Magnetron Based Radar Systems for Millimeter Wavelength Band – Modern Approaches and Prospects

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In honor of my mother, Ninel.

1. Introduction

Historically magnetrons were one of the first devices used to build radar systems. Namely, successful development and utilization of the magnetrons in radars had assisted essentially Allies to win battle for air and see during World War II (Brown, 1999). And definitely they were the first devices, which have allowed developing the radars operating within millimeter wavelengths region. It had happened due to these microwave sources are characterized by a number of advantages. They are rather simple in production. The magnetrons provide both high peak and average power at relatively low operational voltages as well a fair frequency potential. Because of the above advances, the magnetron remains the most utilized type of microwave vacuum tubes until now. Namelly, by virtue of the utilization magnetrons in ovens, millions people over whole world have learned the word "microwave"!

However by the middle of 60th magnetron based radar systems had ceased to meet increasing performance requirements and their development had been curtailed. They had moved considerably to a niche of simple, low cost radars for great demand applications like that for marine navigation. It had happened due to both fundamental peculiarities of the magnetron operation and issues concerning their manufacturing. At first, the magnetron is an oscillator providing no modulation capabilities except the simplest case of pulse modulation. It results in difficulties to introduce advanced signal processing into the magnetron based radars. Next, uncertainty in the conceptual ability of the magnetron to produce oscillations with appropriate short –term frequency stability; considerable difficulties to develop the corresponding highly stable modulators; as well as an analog implementation of a coherence-on-receiver technique did not allow to fetch an actual potential of magnetron based system out. It resulted in the strong opinion that the magnetrons are generally not suitable to build radar systems with relevant Doppler capabilities. Further, a high spatial resolution of magnetron based systems can be achieved practically only by reducing the duration of radiated RF pulse. However, it leads to the following difficulties: (i) the magnetron is a highly resonant device, which limits a minimal possible pulse duration; and (ii) in order to keep the radar potential, pulse repetition rate should be high enough respectively, which reduces unambiguous radar range or requires utilization of dedicated technique to resolve range ambiguity. Further, the first millimeter wavelengths magnetrons demonstrated a low reliability making the result of their utilization rather discouraging in the most cases. Thus, appearance by the middle of 60th efficient power amplifiers based on both vacuum tubes and solid-state devices and great expectations for a rapid progress in their development as well as the introduction a pulse compression technique had given up the magnetrons for lost to use in the high performance radars.

However, since recent time, magnetrons are considered again as a rather attractive choice to develop systems for millimeter wavelengths band namely. This turn has become possible due to: (i) a lack or low availability of other power devices operating within the indicated frequency range; (ii) a significant improvement in magnetrons characteristics, partially, incredible increase in their lifetime; (iii) a dramatic progress in digital signal processing technique; (iv) achievements in the development of high voltage modulators and millimeter wavelengths technique; and (v) a strong demand for millimeter wavelengths radars from non-military applications, which means a great interest in cost effective solutions.

Despite a rather simple internal structure, the magnetron is characterized by a great complexity of the processes taken place inside it. There is no a more or less comprehensive theory of magnetrons until now. Numerical simulation can be accounted as very superficial. In general we prefer to treat the magnetron as something like a magic box characterized often by unpredictable and even surprising behavior. Thus, generally development of modern magnetron based radar, especially operating within millimeter wavelength region, requires profound understanding of principles of the magnetron operation, a great experience, and the utilization of specific design approaches, at a system level partially. However, often the magnetron is considered as old, well known device and respectively radars based on it are designed in a humble way. It results in a humble performance certainly. Probably, a rather uptight attitude to utilize the magnetrons to build contemporary high performance radars is caused by the above reason.

In this paper we do not try to review comprehensively the current state of affairs or to cover as much as possible wide range of issues concerning the development of both millimeter wavelengths magnetrons and radars based on them. Instead, relying on own experience we draw attention to the fact that some noted disadvantages preventing the magnetron utilization in the high performance radar systems are essentially weakened until now, whereas others can be managed successfully by gaining from the achievements of modern electronics. The corresponding design approaches, which have assisted us to develop successfully a number of contemporary magnetron based radar systems operating within millimeter wavelength band and addressed to different application areas, will be disclosed more or less systematically. We hope that the bellow consideration will be helpful for radar designers to keep always in mind the possibilities providing by good old magnetron!

2. Magnetrons in radars – brief overview

We would not like to discuss here the physical principles of magnetron operation. They can be found in a variety of manuscripts (Okress, 1961;Tsimring, 2007). For us it is important that the magnetron is a vacuum crossed field tube, which is capable to produce high power microwave oscillations with a high efficiency, and hence can be adopted conceptually to use in radar transmitter. As fairly noticed in (Skolnik, 2008), a choice of electronic device for the transmitter end stage defines practically completely radar structure and design approaches. Thus, let us outline the most important peculiarities of the magnetrons as related to their utilization in the radars. At first, the magnetrons are characterized fundamentally by a high both peak and average power. Typical values exceed 100 kW and 100 W for Ka band and 4 kW and 4 W for W and G bands correspondingly. It allows utilizing constant frequency pulse, being the simplest possible among radar signals, while keeping an appropriate radar sensitivity without the usage of a sophisticated signal processing technique. Next, any magnetron is an oscillator rather than an amplifier. It means partially that its output signal depends only on the physical layout of the magnetron internals and the parameters of its circumstance, i.e. applied voltage, a strength of magnetic fields, a value of voltage standing wave ratio at the output flange etc. In addition it is practically impossible to manipulate either parameter of the magnetron output signal independently from the other. Further, the magnetron is characterized by a highly resonant design basically. The magnetron oscillations frequency is essentially defined by electromagnetic properties of its internal layout and can be varied within a wide enough range only by changing a mechanical configuration of such layout, i.e. slowly. All above constrict evidently modulation capabilities providing by the magnetron. Three types of modulation are used in modern radar systems commonly – pulse (as a particular type of amplitude); frequency; and phase modulation respectively. Practically it may be considered that the magnetron by itself provides no ability for a fast, highly reproducible, and well-controlled phase/frequency modulation and adopts only the simplest pulse modulation. Probably only a bandwidth of electrical frequency chirp provided by W and G band magnetrons may appeal to use in the high resolution radars (see Section 0). Notice, since the magnetron output pulse is shaped at a radio frequency directly, it occupies it twice wider frequency band than it is required to ensure a definite spatial resolution.

