ТЕХНІЧНІ НАУКИ

УДК 537.868

Olenyuk O. A.
Candidate of Technical Sciences, Senior Lecturer at the Department of Technical Service and General Technical Subjects,
Higher educational institution "Podillia State University"
Kamianets-Podilskyi, Ukraine
***E-mail:** alexander.olenyuk@gmail.com*
***ORCID:** 0000-0003-1463-076X*

Semenyshena R. V.
Candidate of Pedagogical Sciences, Associate Professor,
Senior Lecturer at the Department of Technical Service and General Technical Subjects,
Higher educational institution "Podillia State University"
Kamianets-Podilskyi, Ukraine
***E-mail:** alexrusl@ukr.net*
***ORCID:** 0000-0002-2969-3635*

EVALUATION OF EXISTING MILLIMETER-WAVE RADIATION SYSTEMS FOR PRE-SOWING SEED TREATMENT

Abstract

This paper explores the evaluation and potential development of millimeter-wave (MMW) radiation systems intended for pre-sowing seed treatment in agricultural technologies. The study emphasizes the importance of using low-energy electromagnetic fields to enhance crop yields through informational influence on biological systems. A detailed analysis of existing radiation sources highlights the limitations of traditional vacuum electronic devices, such as backward wave oscillators, traveling wave tubes, and klystrons, which suffer from excessive size, high power consumption, low frequency stability, and complex cooling systems. As an alternative, the authors propose the use of semiconductor devices, particularly avalanche-transit time (IMPATT) diodes, which demonstrate advantages in terms of frequency stability, output power, size, efficiency, and manufacturability. The research focuses on the selection and optimization of resonator systems and antenna designs capable of generating effective electromagnetic radiation for continuous-flow seed processing systems. Among various antenna types, waveguide-slot and surface wave antennas were analyzed and found to be suboptimal due to their narrow operational bandwidth and structural limitations. In contrast, horn antennas, especially H-sectoral horns, are identified as the most suitable emitters for seed treatment applications, owing to their broader bandwidth, better matching characteristics, and ability to form a directed radiation pattern with linear polarization. The paper concludes that further theoretical and experimental investigations are needed to develop high-frequency-stable MMW generators with output power levels of 2–3 W and to model the biotropic effects of electromagnetic fields based on the electrophysical properties of seeds. These findings contribute to the design of innovative, energy-efficient, and ecologically safe technologies aimed at increasing agricultural productivity through the application of modern physical principles in seed treatment processes.

***Key words:** electromagnetic technology, radiation, antennas, generators, oscillations.*

Introduction. A current and highly relevant challenge in modern agricultural science and engineering is the development of innovative technologies that are not only economically viable and energy-efficient but also environmentally sustainable. These technologies are expected to significantly contribute to increasing crop yields without causing harm to ecosystems or introducing excessive energy consumption into production processes. One promising approach to solving this problem lies in the implementation of low-energy, or so-called informational, millimeter-wave (MMW) electromagnetic fields (EMF).

DOI: https://doi.org/10.37406/2706-9052-2025-2.26

Unlike traditional high-energy treatments, informational EMFs exert their influence not through the transfer of substantial energy but by interacting with the informational regulatory systems of living organisms. In agricultural applications, this interaction is realized through exposure to electromagnetic radiation at specific frequencies and modulation-time parameters, which are capable of initiating or enhancing certain physiological processes in biological objects, including seeds. The effectiveness of such exposure is not determined by the intensity or energy level of the radiation itself, but rather by the precise alignment of the electromagnetic signal's parameters with the natural frequencies and rhythms of the biological system.

This method is particularly advantageous for pre-sowing seed treatment, where minimal energy consumption can still lead to measurable improvements in germination rates, resistance to stress factors, and overall productivity of the resulting crops. However, achieving the desired biological outcomes requires an exact match between the EMF's biotropic parameters – such as frequency, power flux density, exposure duration, and modulation characteristics – and the sensitivity thresholds of the treated seeds.

