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BROADBAND TRAVELING WAVE TUBE FOR MOBILE COMBINED DIGITAL TROPOSCATTER-RADIORELAY STATION

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ШИРОКОСМУГОВА ЛАМПА БІЖНОЇ ХВИЛІ ДЛЯ МОБІЛЬНОЇ, КОМБІНОВАНОЇ ЦИФРОВОЇ ТРОПОСФЕРНОЇ РАДІОРЕЛЕЙНОЇ СТАНЦІЇ

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Abstract. The article proposes the use of a traveling wave tube (TWT) as an amplifying device of a microwave transmitter for a mobile combined digital troposcatter-radiorelay station (MCDTrRRS). Such a telecommunication system has two separate components - a troposcatter and a radio relay, but a common frequency-shaping system, a control and diagnostic system, and also can have a single microwave transmitter. The radio relay component can operate in various allowed frequency bands, for example in the range 7.9...8.4 GHz. The troposcatter component operates only in the range 4.4...5 GHz. the single microwave transmitter in this case must have a gain band of 4.4...8.4 GHz or operate in the above two frequency bands. The traveling wave tube can operate in this frequency broadband with an output power of more than 1.5 kW without self-excitation on the reverse wave. Therefore, the presence of the TWT makes it possible to realize a single microwave transmitter for the two components of the MCDTrRRS. The entire microwave transmission path is built on a partially filled of dielectric rectangular waveguide (PFDRW). Thus, an increase in the diameter of the helix of TWT at a length equal to 50 ... 60% of the total length of the helix and the introduction of an absorber from the metamaterial significantly improved the output parameters of the instrument over a wide frequency range 4.4 ... 8.4 GHz without self-excitation on the backward wave. It should be noted that the slow wave structure in the form of a helix has a strong structural connection and good alignment with the coaxial-PFDRW-junction (CPFDRW-junction). The coaxial waveguide has a direct connection of the center conductor to the helix. The use of the own function method allowed us to take into account the electromagnetic field in the opening of the coaxial waveguide and obtain the expressions for the CPFDRW-junction in an explicit form. An increase in the broadband of a traveling wave tube is achieved by applying input and output rectangular waveguides partially filled of dielectric, with a simultaneous change in the helix pitch. This solution allows not only to increase the broadband of the traveling wave tube, but also its electrical strength. Such a construction of a traveling wave tube can find application in microwave *radio systems, including telecommunication ones, which operate in several frequency bands as it shown on MCDTrRRS example.*

Keywords. *a traveling wave tube; partially filled of dielectric rectangular waveguide; coaxial waveguide; CPFDRW-junction; broadband.*

Анотація. *У статті запропоновано застосування лампи біжучої хвилі (ЛБХ) як підсилювального пристрою НВЧ передавача мобільної комбінованої цифрової тропосферно-радіорелейної станції (МКЦТрРРС). Така телекомунікаційна система має дві окремі компоненти - тропосферну і радіорелейну, але загальну систему частотоформування, систему управління і діагностики, а також може мати єдиний передавач СВЧ.*

