ISSN 0735-2727, Radioelectronics and Communications Systems, 2018, Vol. 61, No. 7, pp. 283–291. © Allerton Press, Inc., 2018.
Original Russian Text © D.M. Vavriv, V.D. Naumenko, V.O. Markov, 2018, published in Izvestiya Vysshikh Uchebnykh Zavedenii, Radioelektronika, 2018, Vol. 61, No. 7, pp. 371–382.

Spatial-Harmonic Magnetrons with Cold Secondary-Emission Cathode: State-of-the-Art (Review)

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Received in final form December 18, 2017

Abstract—Spatial-harmonic magnetrons with cold secondary-emission cathode are efficient high-power sources throughout the millimeter wavelength band. In this paper, resent advances in design, modeling, and fabrication of such magnetrons are described. Low-voltage magnetrons, sub-THz tubes, and magnetrons with metamaterial anode structure are described to illustrate these advances. The issue of the lifetime of the magnetrons with a cold secondary-emission cathode is also addressed. The main problems related with the usage of an auxiliary cathode in such tubes are considered and alternative solutions are discussed. Potentials for further improving the performance of spatial-harmonic magnetrons are analyzed as well.

DOI: 10.3103/S0735272718070014

1. INTRODUCTION

The spatial-harmonic magnetron (SHM) is a tube, which utilizes a spatial harmonic of the RF field of a non π-mode (usually the π/2-mode or a neighboring one) for its operation, as opposed to conventional magnetrons utilizing the principal harmonic of the π-mode. As we know, the results of the first experimental studies of the SHM have been published in [1]. Commercial versions of such type of magnetrons were developed and produced in the former Soviet Union [2, 3]. Both, SHMs with cold secondary-emission cathode [2, 3] and SHMs with thermal cathode [4, 5] have been proposed and produced.

In this paper we consider SHMs with cold secondary-emission cathode, which have appeared to be a most effective alternative to conventional magnetrons in the millimeter-wavelength band. For example, the solutions introduced into such magnetrons have allowed developing high power sources for the frequencies up to 210 GHz [6]. These tubes are characterized by a rather high level of both peak and average power, and by an extended lifetime.

During recent years the study and the development of SHMs have been continued to realize further their potential as well as to meet new practical requirements. In this regard, it is worth mentioning the development of low-voltage magnetrons [7], sub-THz tubes [6], and SHMs with a metamaterial anode structure [8]. We review these advantages and analyze other developments and challenges in this research field.

In the next section the design of the SHM and characteristics of practical mm-wavelength tubes are briefly described. Low-voltage SHMs are reviewed in Section 3. In Section 4 a sub-THz magnetron operating at a frequency of 210 GHz is described. Section 5 is devoted to recently developed magnetrons with metamaterial anode structure solutions. In Section 6 possibilities for further increasing the lifetime of SHMs are discussed. Section 7 summarizes the main results of the paper.

2. SHM DESIGN, SIMULATION, AND CHARACTERISTICS

A schematic of a SHM with cold secondary-emission cathode is shown in Fig. 1. The main magnetron elements include an anode with resonators *1*, a cold secondary-emission cathode *2*, an auxiliary thermionic cathode *3*, and DC magnet (not shown in Fig. 1). Typically, slot-type anode resonators without straps are used in SHMs. An example of the application of more complicated anode resonators is described in Section 5.

REFERENCES

1. R. D. Robertshaw, W. E. Willshaw, *Proc. IEE*, *Monograph*, No. 168 R, 103, Pt. B (1956).
2. I. M. Vigdorchik, V. D. Naumenko, and V. P. Timofeev, “The secondary-emission cold cathode pulse magnetrons of the millimeter wavelength,” *DAN USSR*, *Ser. A*, No. 7, 633 (1975).
3. V. D. Naumenko, A. N. Suvorov, A. Sirov, “Tunable magnetron of a two-millimeter-wavelength band,” *Microw. Opt. Technol. Lett.* **12**, No. 3, 129 (1996). DOI: 10.1002/(SICI)1098-2760(19960620)12:3%3C129::AID-MOP3%3E3.0.CO;2-J.
4. A. A. Gurko, “Estimation of opportunity of boosting the efficiency of millimetre-wave magnetron using non π-mode,” *Radio Physics and Radio Astronomy* **5**, No. 1, 80 (2000).
5. S. V. Gritsaenko, V. D. Eremka, M. A. Kopot, O. P. Kulagin, V. D. Naumenko, and A. N. Suvorov, “Vacuum and solid-state electronics. Multiresonator magnetrons with cold secondary-emisson cathode: Achevements, problems, perspectives,” *Radiofiz. Elektron.* **10**, 499 (2005).
6. N. I. Avtomonov, V. D. Naumenko, D. M. Vavriv, Klaus Schunemann, A. N. Suvorov, V. A. Markov, “Toward terahertz magnetrons: 210-GHz spatial-harmonic magnetron with cold cathode,” *IEEE Trans. Electron Devices* **59**, No. 12, 3608 (2012). DOI: 10.1109/TED.2012.2217974.
7. V. D. Naumenko, A. N. Suvorov, V. A. Markov, N. I. Avtomonov, V. D. Yeryomka, M. A. Korol’, O. P. Kulagin, Jung-Il Kim, “Development of Ka-range magnetron for portable radar,” *Proc. of 20th Int. Crimean Conf. on Microwave & Telecommunication Technology*, CriMiCo’2010, 13-17 Sept. 2010, Sevastopol, Crimea, Ukraine (IEEE, 2010), pp. 305-307. DOI: 10.1109/CRMICO.2010.5632848.
8. N. N. Esfahani, Klaus Schunemann, N. I. Avtomonov, D. M. Vavriv, “Epsilon near zero loaded magnetrons, design and realization,” *Proc. of 45th European Microwave Conf.*, 7-10 Sept. 2015, Paris, France (IEEE, 2015), pp. 454-457. DOI: 10.1109/EuMC.2015.7345798.
9. S. V. Sosnytskiy, D. M. Vavriv, “Theory of the spatial-harmonic magnetron: an equivalent network approach,” *IEEE Trans. Plasma Sci.* **30**, No. 3, 984 (2002). DOI: 10.1109/TPS.2002.801616.