As for any other oscillator the magnetron oscillation frequency is subjected to fluctuations. According to common approach, fast and slow fluctuations are considered separately and referred as phase noise and frequency stability respectively. Concerning to radar performance the first defines quality of Doppler processing whereas the second is not so important generally except a number of rather special cases. Certainly, the total frequency variation range should not be too big as well as matching between transmitter and receiver frequencies should be ensured ever. Usually the related magnetron performance is characterized as poor and this fact is a byword to utilize such devices in the radars. On other hand the maximum possible variation of magnetron operational frequency including manufacturing tolerances is less than ± 1% over all millimeter wavelength bands in use even for non-tunable devices and cannot be considered as a serious issue. As for the phase noise, which is referred as a pulse-to-pulse frequency instability in the magnetron based systems, reflecting peculiarities of Doppler processor implementation, the following should be mentioned. Prima facie, it seems to be difficult actually expecting a high pulse-to-pulse frequency stability for the magnetrons. Q-factor of the magnetron resonant system is relatively low even for coaxial devices especially within millimeter wavelengths band as well as frequency pushing is rather big due to a high electron density inside an interaction space. Generally, the behavior of electron cloud has a considerable noise component and not

well predictable at all. Initial conditions to produce successive pulses may not coincide resulting in increase in a value of the pulse-to-pulse frequency instability. This effect observed experimentally when even a single pulse altered the state of magnetron cathode surface (private communication with magnetron developers). Probably it is due to a harsh operational conditions featured by a very high peak power dissipated on as well as a high voltage applied to the elements the magnetron comprises of.
On other hand, in general it is not easily to predict even very roughly what ultimate value of pulse-to-pulse frequency stability of the magnetron can be expected for each definite case. Numerical simulation is hardly useful as well as an independent direct measurement of magnetron frequency stability meets also significant difficulties if achievement of a high accuracy is mandatory. It is due to conceptually pulsed operational mode of the magnetron at rather short pulse duration as well as difficulties relating to ensure an extremely precision and reproducible shape of the high voltage pulse across the magnetron. For this reason, as we have found, despite the above seemingly evident factors, the magnetrons demonstrate a rather good performance in Doppler radar systems, certainly if appropriate design approaches are utilized (see Section 0).
All above can be summarized as follows: (i) magnetron based radars operate always in a pulsed mode; (ii) a spatial resolution is determined by the duration of output magnetron pulse resulting in high peak power requirement to keep a radar potential at an appropriate level under a very low duty cycle operational condition; (iii) since each RF pulse is characterized by an arbitrary phase, a special procedure should be introduced in order to provide Doppler processing capability for the radar; and (iv) especial attention should be drawn to provide as much as possible stable magnetron operational conditions in order to achieve relevant Doppler processing performance. As related to the latter two points, it should be noticed that there is a possibility to lock the phase and frequency of magnetron oscillations with highly stable external oscillator. Unfortunately, an extremely low gain provided, i.e. relation between the output peak magnetron power and the required power of locking signal, especially for millimeter wavelengths frequency region prevent the above possibility to be used in practice.
Next, magnetron life time is considered traditionally to be a serious factor limiting its usability in high performance radar systems. It reflects essentially a state of affair existing in the past, when the magnetron demonstrated actually rather low reliability caused essentially by a limited cathode lifetime. It should be noticed that the magnetron cathode operates at very high current densities as compared with other microwave tubes. In addition, the magnetron cathode is exposed strongly to electron back bombardment inherent to cross-field devices (Okress, 1961) as far as it is sited inside an interaction space. On one hand, such effect results in increase in the emission capabilities of cathode greatly due to secondary emission induced. On other hand it causes cathode overheating and affects the condition of cathode surface. It is considered that the cathode dissipates about 10 % of anode power. It means that a peak power may be as high as several kilowatts. It leads to necessity to reduce the magnetron filament power depending on a value of the anode current. The problem is such induced overheating is not well controlled and depends on many parameters.
Ab initio oxide cathodes are used in the magnetrons. Due to above reasons they demonstrated a poor performance especially for millimeter wavelengths devices owing to a fine internal layout inherent to them. Our experience exposed that lifetime of W band magnetron equipped with oxide cathode was as short as several hours only! Next step was