Радіорелейна компонента може працювати в різних дозволених частотних діапазонах, наприклад, в діапазоні 7,9...8,4 ГГц. Тропосферна компонента працює в діапазоні 4,4...5 ГГц. Єдиний передавач НВЧ в цьому випадку повинен мати смугу в 4,4...8,4 ГГц. Робота лампи біжучої хвилі можлива в такій широкій смузі частот з вихідною потужністю понад 1,5 кВт без самозбудження на зворотній хвилі. Тому, використання ЛБХ дозволяє реалізувати єдиний НВЧ передавач для двох компонент МКЦТрРРС. При цьому весь передавальний тракт станції побудований на частково заповненому діелектриком прямокутному хвилеводі (ЧЗДПВ). За рахунок збільшення діаметра спіралі сповільнюючої системи ЛБХ на довжині, що дорівнює 50...60% загальної довжини спіралі, і введенням поглинача з метаматеріалу вдалося істотно покращити вихідні параметри приладу в зазначеному широкому діапазоні частот без самозбудження на зворотній хвилі. Узгодження ЧЗДПВ зі сповільнюючою системою у вигляді спіралі здійснюється через коаксіальний - ЧЗДПВ перехід (КЧЗДПВ-перехід). В цьому випадку коаксіальний хвилевід має пряме з'єднання центрального провідника зі спіраллю. Застосування методу власних функцій в даній роботі дозволило врахувати електромагнітне поле в розкриві коаксіального хвилеводу і отримати вирази для КЧЗДПВ-переходу в явному вигляді. Таким чином в роботі збільшення широкосмуговості лампи біжучої хвилі досягається шляхом застосування вхідного і вихідного прямокутних хвилеводів, частково заповнених діелектриком, з одночасною зміною кроку спіралі. Таке рішення дозволяє не тільки збільшити широкосмуговість лампи біжучої хвилі, але і її електричну міцність. Така конструкція лампи біжучої хвилі може знайти застосування в радіотехнічних системах НВЧ діапазону, включаючи телекомунікаційні, які функціонують в декількох діапазонах частот як це показано на прикладі МКЦТрРРС

Ключові слова. *лампа біжної хвилі; прямокутний хвилевід; частково заповнений діелектриком, коаксіальний хвилевід; з'єднання CPFDRW; широкосмуговий.*

1 INTRODUCTION

The patent [1] proposed a new type of mobile digital telecommunications microwave system - a mobile combined digital troposcatter-radiorelay station (MCDTrRRS). Such a system has two components - a troposcatter and a radio relay, but a common frequency-shaping system, a control and diagnostic system, and also can have a single microwave transmitter. Since the radio relay component can operate in various allowed frequency bands, for example in the range 7.9...8.4 GHz, and the troposcatter component operates in the range 4.4...5 GHz, then the single microwave transmitter in this case must have a gain band of 4.4...8.4 GHz or operate in the above two frequency bands. To provide communication range on the troposcatter interval of more than 200 km with a probability of erroneous reception of $BER = 10^{-6}$ with a capacity of ≥ 2 Mbit/s, the transmitter output power should be more than 1.5 kW. Naturally, such an output power is not required by a radio relay component and less than 10 W can branch off from a single transmitter. In this case, the radio relay component will allow to transmit STM-1 level signals and Ethernet signals at a speed of 100 Mbit / s for a range of 40...50 km, depending on the height of the antenna support. It should be noted that in the transmitting path of the MCDTrRRS, the solution found in [2] is applied, when the entire microwave transmission path is built on a partially filled of dielectric rectangular waveguide (PFDRW). Therefore, the aim of the work is to show the possibility of using as amplifying device a single microwave transmitter MCDTrRRS, the transmission path of which is built on the PFDRW, a traveling wave tube (TWT) operating in the 4.4...8.4 GHz band with an output power of more than 1.5 kW without self-excitation on the reverse wave.

2 GENERAL DESCRIPTION OF A WIDE BAND TRAVELING WAVE TUBE WITHOUT SELF-EXCITATION ON THE REVERSE WAVE

2.1 The modern features of broadband solid-state microwave amplifiers

The current stage in the development of microwave transmitting devices is characterized by the replacement of microwave electric vacuum devices with solid-state microwave amplifiers. For example, Advantech Wireless developed for the troposcatter communication systems in the range of 4.4...5.0 GHz a GaN power amplifier with an output power $P_{out} = 350/400/500\ \text{W}$, which provides high linearity in this range. However, this linearity of the SapphireBlu™ SSPA/SSPB Super Compact TT Series amplifiers in the 4.4 to 8.4 GHz band can not yet provide. The design of the output stages of the microwave transmitter is even more complicated if P_{out} should be more than 1.5 kW. The use of eight amplifiers of this series in accordance with the scheme of 8×400 W makes it possible to obtain $P_{out} \sim 2{,}5$ kW, but at the same time we have an efficiency of less than 20%, and we also do not maintain linearity requirements. The review of the source [3] as one of the leaders in the field of solid-state microwave amplifiers makes it possible to draw the following conclusions:

– In the C and X ranges, kilowatt capacities (up to 6 kW) are achieved, but not in a wide frequency band.
– Achieving such parameters and characteristics required the use of expensive materials.
– High power is achieved by summing the output power of several amplifiers located on pallets.

