic flux density. The theoretical calculations show that in the case when magnetron type cavity in the peniotron is used it is possible to get values of orbital efficiency 65 % for the third harmonic and 35 % for the 7-th. Experimental values of the total efficiency in the devices of this type usually do not exceed 50 %.

## EXPERIMENTAL CHARACTERISTICS

Fig. 4 illustrates the experimental amplitudinal characteristics of the two-cascade VTM frequency multiplier with coefficient of multiplication n=4. The input cascade oscillation system

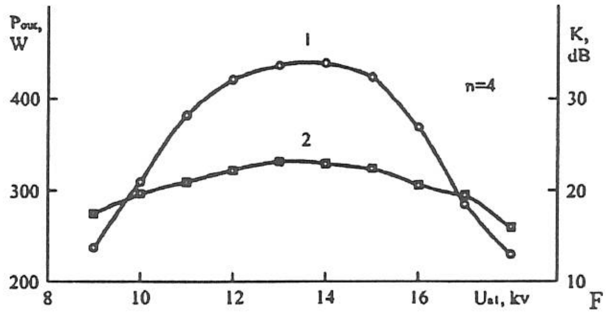


*Fig. 4.* Output signal power (curve 1) and gain (curve 2) versus slow-wave structure voltage of the input cascade.

(interdigital line with quasitoroidal resonator) is tuned to the average wavelength of 40 cm and has four fingers in its interdigital slow-wave structure. This cascade can operate both in the regime of generation and amplification of external signal. The output cascade has the same structure but its oscillation system is tuned to the average wavelength of 10 cm and operates in the regime of amplification of the 4-th harmonic constantly. In this device the idea of the stepped heights of the interaction space in the cascades [4] was applied. The ratio of the heights of the interaction space of the output and input cascades was chosen, in accord with the nonlinear theory of the multipliers [5], optimal and equal 1.33. Thus, the voltages in both cascades were different and changed synchronically. Therefore dependences of output power (curve 1) and gain (curve 2) on the voltage of the first cascade slow-wave structure Ua1 also indicate the dependences of these parameters on $Ua_2$. The characteristic $P_{out} = f(U_{a1})$ was measured when multiplier worked in the regime of frequency multiplication of the signal generated in the input cascade. The maximal output power equals 430 W. In comparison with this multiplier, the VTM using the same oscillation system as in the output cascade of the multiplier, generates maximal power of 500 W. The frequency band (see fig.

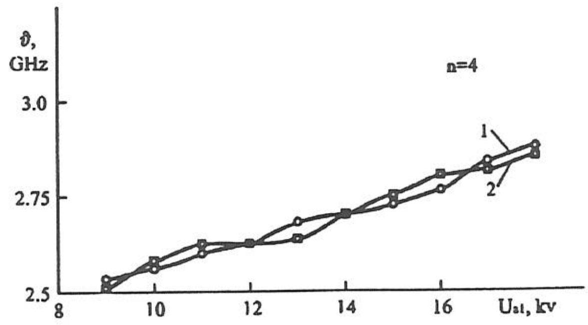


*Fig. 5.* Frequency characteristic of the multiplier in the regime of generation of the 4-th harmonic (curve 1) and amplification of the 4-th harmonic of the input signal (curve 2).

5) on the level of 3 dB is 15 % (generator has 17 %). The top electronic efficiency - 52 % (generator - 70 %).

When multiplier amplifies the 4-th harmonic of the input signal it has maximal gain 23 dB. The characteristics in the fig. 4 are restricted from the side of low voltages by deterioration of electrons-wave synchronism and from the side of large voltages - by the decrease of the interaction impedance of the slow-wave structure.

Fig. 5 represents frequency characteristics of the multiplier. The curve 1 illustrates the dependence of the output signal frequency on the voltage of the first cascade slow-wave structure in the regime of oscillation in this cascade and curve 2 - amplification of the 4-th harmonic of the input signal. Deviation from the straight line in both cases do not exceed 5 % which is characteristic to the powerful VTM and is in a good agreement with the dependence predicted by equation (11). In the regime of amplification of the input signal harmonic, frequency characteristic (curve 2) is more waving because of complementary reflections in the input cascade.

## CONCLUSIONS

1. For widening the frequency band and improvement the main output parameters of the powerful microwave crossed-field frequency multipliers it is necessary to join the idea of cascading and the principles of the voltage tunable magnetron.

2. It is shown both theoretically and experimentally that in cascade VTM frequency multipliers there exists linear frequency dependence on voltage of the slow-wave structure. The deviation from the straight line do not exceed 5 %.

3. The multiplier can operate as a harmonic generator or as an amplifier of the n-th harmonic of input signal. Experimental devices worked on the 4-th harmonic and had output signal in the 10 cm wavelength range.

4. The maximal output signal power is 430 W at the frequency band 15 %. The top efficiency is 52 %, maximal gain 23 dB. The similar data were obtained only in relativistic microwave devices but they have much more complicated structure and feeding.

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BRIEF NEWS

# MOTOROLA ANNOUNCES FIRST CONNECTIVITY TO THE INTERNET

The first two-way messaging application that allows users to navigate the Internet has been unveiled by Motorola's Advanced Messaging Group. Its Tango two-way high-speed wireless messaging device can originate queries and receive information from the World Wide Web - including business news, airline flight details, weather and sports scores.

Motorola linked the Tango to the Web by using a Web server, Skytel's 2-Way Service - based on Motorola's ReFLEX two-way paging transport protocol and simple programming logic to compress the amount of data returned to the Tango. The tools to build this and other types of applications already exist, and can be developed into commercial products.

The company's Messaging Systems Products Group, in cooperation with the Personal Communications Industry Association is now making available the TDP (Telocator Data Paging) suite of protocols free of charge to wireless application developers on the World Wide Web. The TDP protocol suite allows wireless product users to send files, pictures and two-way messages over one- and two-way paging networks.