the usage so called impregnated cathodes (Okress, 1961) in the magnetrons. It has allowed increasing in the magnetrons lifetime up to several hundred hours for Ka band devices. However despite magnetrons equipped with such cathode kept its output power and the ability to start oscillating stably within the above period, we experienced a significant frequency drift even for coaxial magnetrons caused by evaporation of the substance, from which the cathode was made of, with further absorption on the surface of magnetron cavity.
Relative failures to manufacture highly reliable magnetrons have coincided with the aforementioned global drop in the interest in the development of magnetron based radars caused by other reasons. On other hand the millimeter wavelengths magnetrons are considered usually as devices for military application exclusively, and for some such applications the achieved life time seems to be more or less suitable. All above have resulted in the development of magnetron and partially investigations in cathode manufacturing have been curtailed worldwide excepting probably the former USSR. The investigations carried over there have given a new lease of life into the development of millimeter wavelengths magnetron and allowed considerable improvement of their characteristics by the end of 80th. It has been achieved due to: (i) utilization of metallic alloy cathodes; (ii) successes in the development of the magnetrons with cold secondary emission cathodes; and (iii) utilization of spatial harmonics different from π type. The latter was especially important for W and G band magnetrons since it has allowed to enlarge dimensions of the magnetron interaction space and the cathode diameter, which results in a considerable increase in peak and average power as well as the maximal pulse duration. In addition, the usage of samarium cobalt magnet system has allowed reducing the magnetron dimensions and weight as well as developing rather miniature devices. The parameters of several millimeter wavelengths magnetrons developed with utilization of above approaches are summarized in Table I.

Frequency band	Ka	Ka	W	G
Peak output power, kW	50	3	4	10
Maximal duty cycle, %	0.2	0.1	0.1	0.085
Anode voltage, V	14000	6300	10000	5
Efficiency	> 33%	> 20%	> 4%	> 5%
Type	Coaxial	No information	Spatial Harmonic	Spatial Harmonic
Type of cathode	Metallic alloy	Cold with spike autoemmiters	Cold with auxiliary thermionic cathode	Metallic alloy (?)
Frequency agility	Yes	No	No	No
Life time, hours Producer specified Reached during utilization Average Maximal	 >2000 >10000 >30000	 >2000	 >1000 >5000 >10000	No information
Cooling	Forced-air	Forced-air	Forced-air	Liquid
Production status	Full production	Full production	Pre production	Full production

Table I. Parameters of millimeter wavelengths magnetrons.

The indicated values for lifetime of Ka band magnetrons have been obtained during the utilization of a line of Ka band meteorological radars (see Section 0), whereas W-band magnetrons were tested in course of a particular procedure. Achieved value of the magnetron lifetime can be qualified literally as outstanding! It should be noticed that above results were absolutely unexpected for us – we considered reaching 4000 hours only in the best case for Ka band magnetrons. There were no selection for Ka band magnetrons – either among them demonstrates similar performance. Why it has become possible? Beside of the above advances in the cathode manufacturing the overall improvement in production technology should Be mentioned, which ensure keeping a high vacuum condition inside the magnetron during whole utilization term. In addition we dare to claim that an advanced design of a magnetron modulator helps significantly the magnetrons exposing its actual potential by automating providing as much as possible safe and optimal operational mode.
Since W band magnetrons in question are manufactured in one of branch of Institute of Radio Astronomy of National Academy of Sciences of Ukraine we would like to describe their development and production in some more detail. The first millimeter wavelengths devices had been developed in the middle of 60^{th} (Usikov, 1972). Ab initio they utilize operation at spatial harmonics different from π type. Such magnetron demonstrates excellent performance e.g. peak output power achieved was 80 kW and 10 kW for 3 mm and 2 mm wavelengths devices correspondingly. However due to L type oxide cathode was used in the magnetrons, their life time was limited by a value of several tens hours only. In order to overcome this problem, a cold secondary emission cathode has been introduced in the magnetron design. An auxiliary thermionic cathode placed aside an interaction space was used to provide an initial electron density in the magnetron and ensure oscillation running at the front of modulation pulse. Despite such magnetrons demonstrates inherently a lower efficiency, they are much more promising to extend their lifetime. As a result W band 1 kW device has been developed and industrialized by the middle of 80^{th} (Naumenko et al, 1999). It characterized by a guaranteed life time of 2000 hours. By the end of 90^{th} essential efforts has been concentrated to develop W band magnetrons with expected life time of several thousand hours at peak power of 4 kW, pulse duration of 200 nsec, and duty cycle of 0.1 % for meteorological radars and, a bit later, 1 kW devices with target life time of 10000 hours for airport debris radar. These efforts have resulted in a stable output of W band magnetrons characterized by peak power within the range from 1000 to 4000 W and expected lifetime of 10000 hours (Gritsaenko et al, 2005). At the time being every third manufactured magnetron satisfies technical specification and there are serious reasons to expect an improvement of this ratio. Such fact can be considered as a serious claim on further industrialization. The following problems have been solved to extend the magnetron life time: (i) optimal design of the auxiliary thermionic cathode; (ii) correct choice of an operational spatial harmonics; and (iii) equipping the magnetron with a magnetic-discharge vacuum pump. The latter increases the magnetron dimension but is mandatory to ensure its long life operation especially at a heavy operational conditions, such as a long pulse width, a large duty cycle, or a high pulse repetition rate (see Section 0). A photo of 4 kW W band magnetron produced in the Institute of Radio Astronomy is depicted in Fig. 1. During resent time a low voltage, compact Ka band magnetrons with cold secondary emission cathode are under

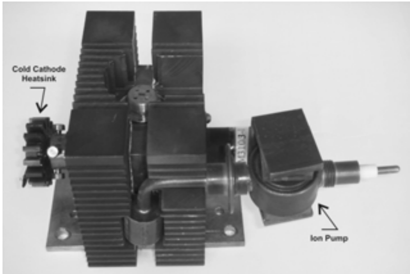


Fig. 1. 4 kW, W band magnetron with cold secondary emission cathode and extended life time.

development. They are intended to be used in low-cost meteorological radar sensors, which are especially convenient for network applications.