Hence the low efficiency of these amplifiers and the inability to achieve high linearity over a wide frequency band (4.4...8.4 GHz).

Another world leader – Sumitomo Company has a wide range of power amplifiers created using GaN technology and power amplifiers MMIC based on GaAs technology. The company owns the technology for the creation of GaN HEMT Pallet Amplifiers. The output power of GaN HEMT in the 8 GHz band reaches 100 W. More information can be found in the materials [4].

2.2 The modern features of broadband TWT

Broadband TWT have been studied in papers [5-11]. A feature of these papers is that the helix was used as a slow wave structure in broadband TWT. In our study uses a waveguide of complex transverse shape – a partially filled of dielectric rectangular waveguide (PFDRW). Various applications of waveguides of complex transverse shape for input and output of energy in TWT are known. In [12-14] TWT is investigated with some waveguides of complex transverse shape, and in [15] – with a planar helix slow-wave structure.

2.3 Application of broadband TWT for modern telecommunication systems

As it was shown, MCDTrRRS operates in a wide frequency band 4.4...8.4 GHz, and the transmission of digital signals via tropospheric communication channels with a speed ≥ 2 Mbit/s requires high linearity of the amplifiers of microwave transmitters. The analysis shows that it is not possible to provide high linearity in such a broad band as 4.4...8.4 GHz with an output power of more than 1.5 kW by a solid-state amplifier to date, as the authors know. If you want to transfer information at a speed of, for example, 8 Mbit/s and even in such a wide bandwidth, the requirements for linearity of the amplifier is significantly tightened. Therefore, the authors propose to use as the microwave transmitter for the MCDTrRRS the amplifier on broadband TWT without self-excitation on the backward wave.

The general approach to the solution of the problem formulated in the goal of the paper is based on the results of [16, 17].

2.4 Elimination of self-excitation by the backward wave in TWT

The risks of self-excitation by the backward wave is increase in broadband TWT. It is known that self-excitation on the backward wave can arise in a TWT with a helix as a type of slow wave structure is due to a decrease in the velocity of the electron beam. This is a result of interaction with the electromagnetic wave. Helix as a slow wave structure has the greatest wideband and from the point of view of mechanical effects it has advantages over other kinds of slow wave structure, which is important for mobile communication complexes. The presence of a helix helps to reduce the cost of TWT, which at an output power of more than 1.5 kW have a cost below the cost of a solid-state microwave amplifier on GaN with equal bandwidth. The broadband TWT with the helix has a better linearity of the amplitude characteristic compared to a solid-state microwave amplifier on GaN with an output power of more than 1.5 kW.

Eliminate self-excitation on the backward wave by changing the diameter of the passageway along the length of the interaction space. For this purpose, the diameter of the part of the helix that is under the absorbers increases by 1.15 times, and the absorber is a plate of metamaterial. The helix is set in such a way that modulation of the velocity of the electrons succeeds in the initial part of the helix. In fact, the enlarged part of the helix is under the central part of the absorber. The extreme parts of the helix are 1.45 times elongated, which increases the length of the interaction space.