Therefore, the realization of such a technology necessitates the use of highly frequency-stable electromagnetic generators, capable of maintaining strict spectral purity and minimal fluctuation. These performance characteristics are essential to ensure reproducibility, reliability, and biological efficacy in field conditions, where even slight deviations in the signal may render the treatment ineffective or inconsistent.

Analysis of recent research and publications. An analysis of commercially produced MMW generators based on parameters such as frequency instability, output frequency setting error, and tuning range has shown that they are unsuitable for biomagnetology applications [1–2].

Generators manufactured in Russia and Lithuania can operate in the frequency range of 20–80 GHz but demonstrate high relative output frequency instability (10^{-3} to 10^{-4}), low signal monochromaticity, and low output power (4–5 mW).

Foreign-made generators have lower frequency instability (10^{-5}), but also low output power (up to 5 mW).

Currently, to generate and amplify electromagnetic oscillations in the MMW wavelength range, vacuum electronic devices such as BWO (Backward Wave Oscillators), TWT (Traveling Wave Tubes), klynotrons, klystrons, and magnetrons are used [3–9].

The analysis shows that vacuum electronic devices have significant drawbacks: large volume and weight, high-voltage power supplies, liquid and air-cooling systems, and frequency instability within 10^{-3}.

An analysis of modern semiconductor technologies indicates that in the MMW range, semiconductor generators based on IMPATT (Impact Avalanche Transit-Time) diodes are widely used. These generators surpass vacuum devices in most electrical (low voltages and currents) and operational parameters (dimensions, weight, reliability) [8; 9].

The power generated by IMPATT diodes ranges from 500 to 2000 mW in the frequency range from 30 to 300 GHz [10].

The performance characteristics of IMPATT-based generators (output power, frequency, efficiency, tuning range, frequency stability, spectral quality), as well as their operation mode, depend not only on the diode parameters but also on the type of resonant system used [9].

In the MMW range, waveguide resonators are the most widely used, as their quality factor is higher compared to coaxial and stripline resonators. In practice, waveguide-pin and radial-waveguide resonators are commonly used. The output power of generators with radial-waveguide structures can range from 250 to 630 mW in the frequency range from 50 GHz to 80 GHz with an efficiency of 10% and frequency tuning of 10–15% [9].

To achieve power levels of 2000–3000 mW in the frequency range of 50–300 GHz in an IMPATT generator, it is necessary to use the method of power combining into a single load, which should be implemented using electrodynamic quasi-optical systems.

Objective. One of the key components of a system for pre-sowing seed treatment is an electromagnetic energy emitter, which must form the required radiation pattern and ensure a sufficient level of power flux density on the grain as it moves along the conveyor belt.

Research methodology. Currently, various types of antennas are widely used in the MMW wavelength range, including waveguide-slot antennas, surface wave antennas, horn antennas, and others [10].

Waveguide-slot antennas, Waveguide-slot antennas, which are formed by cutting a series of precisely positioned slots into the body of a waveguide system, represent a class of linear, multi-element antenna structures widely used in high-frequency electromagnetic applications. These antennas are capable of forming a directive radiation pattern (RP), particularly narrowing it in the plane that coincides with the axis of the waveguide, thus making them suitable for applications where controlled beam directionality is essential.

Depending on the spatial configuration and electrical characteristics of the slots, waveguide-slot antennas can be classified into three main types: resonant, non-resonant, and matched-slot antennas. In resonant designs, the distance between adjacent slots (denoted as *d*) corresponds to the guided wavelength within the waveguide (λ_e), resulting in constructive interference and efficient radiation at specific frequencies. In non-resonant antennas, the slot spacing is deliberately chosen to be less than half the guided wavelength ($d < \lambda_e/2$) or less than half the free-space wavelength ($d < \lambda/2$), allowing for broader operational bandwidth and altered radiation characteristics. Matched-slot antennas, by contrast, employ specialized matching elements – such as reactive vibrators or diaphragms—at each slot to achieve individual impedance matching with the waveguide, thereby improving transmission efficiency and minimizing reflection losses.