Above we have considered the peculiarities of the magnetron utilization in the radars as well as demonstrated that the life time is not an issue preventing magnetrons from usage in high performance radars. Now we would like to discuss further benefits and disadvantages of such approach in a comparative manner. Table II provides a brief comparison between some high power millimeter wavelengths devices available at the time being in respect to their possible usage in the radars. A comprehensive review of current state of the development of power millimeter wavelengths sources can be found in (Barker et al, 2005). Some remarks should be done in addition. As usual the possibility to introduce a sophisticated signal modulation is mentioned as the essential benefit provided by using an amplifier in the radar transmitter. Actually the utilization of a pulse compression technique allows attaining the highest possible resolution for the radars, which is of centimeters grade now. Certainly, the magnetron based radars cannot provide a similar performance level. However for the most applications an extreme resolution is not required and pulse compression is used only to ensure suitable radar sensitivity.

	Magnetron	Traveling wave tube	Klystron with extended interaction	Solid state power amplifier
Peak (average) output power, kW(W) Ka band W band	70 (100)[1] 4 (4)[1]	1 (300) [1] [50 (500)][2] 1 (10) [1] [3 (300)][2]	3 (300)[1] 1.5 (90)[1] [1.5 (150)][2]	0.004 (0.004) (single chip) 0.0002 (0.0002) (single chip)
Type	Oscillator	Amplifier	Amplifier	Amplifier
Resolution achievable	High	Highest	Highest	Highest
Life time	Long	Long	Long	Long
Cost	Low	High	High	Low (single chip)
Mandatory options of signal processing	Coherence on receiver	Pulse compression	Pulse compression	Pulse compression; Power combining
Total system cost at similar specifications	Low/moderate	High	High	Very High

Table II. Parameters of power microwave devices.

[1] Air or conductive cooling
[2] Water cooling

In this case an inherent adverse effect of pulse compression utilization, namely, appearance of spurious targets or, instead, masquerading low RCS targets in presence of that with a strong reflectivity due to side-lobes of the autocorrelation function, should be always taken into consideration. For example, the necessity to monitor simultaneously meteorological phenomena (clouds, precipitation) with a reflectivity range of about 100 dB restricts essentially the application of pulse compression technique for weather radars. Certainly the utilization of such technique providing a relevant performance level requires much more complicated signal processing hardware. Relatively inexpensive implementation of such hardware, suitable to use in mainstream commercial radars, has become to be allowable since very recent time.

Next issue, mentioned usually to accent benefits of truly coherent systems based on utilizing an amplifier in the transmitter, is much higher quality of Doppler processing in this case. However recently developed magnetron based radar systems (see Section 3) demonstrates a competitive Doppler performance within at least Ka band where coaxial magnetrons are available. In addition, further advances in the magnetron modulator design as well as the utilization of a sophisticated digital signal processing allows us to expect over and above improvements in this area, especially for W band radars. The accuracy achieved currently for the phase processing in the magnetron based radars allows us to suggest retrieving appropriate performance even for applications requiring the utilization of synthetic aperture. Interestingly, the approach, based on sampling the radiated signal to provide an enhanced signal processing, inherent to the magnetron based radars, can be useful to improve processing of compressed pulses by avoiding the influence of the distortions introduced by Tx/Rx chains (Zhu, 2008). It is an extra sign that signal processing approaches and, then, capabilities providing by both truly and pseudo coherent radars become closer.

Probably the only area the magnetron based radars cannot compete beyond any doubts with truly coherent systems is radars requiring fast frequency agility.

It should be noticed that despite a low power produced by a single chip, solid state devices allows conceptually developing the most advanced radar systems ever with an unprecedented performance level due to utilization of active phased array technique. Certainly, within millimeter wavelength band such approach is on the technology edge currently and requires enormous efforts to be implemented.

All above mentioned allow us to declare that the achievable performance level of the magnetron based radars is appropriate to meet the most requirements for mainstream applications. Their relatively low cost and complexity make them being very attractive solution especially in the case if the radar system benefits essentially from a shorter wavelengths, as for meteorological applications ($1/\lambda^2$ law for the reflectivity of meteors). Applications where dimensions and weight is among major requirements can be considered also as the area of preferable utilization of the magnetron based radars especially operating within W and G bands.