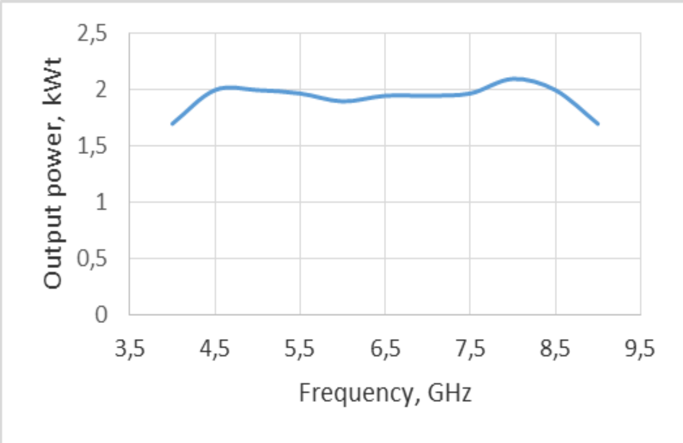

Figure 1 – Dependence of output power on frequency

To reduce the jump in the phase velocities at the junctions of the parts of the helix with different diameters, the pitch of the helix changes. In this case, not only the close values of the deceleration factor are obtained, but the reflection coefficient from the shock also decreases. The starting self-excitation current on the backward wave increases not only in saturation mode, but also in the entire thirty decibel range of input power variation. The focusing of the electron beam is realized with the aid of a solenoid with a current creating a uniform longitudinal constant magnetic field along the axis of the helix. The dependence of output power on frequency is shown in Figure 1. The working parameters are i = 1,25A and the voltage on the decelerating system U_0 = 8 kV. The output power at the level of 2 kW is achieved practically in the entire frequency range 4.4...8.4 GHz.

At the same time, the efficiency of the device studied was 44% in the same frequency range (Figure 2).

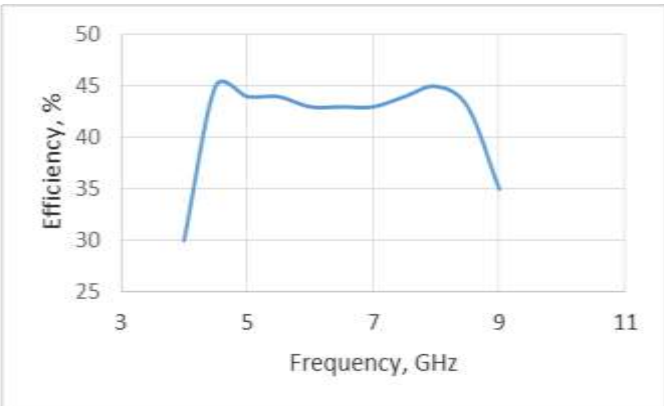

Figure 2 – Dependence of efficiency on frequency

In Figure 3 shows the dependence of the gain on frequency. With these operating parameters, the TWT was resistant to self-excitation on the backward wave.

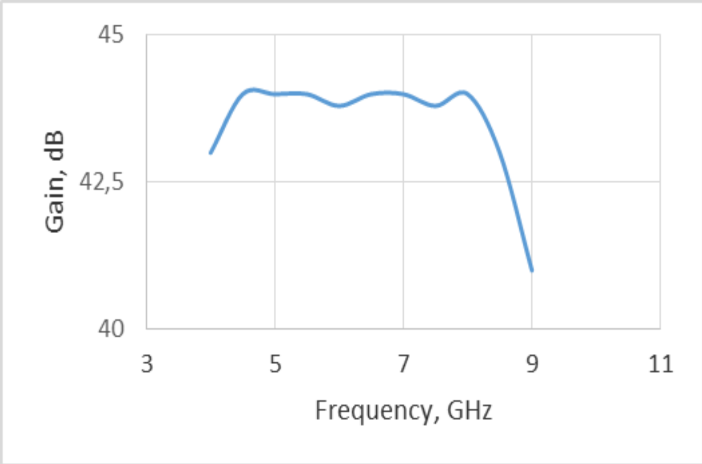

Figure 3 – Dependence of the gain on frequency

In order to increase the broadband of devices of input and output energy is suggest to use PFDRW.