From a geometric standpoint, the typical slot length in these systems is approximately half the free-space wavelength (λ/2), while the slot width is relatively narrow, usually falling within the range of 0.05λ to 0.1λ. However, when operating in the millimeter-wave region—particularly at wavelengths below 7 mm – several practical difficulties arise. One of the key limitations is the miniaturized physical scale required for waveguide components at such short wavelengths. For instance, the cross-sectional dimensions of a standard single-mode rectangular waveguide at these frequencies are in the order of 3.6 mm by 1.8 mm, necessitating extremely precise fabrication and alignment techniques.

Moreover, one of the inherent drawbacks of waveguide-slot antennas lies in their relatively narrow operational bandwidth. Since the radiation pattern of such antennas is highly sensitive to frequency variations, any deviation – especially those resulting from the use of microwave sources lacking adequate frequency stabilization – can lead to significant detuning. This detuning manifests as a shift in the main lobe of the radiation pattern away from the intended direction, changes in beamwidth, and a mismatch with the feeding waveguide. Such effects degrade the performance of the antenna and reduce its efficiency and reliability in practical applications, particularly in systems requiring consistent and focused energy delivery, such as electromagnetic seed treatment technologies.

Thus, considering the aforementioned structural and functional limitations, the use of waveguide-slot antennas for irradiating vegetable seeds in pre-sowing treatment systems is deemed impractical. Their narrow bandwidth, high sensitivity to frequency instability, and complex design requirements make them unsuitable for applications that demand high reliability, precision, and ease of integration into compact electromagnetic treatment setups.

Let us now turn our attention to surface wave antennas, which represent another class of radiating systems. These antennas are characterized by the propagation of electromagnetic waves with a phase velocity (*Vf*) that is lower than the speed of light in a vacuum (*C*), i.e., $Vf < C$. This reduced phase velocity is achieved through the use of specialized slowing structures, which modify the wave propagation characteristics to enable more compact antenna designs and, in some cases, improved directivity.

One of the defining features of surface waves with $Vf < C$ is the exponential attenuation of the electromagnetic field as the distance from the slowing structure increases. In other words, the energy becomes increasingly concentrated near the surface, and the field strength rapidly diminishes with lateral displacement. This phenomenon permits the construction of antennas with small transverse dimensions, which is advantageous in systems with limited spatial capacity.

Flat slowing structures typically fall into two main categories: comb-like metallic structures and thin dielectric layers mounted on conductive substrates. When using comb-type structures as slowing systems, strict design conditions must be satisfied to ensure optimal performance. Specifically, the structural period *D* must be less than or equal to 0.1λ, and the groove depth *h* must not exceed λ/4, where λ denotes the free-space wavelength. These constraints imply extremely fine geometrical tolerances when designing antennas for the 4-millimeter wavelength range, which not only complicates the manufacturing process but also significantly increases the production cost.

In addition to fabrication challenges, the successful implementation of surface wave antennas requires precise excitation of the slowing structure, avoiding the generation of higher-order propagation modes and minimizing signal reflection. Even minor imperfections in excitation or structural uniformity can degrade the antenna's performance. Furthermore, surface wave antennas generally exhibit relatively low gain compared to other antenna types and suffer from elevated sidelobe levels, which can lead to unwanted radiation leakage and reduced efficiency. Taking into account these disadvantages, the use of surface wave antennas in systems for seed irradiation is not considered rational or technically justified.

The third category of antennas considered in this context is the horn antenna. Unlike the previously discussed types, horn antennas are broadband devices capable of supporting a relatively wide frequency range – often up to 1.5 times their central operating frequency. This broadband characteristic is particularly valuable in systems requiring stable performance across varying frequencies or in cases where precise frequency stabilization of the source is difficult to maintain. Additionally, horn antennas are structurally simple and cost-effective to manufacture, making them attractive for both laboratory and industrial applications.