3. Magnetron based radar systems – development experience

Development of the magnetron based radar systems had started in the Institute of Radio Astronomy of National Academy of Sciences of Ukraine since the middle of 90^{th} of the last century. By the time indicated we experienced with success during many years in the development and manufacturing of millimetre wavelengths magnetrons with cold secondary emission cathode (Gritsaenko et al, 2005). At the same time, it was clear that existing circumstance for the magnetron usage did not meet modern requirements and did not allow disclosing an actual potential of such devices in radar applications. Then considerable efforts were made in order to develop advanced modulators to drive the above magnetrons, which require furthermore a tighter control of modulation pulse shape as compared to traditional types. Such situation has coincided with a growing interest in radars for environmental investigations operating within millimeter wavelength band. In the course of above tendency the first magnetron based radar sensor has been developed and tested by us (Jenett et all, 1999). It was a rather simple Ka and W band double frequency airborne side looking system intended to detect oil spills on water surface. Since this task benefits strongly from the wavelengths shortening, the utilization of magnetrons has allowed developing the radar rapidly by using simple non coherent signal processing. Nevertheless it demonstrated unexpectedly good performance and was capable to detect a rather weak oil spills even under a low waves condition inherent for internal reservoirs. Obtained experience has allowed us to proceed with radar development and, naturally, the next step was the introduction of Doppler processing capabilities in the radar (Schunemann et al, 2000). After the first usage of a traditional analogue coherence-on-receiver technique, its digital implementation has been introduced. Experiments with a prototype of Ka band meteorological radar demonstrated a good Doppler performance, which was appropriate for the most atmospheric researches as well as to monitor atmospheric conditions. In addition, a capability of the magnetron to work continuously during over several thousand hours has been proven. However our first full functional Doppler polarimetric meteorological radar was equipped with two magnetron based transmitters in order to ensure its reliable unattended continuous operation for at least several months interval. The experience of first year utilization of this radar has disclosed a surprisingly high stability of the magnetron operation. It has allowed to lead off developing a line of high performance magnetron based meteorological radars. It includes both vertically pointed and scanning systems with a high mobility as depicted in Fig. 2. Until now

Fig. 2. Ka band magnetron based meteorological radars.

seven radars has been produced and delivered in cooperation with METEK GmbH (Elmshorn, Germany). Some of them are included into European weather radar network.

Coaxial magnetrons are used in the radars (see Table I). Many improvements have been brought into design with every new item including a double frequency conversion in the receiver; a digital automatic frequency control; a digital receiver technique implementation; modifications in receiver protection circuitry; introduction of the circuits ensuring more magnetron operation safety etc. The essential parameters of most resent radars are summarized in Table III.

The quality of Doppler processing provided by such radars is illustrated by Fig. 3 where Doppler spectrum obtained from a stationary target located at the distance of about 5.5 km is depicted. Signal processing parameters were as follows: pulse repetition frequency – 10 kHz; fast Fourier transform length – 512; spectrum averaging – 10 (dwell time - 0.5 sec). As follows from this figure, Doppler dynamical range exceeds 60 dBc, which corresponding to the value of wideband noise floor of -73 dBc/Hz. From this data it is possible to estimate a value of the magnetron pulse-to-pulse frequency instability. Actually, the total power of the received signal can be considered as a sum of coherent P_{coh} and incoherent P_{incoh} components respectively. According to general principles of Doppler processing in radars (Skolnik, 2008), taking into account that the above data are product of a discrete Fourier transform (DFT), and assuming that the magnetron introduces a noise distributed evenly in frequency domain, the ratio between the above components for the signal backscattered by a stationary target, producing definitely monochromatic response, can be set down as:

$$P_{incoh}/P_{coh} = NFl \cdot PRF, \tag{1}$$

where NFl is the noise floor of the radar Doppler processing and PRF is pulse repetition frequency of the radar. On other hand, the phase lag of the signal reflected from a stationary target located at a fixed distance R is $4\pi R/_{\lambda_0 + \Delta\lambda_i}$, where $\Delta\lambda_i$ is the deviation of the wavelengths for i[th] pulse from a constant value of λ_0. Assuming that $\Delta\lambda_i \ll \lambda_0$, the corresponding discrete time complex signal S at the input of DFT may be written as follows:

$$S_i = A \cdot \left((\sin\varphi_0 + \mathrm{i} \cdot \cos\varphi_0) + \varphi_0 \cdot \Delta\lambda_i/_{\lambda_0} \cdot (\sin\varphi_0 - \mathrm{i} \cdot \cos\varphi_0) \right), \tag{2}$$

where $\varphi_0 = 4\pi R/_{\lambda_0}$. The second term in the above equation reflects the entity of incoherent components in the received signal due to the magnetron pulse-to-pulse frequency instability and determines the value of noise floor NFl on

Operating frequency, GHz	35.5±0.15
Peak transmitter power, kW	30
Average power (max), W	50
Losses, dB, Tx path Rx path	1 2.5
Pulse duration, nsec	100, 200, 400
Pulse repetition rate, kHz	5…10
Receiver noise figure, dB	3.0
Radar instantaneous dynamical range including STC, dB	>80
Distance for sensitivity, m at -10 dB at -1 dB	 180 330

Antenna gain	>50 dB
Polarization decoupling	>40 dB
Total impressed composite wideband noise of Doppler processing @ 5 km, dBc/Hz	-70
Number of range bins	500
Volume Transmitter Receiver	 9U 4U
Weight of Tx/Rx units, kg	40

Table III. Parameters of Ka band meteorological radars.

Doppler spectrum assuming that the contribution from other sources like a local oscillator is negligible. Thus finally from formulas (1) and (2), the following expression for the magnetron pulse-to-pulse frequency instability reads as:

(3)

Substitution of variables in (3) with the above values, namely, noise floor of -73 dBc/Hz, PRF of 10 kHz, of 8.2 mm, and R of 5.5 km results in pulse-to-pulse frequency instability of about .