3 ELECTRODYNAMIC ANALYSIS OF THE COAXIAL-PFDRW-JUNCTION ON THE INPUT AND OUTPUT OF TRAVELING WAVE TUBE

It is known that in order to improve broadband matching at the input and output, waveguide transformers are often used, for example, as a piece of a rectangular waveguide with a smoothly decreasing size of a narrow wall. With the same purpose in the TWT, the helix pitch at its ends increases smoothly.

The coordination of the PFDRW with the decelerating system in the form of a helix is realized through a coaxial-to-moderated junction. In this case, the coaxial waveguide will have a direct connection of the center conductor to the helix. Here, the most difficult for electrodynamic analysis is the coaxial-PFDRW-junction (CPFDRW-junction).

The rectangular waveguide contains a dielectric also of rectangular cross section, not touching the walls of the waveguide. The junction in the general case can be asymmetric. The equivalent circuit of the CPFDRW-junction contains an ideal transformer with a transformation coefficient n_0 and a reactance jX, which takes into account the response of local fields arising at the junction of the PFDRW with the wave impedance Z_W and the coaxial waveguide with the Z_T wave resistance [2]. The values entered have the following expressions:

$$Z_W = 120\pi k_0 / \gamma_{h10}; \qquad Z_T = 60\ln(R_2 / R_1),$$

where k_0 – the wave number, γ_{h10} – the propagation constant of the quasi-H_{10} wave PFDRW, R_2, R_1 – the outer and inner radii of the coaxial waveguide, respectively.

The transformation coefficient has the following form:

$$n_0 = \int_S \bar{\varepsilon}_{h10} \bar{\varepsilon}_T ds,$$

where:

– $\bar{\varepsilon}_{h10}$ – the transverse electric own function of the PFDRW for the main wave [2];

– $\bar{\varepsilon}_T = \left(1\big/\sqrt{2\pi \ln\left(R_2/R_1\right)}\right)\left(\bar{r}^0/r\right)$ – eigenvector function of a coaxial waveguide.

The reactance X can be represented in the form:

$$X = \frac{1}{2}\sum_{k=1}^{\infty} n_k^2 Z_k,$$

$$n_k = \int_S \bar{\varepsilon}_{h10}\bar{\varepsilon}_k ds,$$

where:

– $\bar{\varepsilon}_k$ – own function of the coaxial waveguide for higher types of waves;

– Z_k – characteristic impedances of higher types of waves of a coaxial waveguide;

– k – index of summation over non-propagating waves.

In the special case, if the coaxial waveguide is a coaxial transmission line with a thin internal conductor $\left(k_0 R_1 \le 0.25\right)$, then the expression for n_0 is as follows:

$$\begin{gathered} n_0 = -\int_0^l \left[I(l)/I_0\right]\bar{\varepsilon}_{h10}\bar{l}^0 dl, \\ \int_0^l \left[I(l)/I_0\right] dl = l_e, \end{gathered} \tag{1}$$

where:

– l_e – the effective height of the conductor;

– $I(l)$ – the current in the conductor;

– I_0 – the initial current at the base of the conductor.

For example, if the current distribution in the conductor is uniform, $l_e = l$, and for a linear current distribution in the conductor, $l_e = l/2$, where l – the height of the inner conductor of the coaxial transmission line in the PFDRW.

If the conductor is introduced through a wide wall of the PFDRW, then $\bar{l}^0 = \bar{y}^0$ and expression (1) takes the form:

$$\begin{gathered} n_0 = \sqrt{128\big/ab\left(64 + q^2 + p^2 + q^2p^2\right)}\Big/\left(1\big/\chi_{h10}\right)\times \\ \times\left\{\left(\pi/a\right)\sin\left(\pi x_0/a\right) - \left(p\pi/2a\right)\sin\left(\pi x_0/a\right)\cdot\cos\left(2\pi l/b\right) - \left(3q\pi/8a\right)\sin\left(3\pi x_0/a\right) + \right. \\ \left. +\left(3qp\pi/16a\right)\sin\left(3\pi x_0/a\right)\cos\left(2\pi l/b\right)\right\} l_e, \end{gathered}$$

where:

– $a,\ b$ – the wide and narrow walls of the PFDRW;

– $q,\ p$ – parameters that depend on the dielectric filling of the waveguide;

– χ_{h10} – the transverse wave number of the main wave;

– x_0 – the distance from the narrow wall of the waveguide to the conductor.