In essence, a horn antenna operates as a wave transformer. It gradually transitions the electromagnetic wave propagating through a feeding waveguide into a broader, more planar wavefront as it emerges from the aperture. This transformation increases the effective radiating area and reduces beam divergence. Simultaneously, the progressive change in wave impedance along the horn's length ensures efficient impedance matching between the waveguide and free space, thereby minimizing reflection losses and maximizing forward-directed energy transmission.

Horn antennas are commonly categorized into conical, pyramidal, and sectoral types. Conical horns utilize circular waveguides and are based on the dominant TE_{11} mode. However, they are prone to certain disadvantages, such as unstable polarization planes due to sensitivity to minor deformations in the waveguide walls and non-uniform field polarization across the aperture. These issues limit their applicability in systems requiring consistent linear polarization and uniform energy distribution.

Moreover, the radiation pattern of conical horns tends to be axially symmetric, which does not align well with the directional requirements of seed treatment systems. In such systems, the electromagnetic field must be linearly polarized, and the radiation pattern should be significantly narrower in the direction of seed motion along the conveyor belt, while remaining broader in the perpendicular direction to cover the seed row uniformly.

Given these considerations, our attention shifts to pyramidal and sectoral horn antennas. Both types are constructed using rectangular waveguide structures and can be designed to produce linearly polarized fields with tailored radiation patterns. These antennas provide the directional control, polarization stability, and bandwidth required for effective and consistent electromagnetic treatment of vegetable seeds in pre-sowing applications.

Results. Since antennas of the first type are typically used to obtain a narrow radiation pattern (RP) in two mutually perpendicular planes by increasing the transverse dimensions of the horn aperture, the most suitable option for seed irradiation appears to be sectoral horn radiators. In general, a horn is called *sectoral* if only one dimension of the rectangular waveguide's cross-section increases, while the other remains unchanged. Accordingly, two types are distinguished:

− the H-sectoral horn, which expands in the plane of the H-vector of the dominant TE_{10} wave;
− the E-sectoral horn, which expands in the plane of the E-vector.

Since the reflection coefficient of the TE_{10} wave at the junction between the waveguide and the H-sectoral horn is lower than that for the E-sectoral horn, the radiator with expansion in the H-plane should be considered for continuous-flow pre-sowing seed treatment [10].

Conclusions and Prospects. To determine the biotropic parameters of millimeter-wave electromagnetic fields (frequency, power flux density, exposure) that contribute to increasing root crop yields, theoretical studies are required. These should focus on a biocybernetic model of the seed, taking into account its electrophysical parameters and the informational-resonant effect of EMF on the membrane potential of seed cells.

Furthermore, to develop an electromagnetic technology for pre-sowing seed treatment in continuous flow, it is necessary to research and design an H-sectoral horn antenna and a high-frequency-stable (10^{-7} to 10^{-9}) millimeter-wave generator with an output power of 2–3 W.

References

1. Bereka, O.M. (2011). Obrobka nasinnja sil's'kogospodars'kyh kul'tur v syl'nomu elektrychnomu poli. [Treatment of Agricultural Crop Seeds in a Strong Electric Field]. Kyi'v: CP "KOMPRYNT". 335 s. [in Ukrainian].

2. Il'i'nov, M.D., Gurs'kyj, T.G., Borysov, I.V., & Grycenok, K.M. (2018). Linii' radiozv'jazku ta antenni prystroi': navchal'nyj posibnyk. [Radio Communication Lines and Antenna Devices: A Textbook]. Kyi'v: VITI. 250 s. [in Ukrainian].