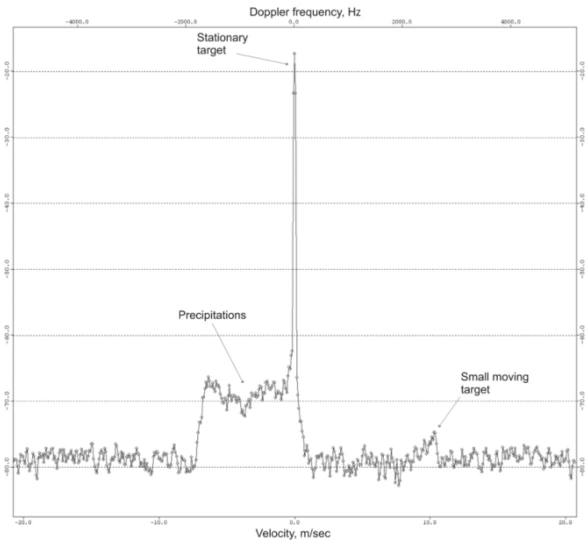
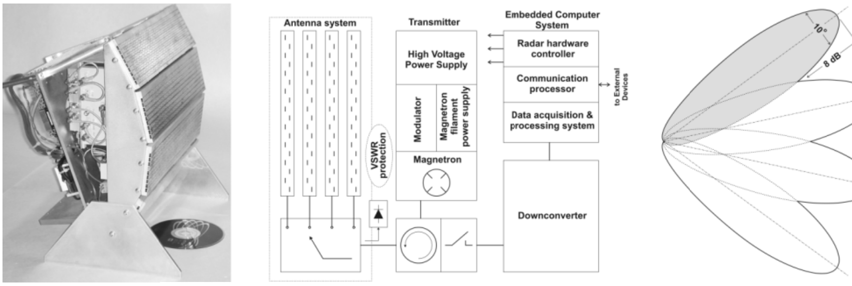


Fig. 3. Doppler spectrum from stationary target located at 5.5 km distance retrieved with Ka band meteorological radar.

Another type of a compact magnetron based Ka band radar is airborne multipurpose radar (Volkov et al, 2007).The developed radar system has been designed especially for applications related to enhancing helicopter flight safety including the detection of power lines and other obstacles, monitoring meteorological conditions, and providing secure landing. But the achieved radar performance enables us to consider it as a versatile sensor, which can be used for other applications. The radar benefits from some novel and cost-effective solutions including a low-noise; digital receiver; an electrically switchable slotted waveguide antenna array as well as a multifunctional data acquisition and signal processing system. The radar outline; a simplified block diagram; and antenna pattern are depicted in Fig. 4 a, b, and c



a) b) c)

Fig. 4. Outline (a), block diagram (b), and antenna pattern (c) of Ka band airborne scanning radar.

correspondingly. In the radar there is no a separate channel to sample the radiated pulse for coherence-on-receiver implementation. Instead the signal leaked through the receiver protection circuitry is used for this purpose (see Section 0). Single frequency conversion as well as a local oscillator based on a direct digital synthesizer has been used in the radar. The essential radar parameters are summarized in Table IV.

Operating frequency, GHz	35±0.2
Peak transmitter power, kW	2.5
Losses, dB, Tx path Rx path	 1.5 2.5
Pulse duration, nsec	50…500
Pulse repetition rate, kHz	1…10
Receiver noise figure, dB	3.0
Receiver dynamical range (max), dB	>90 dB
Time-variation gain control range	24 dB
Minimal distance for full sensitivity, m	50
Antenna	4-sections
Antenna polarization	vertical
Antenna section switching	electrical
Antenna section switching time, μsec	1
Antenna switch decoupling, dB	> 25
Single-pulse sensitivity at 2 km, dBm^2	-13
Total impressed composite wideband noise of Doppler processing @ 3 km, dBc/Hz	-53
Primary power supply, V	18-32 DC
Power consumption (max), W	70
Volume, litre	12
Weight, kg	12

Table IV. Parameters of airborne Ka band scanning radar

A prototype of meteorological W band radar has been developed in the Institute of Radio Astronomy of National Academy of Sciences of Ukraine (Vavriv et al, 2002). It utilizes a proprietary magnetron with cold secondary emission cathode. (see Table I). It is featured by: (i) two separate antennas; (ii) a separate downconverter to sample the radiated signal; and (iii) a high power quasi-optical polarization rotators both in Tx and Rx channels. The radar characteristics are summarized in Table V.
It should be noticed that the radar in question has been developed several years ago and unfortunately no modifications have been provided till now due to our effort were concentrated on the radars operating within Ka band essentially.

Operating frequency, GHz	94
Peak power (max), kW	4
Pulse width, ns	50 - 400
Pulse repetition frequency, kHz	2.5 - 10
Receiver noise temperature, K	1200
Total dynamical range, dB	70
Polarization	HH, VV, HV, VH
Cross-polarization isolation, dB	-25
Antenna diameter, m	0.5
Antenna beam width, deg	0.45
Total impressed composite wideband noise of Doppler processing @ 5 km, dBc/Hz	-47
Sensitivity at 5 km with the integration time of 0.1 sec, dBZ	-41

Table V. Parameters of prototype of W band meteorological radar.

Therefore a serious improvement of its parameter may be expected due to: (i) utilization of a single antenna due to increase in availability of high power circulators and P-i-N switches for the receiver protection circuitry; (ii) an introduction of digital receiver technique as well as a digital frequency control similarly to the above Ka band radars; (iii) the introduction of a low noise amplifier, which have become available during resent time; (iv) the introduction of a synthesized local oscillator; and (v) the introduction of an advanced magnetron modulator.
And at last we would like to provide a brief description W band short pulse transmitter for airport debris radar (Belikov et al, 2002). As known debris are very serious problem to provide enough flight safety. A high resolution as well as a high reliability is a mandatory requirement conceptually for such radars. In the case of magnetron based radar an appropriate resolution may be achieved in a rather simple way, without the utilization of pulse compression. The magnetron with cold-secondary emission cathode used in the transmitter in question provides in addition an extended life time of 10000 hours at least. The parameters of the transmitter are given in Table VI.