The input resistance of the CPFDRW-junction from the side of the coaxial waveguide (the PFDRW is matched on both sides) has the following form:

$$Z_{in} = \left(n_0^2/2\right) Z_W + jX. \tag{2}$$

Then the reflection coefficient has the form:

$$S_{11} = (Z_{in} - Z_T)/(Z_{in} + Z_T). \tag{3}$$

The calculation of the reflection coefficient S_{11} from the considered junction by formula (2) with sufficient accuracy for practice can be performed without taking into account local fields in the case when the condition $k_0 R_2 << 1$ is satisfied. In this case, the extent of the "near" zone is much smaller than the wavelength λ and therefore $X \approx 0$. If this condition is not met, then the extension of the "near" zone grows and it is necessary to take into account the waveguide waves of the coaxial waveguide. For this, it is necessary to substitute (2) in (3).

Figure 4 shows the equivalent circuit of the junction, when PFDRW one side shorted. This equivalent circuit also takes into account the effect of the coaxial waveguide hole. It is assumed that the local field to attenuate the short end walls [18].

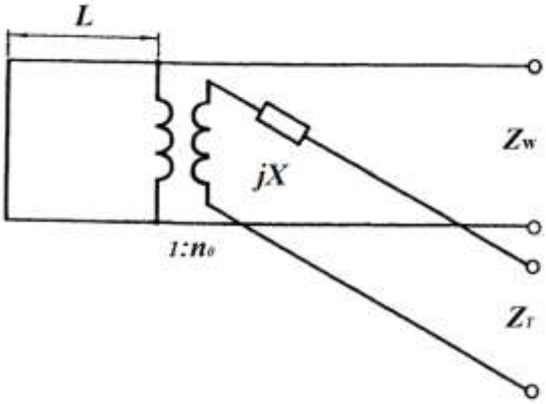

Figure 4 – Equivalent circuit of a CPFDRW-junction with a short-circuited waveguide section

The input impedance of such a junction from the side of the coaxial waveguide (PFDRW matched on one side) has the following form:

$$Z_{in} = n_0^2 Z_W \sin^2\theta + j\left[\left(n_0^2/2\right) Z_W \sin 2\theta + X\right], \tag{4}$$

where $\theta = \gamma_{h10} L$, L – the length of the short-circuited segment of the PFDRW. For the equivalent circuit under consideration, the coaxial waveguide is aligned with the PFDRW, if $n_0^2 Z_W \sin^2\theta = Z_T, \left(n_0^2/2\right) Z_W \sin 2\theta + X = 0.$

The technique of integration in determining the transformation coefficient is the representation of the transverse electric eigenvector function of the fundamental PFDRW wave, expressed in Mathieu functions, through their trigonometric series. In determining the transformation coefficients, the Bessel functions of the first and second kinds and their derivatives appearing in the transverse electric vector own functions of the coaxial waveguide for higher types of waves were expressed in terms of the power series in which the first six terms were retained. For example, the power series of the Bessel functions of the first and second kind of the zeroth order was limited to the term containing the argument to the tenth power [19].

Numerically investigated actively $\tilde{r}$ and reactive $\tilde{x}$ the input impedances of the CPFDRW-junction, the equivalent circuit of which is shown in Figure 4. Expression (4) is represented as follows:

$$Z_{in} X = R + jX.$$

In Figure 5 shows the dependencies $\tilde{r} = R / Z_T$ and $\tilde{x} = X / Z_T$ of the value of χ_{h10}/k_0 :

– Curve 1 is constructed for $\tilde{r}$ at $L = a/4$.