3. Olenjuk, O.A., & Tkach, O.V. (2020). Doslidzhennja vplyvu elektromagnitnogo polja KVCh diapazonu na peredposivnu obrobku nasinnja. [Study of the Influence of Millimeter-Wave Electromagnetic Field on Pre-sowing Seed Treatment]. *Podil's'kyj visnyk: sil's'ke gospodarstvo, tehnika, ekonomika,* 32, 125–130 [in Ukrainian].

4. Potapov, V.O., & Zhyla, V.I. (2024). Teoretychni ta praktychni aspekty zastosuvannja mikrohvyl'ovogo j infrachervonogo vyprominjuvannja v harchovyh tehnologijah: monografija. [Theoretical and Practical Aspects of the Application of Microwave and Infrared Radiation in Food Technologies: A Monograph]. Harkiv: DBTU. 136 s. [in Ukrainian].

5. Romanenko, O.I., & Chervins'kyj, L.S. (2015) Elektrofizychni metody peredposivnoi' obrobky nasinnja. [Electrophysical Methods of Pre-sowing Seed Treatment]. *Naukovyj visnyk NUBiP Ukrai'ny*. Kyi'v: VC NUBiP Ukrai'ny. 283 p. [in Ukrainian].

6. Savchenko, V., Synjavs'kyj, O., & Ivashhuk, V. (2018). Zmina energii' aktyvacii' pislja magnitnogo polja pry peredposivnij obrobci nasinnja. [Change in Activation Energy after Magnetic Field Exposure during Pre-sowing Seed Treatment]. *Energetyka ta avtomatyka,* 3, 106–112 [in Ukrainian].

7. Sova, O.Ja., & Panchenko, I.V. (2018). Linii' radiozv'jazku ta antenni prystroi': navchal'nyj posibnyk. [Radio Communication Lines and Antenna Devices: A Textbook]. Kyi'v: VITI. 250 s. [in Ukrainian].

8. Chervins'kyj, L.S., & Pashkovs'ka, N.I. (2019). Peredposivna stymuljacija ozymoi' pshenyci optychnym vyprominjuvannjam. [Pre-sowing Stimulation of Winter Wheat with Optical Radiation]. *Naukovyj visnyk TDATU*. Vyp. 9, T. 1. 13–19 [in Ukrainian].

9. Shysh, S.M., Shutova G.G., Mazec' Zh.E., Fatyhova S.A., & Shabunja P.S. (2019). Vplyv peredposivnoi' obrobky na sklad olii' chornushky posivnoi'. [Influence of Pre-sowing Treatment on the Oil Composition of Black Cumin (Nigella sativa)]. *Fiziologija roslyn i genetyka.* 2019. T. 51, № 2. S. 161–171 [in Ukrainian].

10. Ling, B., & Wang, S. (2024). Microwave Disinfestations of Postharvest Agricultural Products. Food Engineering Series. Cham. S. 515–528 [in English].

Оленюк О. А.
кандидат технічних наук, асистенти кафедра ремонту машин та енергообладнання,
Заклад вищої освіти «Подільський державний університет»
Кам'янець-Подільський, Україна
E-mail: *alexander.olenyuk@gmail.com*
ORCID: *0000-0003-1463-076X*

Семенишена Р. В.
кандидат педагогічних наук, доцент,
доцент кафедри технічного сервісу і загальнотехнічних дисциплін,
Заклад вищої освіти «Подільський державний університет»
Кам'янець-Подільський, Україна
E-mail: *alexrusl@ukr.net*
ORCID: *0000-0002-2969-3635*