Parameter	Measure Unit	Measured Value
Output Frequency(25°C)	GHz	95.086
Frequency Temperature Coefficient	MHz/°C	-1.75
RF Pulse Width (@-3dB, 25°C)	ns	17.5
RF Pulse Width (@-6dB, 25°C)	ns	20
RF Output Peak Power	kW	2

RF Pulse Jitter	ns	3
PRF	kHz	3…30
Supply Voltage min	V	18…32
Current consumption, max @ 28 V	A	14.1
Weight	kg	25
Dimensions		19”, 5U unit

Table VI. Parameters of W band short pulse magnetron transmitter.

In the next section some design approaches used in the above mentioned radars are described briefly.

4. Magnetron based radars – design approaches

4.1 General consideration

Let us to remind briefly that any magnetron based radar is featured as follows: (i) a pulsed operational mode is used; (ii) each RF pulse is characterized by an arbitrary phase; and (iii) the spectrum of RF oscillation depends strongly on a shape of modulation voltage as well as on the parameters of external microwave circuits. On other hand, radar operation consists conceptually in locating the received signal as respect to the radiated one in a corresponding space of signal parameters depending of the radar measurement capabilities. For example in the simplest case of non-coherent pulsed radar this space is two dimensional, with coordinates of amplitude and time respectively. For Doppler radar the phase and frequency dimensions should be added. In truly coherent radar systems the exact location of radiated signal in the space of signal parameters is known a priori. Instead, the above peculiarities attending the magnetron utilization in the radars require introduction of specific approaches to provide a precise location of radiated signal in such space and extend its dimensions, i.e. measurement capabilities of the radar.

The most evident but comprehensive method to ensure exact location of the radiated signal is simply to measure its parameters. It is the only way to get phase information, which is a key issue to implement Doppler processing. Thus each magnetron based Doppler radar should be provided with corresponding circuits to sample a small portion of radiated signal in order to measure its parameters like it is depicted in Fig. 5. The magnetron oscillation frequency is next important parameter, whose measurement accuracy affects strongly the overall radar performance. At first, it determines how precisely a target velocity can be measured.

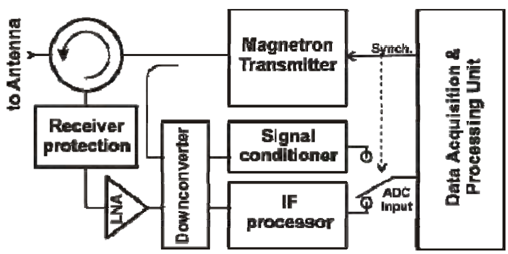


Fig. 5. Typical block-diagram of magnetron based radar.

It does not require a great accuracy and may be implemented relatively easily. Practically in the most cases no measurements are required at all due to a specified magnetron frequency deviation does not exceed a portion of percent in the worst case. A different matter is a pulse-to-pulse frequency deviation. This parameter introduces both non-coherent (noise) and regular components (spurs) into Doppler signal processing (see Fig. 3). In part it determines the ability of the radar to resolve targets with different velocities and reflectivity in the same range bin, e.g. clouds in a strong rain or a moving target in presence of a much stronger reflection from a clutter. As it has been exposed above, the magnetron frequency should be measured with accuracy of about 10^{-7} for a period of several hundred nanoseconds typically or even less, if a higher spatial resolution is required, in order to provide 70 dB spectral dynamical range for Ka band radar and the distance of 5 km. The indicated accuracy is on the edge of contemporary technical capabilities or beyond them, not even to mention the situation inherent to very recent time. Thus at the time being, achieving the maximal possible Doppler performance is the responsibility for the radar circuits, which should ensure as much as possible tight control of magnetron operational parameters – voltage, filament, loading etc, and, finally, its frequency stability. In the nearest future due to a dramatically fast progress in the development of data acquisition and processing hardware we expect that precise measurements of the parameters of the radiated pulse will be a basic method defining radar resolution and instrumentation capabilities. Some promising prospects concerned to this possibility will be discussed later (see Section 4.3.5).
Below in this section we will try to analyze requirements to high performance magnetron based radar and discuss some methods to meet them.

4.2 Transmitter.

4.2.1 General consideration

As mentioned above the modern requirements to the radar performance cannot be met otherwise than designing the magnetron environment to ensure as much as possible stability and safety of its operation. Therefore, the transmitter is probably the most valuable part of either magnetron based high performance radar. Before we will proceed to discuss some design approaches used in the transmitters, let us make a simple calculation in order to give an impression about how precisely its circuits should work. Assume that the aforementioned value of pulse-to-pulse frequency stability $\delta f/f$ of 10^{-7} should be provided. The variations of the amplitude of voltage pulse across magnetron should not exceed value given by the following expression:

$$\Delta V \leq \frac{f_{osc}}{F_{volt}} \cdot \left(\frac{\delta f}{f_{osc}}\right) \cdot R_d \tag{4}$$

where f_{osc} is a magnetron oscillation frequency, F_{volt} – a magnetron oscillation frequency pushing factor, R_d - a dynamical resistance of the magnetron in an operational point, i.e. the slope of its volt-ampere characteristic in this point. Let us take into consideration Ka band magnetron and suggest that the magnetron frequency pushing factor is of 500 kHz/A – a very respectable value, inherent to a highly stable coaxial magnetron rather than any other type, and a dynamical resistance of 300 Ohms – a typical value for devices with 10-100 kW peak power. Then the above expression gives an impressive value of about 2 V, or less than 200 ppm typically, for the required value of pulse-to-pulse amplitude instability of magnetron anode voltage! Note, that the indicated value should be ensured during the