– Curve 2 is constructed for $\tilde{x}$ at $L = a/4$;

– Curve 3 is constructed for $\tilde{x}$ at $L = a/3$.

The remaining parameters of the CPFDRW-junction are the following: $\varepsilon_r = 4$, $c/a = 0.1$, $d/b = 0.8$, $x_0/a = 0.5$, $R_1/a = 0.05$, $l/b = 0.8$. It should be noted that accounting for higher types of waves depends on the ratio R_2/R_1.

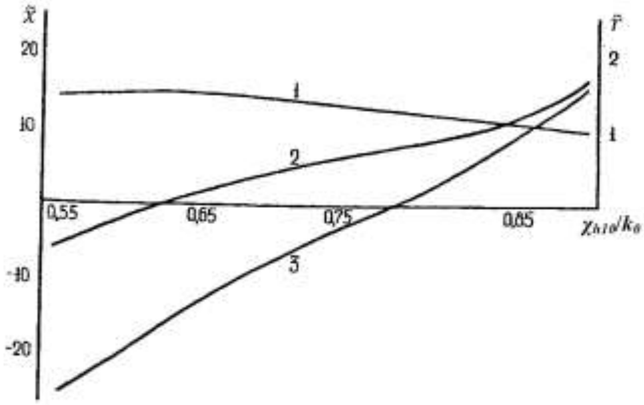

Figure 5 – Equivalent circuit of a CPFDRW-junction with a short-circuited waveguide section

Analysis of the obtained dependences shows that, firstly, the active input resistance $\tilde{r}$ weakly depends on the wavelength, which can be the basis for the design of broadband junction, and secondly, in the lower part of the operating band, the PFDRW reactive input impedances $\hat{x}$ little differ from each other, which facilitates the provision of stable alignment for various variations in the parameters of the PFDRW.

CONCLUSION

Thus, an increase in the diameter of the helix of TWT at a length equal to 50 ... 60% of the total length of the helix and the introduction of an absorber from the metamaterial significantly improved the output parameters of the instrument over a wide frequency range 4.4 ... 8.4 GHz without self-excitation on the backward wave. In combination with a sufficiently high operating current i = 1,25A, such a combination of "techniques" made it possible to have high values of output power, efficiency, gain in a wide frequency range 4.4...8.4 GHz, while not having the highest value U_0. Despite the high output power, focusing with a solenoid made it possible to create a high uniformity of the electron beam, which helped to reduce the noise level at the output of the TWT.

The presence of such a TWT makes it possible to realize a single microwave transmitter for the two components of the MCDTrRRS and, at the same time, to create the entire transmitting path to the PFDRW. It should be noted that the slow wave structure in the form of a helix has a strong structural connection and good alignment with the CPFDRW-junction. The use of the own function method allowed us to take into account the electromagnetic field in the opening of the coaxial waveguide and obtain the expressions for the CPFDRW-junction in an explicit form.

REFERENCES

[1] V.M. Pochernyaev and V.S. Povhlib, “Mobile digital troposcatter-radiorelay station”, UA 112217 C2, 10.08.2016, No 15.

[2] V.N. Pochernyaev, Devices on partially filled of dielectric waveguides, Kiev:UKNIPSK, 2000, 222 p.

[3] "Products of Advantech Wireless", Available at: http://www.advantechwireless.com/all-products/ (accessed 21 March 2018)

[4] "Products: Electron Devices", Available at: https://www.sedi.co.jp/products/wireless/ (accessed 21 March 2018).

[5] Patrick Y. Wong, Y.Y. Lau, David Chernin, Brad W. Hoff and Ronald M. Gilgenbach, "Origin of Second-Harmonic Signals in Octave Bandwidth Traveling-Wave Tubes", IEEE Transactions on Electron Devices, Volume: 65, Issue: 2, pp. 710-715, Feb. 2018, DOI: 10.1109/TED.2017.2785284.