ОЦІНЮВАННЯ НАЯВНИХ СИСТЕМ МІЛІМЕТРОВОГО ВИПРОМІНЮВАННЯ ДЛЯ ПЕРЕДПОСІВНОЇ ОБРОБКИ НАСІННЯ

Анотація

У статті розглядається оцінювання та перспективи розвитку систем міліметрового (ММХ) випромінювання, призначених для передпосівної обробки насіння в аграрних технологіях. У дослідженні акцентується увага на важливості використання низькоенергетичних електромагнітних полів для підвищення врожайності за рахунок інформаційного впливу на біологічні системи. Детальний аналіз наявних джерел випромінювання виявив обмеження традиційних вакуумних електронних пристроїв, таких як генератори зворотної хвилі, лампи біжучої хвилі та клістрони, які мають надмірні розміри, високе енергоспоживання, низьку стабільність частоти й складні системи охолодження. Як альтернативу автори пропонують використання напівпровідникових пристроїв, зокрема діодів лавинного-пролітного типу (IMPATT), які мають переваги за такими параметрами, як стабільність частоти, вихідна потужність, розміри, ефективність і технологічність виробництва. У дослідженні зосереджено увагу на виборі й оптимізації резонаторних систем і конструкцій антен, здатних генерувати ефективне електромагнітне випромінювання для систем обробки насіння в безперервному потоці. Серед різних типів антен проаналізовані щілинні хвилеводні та поверхневохвильові антени, які виявилися недостатньо ефективними через вузьку робочу смугу частот і конструктивні обмеження. Натомість рупорні антени, особливо Н-секторальні, визначено як найпридатніші випромінювачі для обробки насіння завдяки їх широкій смузі частот, кращим погоджувальним характеристикам і здатності формувати спрямовану діаграму випромінювання з лінійною поляризацією. Зроблено висновок про необхідність подальших теоретичних та експериментальних досліджень для створення високостабільних ММХ-генераторів із вихідною потужністю 2–3 Вт і моделювання біотропної дії електромагнітних полів на основі електрофізичних властивостей насіння. Отримані результати сприяють розробленню інноваційних, енергоефективних та екологічно безпечних технологій, спрямованих на підвищення продуктивності сільського господарства шляхом застосування сучасних фізичних принципів у процесах обробки насіння.

Ключові слова: *електромагнітна технологія, випромінювання, антени, генератори, коливання.*

Bibliography

1. Берека О.М. Обробка насіння сільськогосподарських культур в сильному електричному полі. Київ : ЦП «КОМПРИНТ», 2011. 335 с.
2. Лінії радіозв'язку та антенні пристрої : навчальний посібник / М.Д. Ільїнов та інші. Київ : ВІТІ, 2018. 250 с.
3. Оленюк О.А., Ткач О.В. Дослідження впливу електромагнітного поля КВЧ діапазону на передпосівну обробку насіння. *Подільський вісник: сільське господарство, техніка, економіка.* 2020. Вип. 32. С. 125–130.
4. Потапов В.О., Жила В.І. Теоретичні та практичні аспекти застосування мікрохвильового й інфрачервоного випромінювання в харчових технологіях : монографія. Харків : ДБТУ, 2024. 136 с.
5. Романенко О.І., Червінський Л.С. Електрофізичні методи передпосівної обробки насіння. *Науковий вісник НУБіП України.* Київ : ВЦ НУБіП України, 2013. Вип. 184. Ч. 1. 283 с.
6. Савченко В., Синявський О., Іващук В. Зміна енергії активації після магнітного поля при передпосівній обробці насіння. *Енергетика та автоматика.* 2018. № 3. С. 106–112.
7. Сова О.Я., Панченко І.В. Лінії радіозв'язку та антенні пристрої : навчальний посібник. Київ : ВІТІ, 2018. 250 с.
8. Червінський Л.С., Пашковська Н.І. Передпосівна стимуляція озимої пшениці оптичним випромінюванням. *Науковий вісник ТДАТУ.* 2019. Вип. 9. Т. 1. С. 13–19.
9. Шиш С.М., Шутова Г.Г., Мазець Ж.Е., Фатихова С.А., Шабуня П.С. Вплив передпосівної обробки на склад олії чорнушки посівної. *Фізіологія рослин і генетика.* 2019. Т. 51, № 2. С. 161–171.
10. Ling B., Wang S. Microwave Disinfestations of Postharvest Agricultural Products. Food Engineering Series. Cham, 2024. p. 515–528.