10. K. Schunemann, S. V. Sosnytskiy, D. M. Vavriv, "Self-consistent simulation of the spatial-harmonic magnetron with cold secondary-emission cathode," *IEEE Trans. Electron. Devices* **48**, No. 5, 993 (2001). DOI: 10.1109/16.918248.
11. K. Schunemann, A. E. Serebryannikov, S. V. Sosnytskiy, D. M. Vavriv, "Optimizing the spatial-harmonic millimeter-wave magnetron," *Phys. Plasmas* **10**, No. 6, 2559 (2003). DOI: 10.1063/1.1565337.
12. V. D. Naumenko, K. Schunemann, D. M. Vavriv, "Miniature 1 kW, 95 GHz magnetrons," *Electron. Lett.* **35**, No. 22, 1960 (1999). DOI: 10.1049/el:19991337.
13. K. Schuenemann, B. V. Trush, D. M. Vavriv, V. A. Volkov, "Magnetron transmitters for millimeter-wave coherent radar systems," *Radio Physics and Radio Astronomy* **4**, No. 4, 357 (1999).
14. P. H. Siegel, "Terahertz technology," *IEEE Trans. Microwave Theory Tech.* **50**, No. 3, 910 (2002). DOI: 10.1109/22.989974.
15. D. Dragoman, M. Dragoman, "Terahertz fields and applications," *Proc. Quantum Electron*. **28**, No. 1, 1 (2004). DOI: 10.1016/S0079-6727(03)00058-2.
16. Y. Dong, T. Itoh, "Promising future of metamaterials," *IEEE Microwave Mag*. **13**, No. 2, 39 (2012). DOI: 10.1109/MMM.2011.2181447.
17. G. V. Eleftheriades, "Metamaterials: The first ten years," *IEEE Microwave Mag.* **13**, No. 2, 8 (2012). DOI: 10.1109/MMM.2011.2181602.
18. A. E. Moiseenko, V. D. Naumenko, A. N. Suvorov, A. R. Syrov, "Long life 3 mm pulse magnetron," *Radio Physics and Radio Astronomy* **8**, No. 4, 421 (2003).
19. N. I. Avtomonov, S. V. Sosnytskiy, D. M. Vavriv, "Investigation and optimization of auxiliary cathode for secondary emission cold-cathode magnetrons," *Radio Physics and Radio Astronomy* **12**, No. 3, 320 (2007).
20. M. F. Kopylov, "Design and technology features of heating-free magnetrons with autoemission excitation," *J. Vacuum Sci. Technol. B: Microelectron. Nanometer Structures Processing*, *Measurement*, *and Phenomena* **11**, No. 2, 481 (1993). DOI: 10.1116/1.586845.
21. V. D. Naumenko, S. A. Cherenshchikov, "Investigation of the start-up of a magnetron with a cold secondary-emission cathode of the decay side of the voltage pulse," *Radiophys. Quantum Electron.* **27**, No. 2, 168 (1984). DOI: 10.1007/BF01035126.
22. N. I. Avtomonov, D. M. Vavriv, S. V. Sosnytsky, "Theoretical study of cold start of magnetrons with secondary emission cathode," *Radioelectron. Commun. Syst.* **53**, No. 1, 1 (2010). DOI: 10.3103/S0735272710010012.
23. A. V. Soin, "Excitation of microwave oscillation in magnetron with cold secondary-emission cathode by injecting a microwave signal," *Radio Physics and Radio Astronomy* **8**, No. 3, 333 (2003).