[6] Y.D. Joo, A.K. Sunha and G.S. Park, "Helix traveling wave tube performance optimization through circuit tapering", The 30th International Conference on Plasma Science, June 2003 [ICOPS 2003. IEEE Conference Record – Abstracts], DOI: 10.1109/PLASMA.2003.1228635.

[7] H.S. Kim, H.S. Uhm and G.S. Park, "Manufacturing and measurement of heavily-loaded helix traveling wave tube", The 30th International Conference on Plasma Science, June 2003 [ICOPS 2003. IEEE Conference Record –Abstracts], DOI: 10.1109/PLASMA.2003.1228633.

[8] H.S. Kim, H.S. Uhm and S.W. Baek, "Thermal and structural analysis on output coupler of helix-TWT", The 30th International Conference on Plasma Science, June 2003 [ICOPS 2003. IEEE Conference Record – Abstracts], DOI: 10.1109/PLASMA.2003.1228632.

[9] Chong Gao and En Li, "The study of the TWT nonlinear parameters test system", IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP), July 2016, DOI: 10.1109/IMWS-AMP.2016.7588447.

[10] P.D. Shalaev and D.L. Simonov, "Results of experimental researches high electronic efficiency Helix TWT in a two-frequency operating mode", International Conference on Actual Problems of Electron Devices Engineering, Sept. 2010, DOI: 10.1109/APEDE.2010.5624041.

[11] Qiru Lu, Weifeng Peng, Bo Chen, Yanjun Cui, Jing Feng and Jinjun Feng, "Thermal analysis of slow wave structures for a high power Ka-band helix TWT", IEEE International Vacuum Electronics Conference (IVEC), April 2015, DOI: 10.1109/IVEC.2015.7223981.

[12] Yan Hou, Jin Xu, Shaomeng Wang, Lingna Yue, Zhigang Lu, Yanyu Wei and Yubin Gong, "A novel H-plane loaded folded waveguide slow wave structure for traveling wave tube", 6th UK, Europe, China Millimeter Waves and THz Technology Workshop (UCMMT), Sept. 2013, DOI: 10.1109/UCMMT.2013.6641535.

[13] Vishal Kesari, "Analysis of Alternate Dielectric and Metal Vane Loaded Circular Waveguide for a Wideband Gyro-TWT", IEEE Transactions on Electron Devices, Volume: 61, Issue: 3, pp. 915-920, March 2014, DOI: 10.1109/TED.2014.2301273.

[14] Simhadri Uma Maheswara Reddy, Subrata Kumar Datta, P. Raja Ramana Rao, P.K. Jain and Lalit Kumar, "Analysis of dispersion and interaction impedance for vane-loaded coaxial waveguide structure", IEEE International Vacuum Electronics Conference (IVEC), May 2010, DOI: 10.1109/IVELEC.2010.5503397.

[15] Cier Siang Chua, Chen Zhao and Sheel Aditya, "Design and Fabrication of a Planar Helix Slow-Wave Structure for C/X-Band TWT", IEEE Transactions on Components, Packaging and Manufacturing Technology, Volume: 7, Issue: 10, pp. 1663-1669, Oct. 2017, DOI: 10.1109/TCPMT.2017.2692303.

[16] L.A. Weinstein and V.A. Solntsev, Lectures of microwave electronics, M: Sov. Radio, 1973, 400 p.

[17] L. Clampitt, Powerful electrovacuum microwave devices, M: Mir, 1974, pp. 9-32, pp. 33-69.

[18] Mashkovtsev B.M., Tsibizov K.N. and Emelin B.F., Theory of waveguides, M: Nauka, 1966, 351 p.

[19] Pochernyaev V. N. Integrals from products of Bessel functions for applied problems of electrodynamics, Ukrainian Mathematical Journal, vol. 4, 1995, 566-570 pp.