interval of data accumulation for Fourier processing. As usual the duration of this interval may vary within the range from tens millisecond up to several portions of second.
Now, when a reference point for the magnetron transmitter design is indicated in some way or other, it is possible to consider solutions enabling its consummation. A simplified block-diagram of a transmitter is depicted in Fig. 6. It includes the following essential units: (i) a high voltage power supply; (ii) a modulator; (iii) a filament power supply; and (iv) a controller. Let us leave the latter unit beyond a more detailed consideration, mention only that it handles other units according the procedures ensuring the most optimal and safe magnetron operational mode as well as provides the

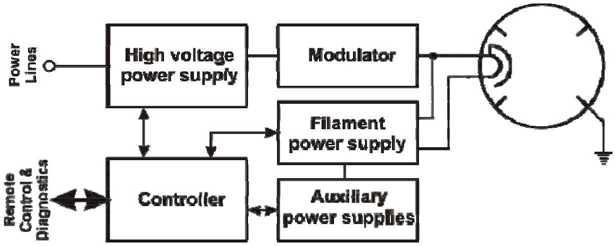


Fig. 6. Block-diagram of magnetron transmitter.

transmitter with remote control and diagnostics abilities. Other above units affect directly the magnetron performance, thus we would like to outline their design in more detail.

4.2.2 High voltage power supply

The high voltage power supply determines essentially the short term magnetron frequency stability, i.e. Doppler performance of whole radar. Thus ensuring its maximal stability is a matter of the highest priority under the development.
A switching mode power supply, based on the utilization of pulse width modulation (PWM) converter, cannot be alternated to produce high voltage in modern systems due to inherent high efficiency, small dimensions, and light weight. However the voltage stability provided by such supply is lower generally than that of linear regulators. On other hand, characteristics of PWM converter may be improved to an extent allowing its standalone utilization. Our experience to develop the high voltage power supplies for the magnetron based radars demonstrates a benefit of the following rules. At first, PWM converter should utilize operation in either peak current or close to it mixed mode rather than in pure voltage mode. Such approach as well as the usage of a frequency compensated high voltage divider assists maximizing both rejection of the input voltage ripples and the overall stability of the voltage regulation loop. Next, it is mandatory to synchronize PWM converter at a frequency multiple to the pulse repetition frequency of the radar, which eliminates practically completely the influence of ripples at PWM operational frequency. And at last, the utilization of a particular pre-regulator is preferably. In this respect, the usage of a power factor corrector for AC powered systems is virtually compulsorily.
For information, the line of Ka band meteorological radar demonstrating a very solid Doppler performance (see Section 0) is equipped with the high voltage power supply developed according strictly to the above recommendations. A flyback topology is used for PWM converter. From our opinion, such topology is the most suitable to the high voltage

applications with the output power up to 1 kW and voltages up to 20 kV for AC powered radar systems or even airborne DC powered radars if an appropriate step-up pre-regulator is used. The essential advance of such scheme is a stable operation with a capacitive load within a wide range of output power as well as the ability to provide the output voltage swing across the primary windings of the high voltage transformer much greater than a supply voltage. The above peculiarities meet perfectly actual operational conditions of the high voltage power supply in a magnetron based transmitters. As can be easily seen form Fig. 3 there is no regular spurious components caused by ripples of the output voltage of high voltage power supply at the harmonics of both AC power line frequency and the operational frequency of PWM converter (folded).

4.2.3 Modulator

In this section we will consider briefly some issues related to the development of up-to date high voltage modulators used in high performance radars. In general the modulator includes circuits to form the pulse with a definite shape across the magnetron terminals. In the most cases a near-rectangle shape of RF pulse is a target under the modulator development. Since the magnetron frequency depends strongly on the applied voltage, any deviation of the pulse shape from the rectangular one results in a drop in the radar sensitivity. Thus, both transients and the distortions of flat part of the pulse should be minimized. Especially it is important for the millimeter wavelengths magnetrons, which are characterized by a rather short width of the output pulse. On other hand the most types of magnetrons requires a well controllable voltage rate during the leading edge of the modulation pulse to facilitate running oscillation (Okress, 1961). In this case faster does not mean better! An opposite situation appears for the trailing edge. As usual a less attention is drawn to ensure its appropriately short duration. However, not only shape of RF envelope should be taken into consideration there. It is due to the magnetrons have a rather considerable threshold current to produce RF oscillation as usual. It means that the current pulse through the magnetron may be much longer than RF pulse as depicted in Fig. 7. Notice that at lower voltages the power of back bombardment of the magnetron cathode is much greater as respect to anode power as indicated in Fig. 7. Evidently, the shorter RF pulse duration and higher pulse repetition rate the stronger the above effect affects the magnetron performance. Thus the above issue should be always taken into consideration while a pulse repetition rate greater than several kilohertz is required.

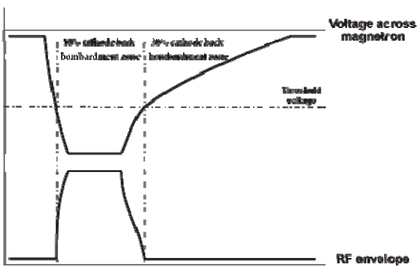


Fig. 7. Waveforms of voltage pulse across magnetron and RF envelope.